

Introduction to the Smart Grid:

Concepts, Technologies and Evolution

Salman K. Salman



IET ENERGY ENGINEERING SERIES 94

Introduction to the Smart Grid

Other volumes in this series:

Volume 1	Power Circuit Breaker Theory and Design C.H. Flurscheim (Editor)
Volume 4	Industrial Microwave Heating A.C. Metaxas and R.J. Meredith
Volume 7	Insulators for High Voltages J.S.T. Looms
Volume 8	Variable Frequency AC Motor Drive Systems D. Finney
Volume 10	SF₆ Switchgear H.M. Ryan and G.R. Jones
Volume 11	Conduction and Induction Heating E.J. Davies
Volume 13	Statistical Techniques for High Voltage Engineering W. Hauschild and W. Mosch
Volume 14	Uninterruptible Power Supplies J. Platts and J.D. St Aubyn (Editors)
Volume 15	Digital Protection for Power Systems A.T. Johns and S.K. Salman
Volume 16	Electricity Economics and Planning T.W. Berrie
Volume 18	Vacuum Switchgear A. Greenwood
Volume 19	Electrical Safety: A guide to causes and prevention of hazards J. Maxwell Adams
Volume 21	Electricity Distribution Network Design, 2nd Edition E. Lakervi and E.J. Holmes
Volume 22	Artificial Intelligence Techniques in Power Systems K. Warwick, A.O. Ekwue and R. Aggarwal (Editors)
Volume 24	Power System Commissioning and Maintenance Practice K. Harker
Volume 25	Engineers' Handbook of Industrial Microwave Heating R.J. Meredith
Volume 26	Small Electric Motors H. Moczala <i>et al.</i>
Volume 27	AC–DC Power System Analysis J. Arrillaga and B.C. Smith
Volume 29	High Voltage Direct Current Transmission, 2nd Edition J. Arrillaga
Volume 30	Flexible AC Transmission Systems (FACTS) Y.-H. Song (Editor)
Volume 31	Embedded generation N. Jenkins <i>et al.</i>
Volume 32	High Voltage Engineering and Testing, 2nd Edition H.M. Ryan (Editor)
Volume 33	Overvoltage Protection of Low-Voltage Systems, Revised Edition P. Hasse
Volume 36	Voltage Quality in Electrical Power Systems J. Schlabbach <i>et al.</i>
Volume 37	Electrical Steels for Rotating Machines P. Beckley
Volume 38	The Electric Car: Development and future of battery, hybrid and fuel-cell cars M. Westbrook
Volume 39	Power Systems Electromagnetic Transients Simulation J. Arrillaga and N. Watson
Volume 40	Advances in High Voltage Engineering M. Haddad and D. Warne
Volume 41	Electrical Operation of Electrostatic Precipitators K. Parker
Volume 43	Thermal Power Plant Simulation and Control D. Flynn
Volume 44	Economic Evaluation of Projects in the Electricity Supply Industry H. Khatib
Volume 45	Propulsion Systems for Hybrid Vehicles J. Miller
Volume 46	Distribution Switchgear S. Stewart
Volume 47	Protection of Electricity Distribution Networks, 2nd Edition J. Gers and E. Holmes
Volume 48	Wood Pole Overhead Lines B. Wareing
Volume 49	Electric Fuses, 3rd Edition A. Wright and G. Newbery
Volume 50	Wind Power Integration: Connection and system operational aspects B. Fox <i>et al.</i>
Volume 51	Short Circuit Currents J. Schlabbach
Volume 52	Nuclear Power J. Wood
Volume 53	Condition Assessment of High Voltage Insulation in Power System Equipment R.E. James and Q. Su
Volume 55	Local Energy: Distributed generation of heat and power J. Wood
Volume 56	Condition Monitoring of Rotating Electrical Machines P. Tavner, L. Ran, J. Penman and H. Sedding
Volume 57	The Control Techniques Drives and Controls Handbook, 2nd Edition B. Drury
Volume 58	Lightning Protection V. Cooray (Editor)
Volume 59	Ultracapacitor Applications J.M. Miller
Volume 62	Lightning Electromagnetics V. Cooray
Volume 63	Energy Storage for Power Systems, 2nd Edition A. Ter-Gazarian
Volume 65	Protection of Electricity Distribution Networks, 3rd Edition J. Gers
Volume 66	High Voltage Engineering Testing, 3rd Edition H. Ryan (Editor)
Volume 67	Multicore Simulation of Power System Transients F.M. Uriate
Volume 68	Distribution System Analysis and Automation J. Gers
Volume 69	The Lightning Flash, 2nd Edition V. Cooray (Editor)
Volume 70	Economic Evaluation of Projects in the Electricity Supply Industry, 3rd Edition H. Khatib
Volume 72	Control Circuits in Power Electronics: Practical issues in design and implementation M. Castilla (Editor)
Volume 73	Wide Area Monitoring, Protection and Control Systems: The enabler for Smarter Grids A. Vaccaro and A. Zobaa (Editors)
Volume 74	Power Electronic Converters and Systems: Frontiers and applications A.M. Trzynadlowski (Editor)
Volume 75	Power Distribution Automation B. Das (Editor)
Volume 76	Power System Stability: Modelling, analysis and control B. Om P. Malik
Volume 78	Numerical Analysis of Power System Transients and Dynamics A. Ametani (Editor)
Volume 79	Vehicle-to-Grid: Linking electric vehicles to the smart grid J. Lu and J. Hossain (Editors)
Volume 81	Cyber-Physical-Social Systems and Constructs in Electric Power Engineering Siddharth Suryanarayanan, Robin Roche and Timothy M. Hansen (Editors)
Volume 82	Periodic Control of Power Electronic Converters F. Blaabjerg, K. Zhou, D. Wang and Y. Yang
Volume 86	Advances in Power System Modelling, Control and Stability Analysis F. Milano (Editor)
Volume 88	Smarter Energy: From Smart Metering to the Smart Grid H. Sun, N. Hatziaargyriou, H.V. Poor, L. Carpanini and M.A. Sánchez Fornié (Editors)
Volume 89	Hydrogen Production, Separation and Purification for Energy A. Basile, F. Dalena, J. Tong, T.N. Veziroğlu (Editors)
Volume 93	Cogeneration and District Energy Systems: Modelling, Analysis and Optimization M.A. Rosen and S. Koohi-Fayegh
Volume 95	Communication, Control and Security Challenges for the Smart Grid S.M. Mueyen and S. Rahman (Editors)
Volume 97	Synchronized Phasor Measurements for Smart Grids M.J.B. Reddy and D.K. Mohanta (Editors)
Volume 100	Modeling and Dynamic Behaviour of Hydropower Plants N. Kishor and J. Fraile-Ardanuy (Editors)
Volume 101	Methane and Hydrogen for Energy Storage R. Carrière and David S.-K. Ting
Volume 905	Power system protection, 4 volumes

Introduction to the Smart Grid:

Concepts, Technologies and Evolution

Salman K. Salman

Published by The Institution of Engineering and Technology, London, United Kingdom

The Institution of Engineering and Technology is registered as a Charity in England & Wales (no. 211014) and Scotland (no. SC038698).

© The Institution of Engineering and Technology 2017

First published 2017

This publication is copyright under the Berne Convention and the Universal Copyright Convention. All rights reserved. Apart from any fair dealing for the purposes of research or private study, or criticism or review, as permitted under the Copyright, Designs and Patents Act 1988, this publication may be reproduced, stored or transmitted, in any form or by any means, only with the prior permission in writing of the publishers, or in the case of reprographic reproduction in accordance with the terms of licences issued by the Copyright Licensing Agency. Enquiries concerning reproduction outside those terms should be sent to the publisher at the undermentioned address:

The Institution of Engineering and Technology
Michael Faraday House
Six Hills Way, Stevenage
Herts, SG1 2AY, United Kingdom

www.theiet.org

While the author and publisher believe that the information and guidance given in this work are correct, all parties must rely upon their own skill and judgement when making use of them. Neither the author nor publisher assumes any liability to anyone for any loss or damage caused by any error or omission in the work, whether such an error or omission is the result of negligence or any other cause. Any and all such liability is disclaimed.

The moral rights of the author to be identified as author of this work have been asserted by him in accordance with the Copyright, Designs and Patents Act 1988.

British Library Cataloguing in Publication Data

A catalogue record for this product is available from the British Library

ISBN 978-1-78561-119-3 (hardback)

ISBN 978-1-78561-120-9 (PDF)

Typeset in India by MPS Limited

Printed in the UK by CPI Group (UK) Ltd, Croydon

Contents

About the Author	xiii
Preface	xv
Acknowledgments	xxi
Terminologies and abbreviations	xxiii
1 Introduction to the Smart Grid concept	1
1.1 Background and history of Smart Grid evolution	1
1.2 Definition of the Smart Grid	3
1.3 Characteristics of the Smart Grid	5
1.4 Smart Grid benefits	9
1.5 Smart Grid vision and its realization	10
1.5.1 Definition of Smart Grid vision	10
1.5.2 The IEEE Computer Society Smart Grid Vision	11
1.6 Examples of Smart Grid projects/initiatives	13
1.6.1 US Smart Grid efforts	13
1.6.2 European Smart Grid efforts	15
1.6.3 China's Smart Grid efforts	18
1.7 Summary	20
References	20
2 Smart Grid versus conventional electrical networks	25
2.1 Introduction	25
2.2 Conventional electrical networks	25
2.2.1 Infrastructure of conventional electrical networks	25
2.2.2 Main characteristics of conventional electrical networks	26
2.3 Motives behind developing the Smart Grid concept	26
2.3.1 Aging of conventional electrical networks coupled with the emergence of new applications	27
2.3.2 Political and environmental factors	27
2.3.3 Liberalization of electricity market (economic factors)	28
2.3.4 Motivation and inclusion of customers	28
2.4 Comparison between Smart Grid and conventional electrical networks	28
2.5 Evolution of Smart Grid concept	28
2.5.1 Characteristics of Smart Grid as defined by EU and US Smart Grid visions	29
2.5.2 Advanced metering infrastructure	32

2.6	An overview of the Smart Grid infrastructure	40
2.7	Summary	40
	References	41
3	Smart Grid infrastructure	45
3.1	Introduction	45
3.2	Composition of the Smart Grid	46
3.2.1	Composition of Smart Grid based on standards adaptation	46
3.2.2	Composition of Smart Grid based on technical components' perspective	47
3.2.3	Composition of Smart Grid based on technical perspective	51
3.2.4	Composition of Smart Grid based on conceptual reference model perspective	52
3.3	Basic components of Smart Grid and its technical infrastructure	56
3.3.1	Basic components of Smart Grid	56
3.3.2	Smart Grid infrastructure	58
3.4	Summary	60
	References	60
4	Smart Grid interoperability standards	63
4.1	Introduction	63
4.2	Analogy between the interoperability of a digitally based device and human interoperability	63
4.2.1	Definition	63
4.3	Cyber interoperability standards	64
4.3.1	Aim of interoperability standards	64
4.3.2	Type and characteristics of interoperability standards for Smart Grid	65
4.4	Interoperability standards development organizations	65
4.5	Electrical power industry standards development organizations (SDOs) and key interoperability standards	66
4.5.1	The International Electrotechnical Commission	66
4.5.2	Institute of Electrical and Electronic Engineers (IEEE)	66
4.5.3	Internet Engineering Task Force	67
4.5.4	American National Standards Institute (ANSI)	68
4.5.5	National Institute of Standards and Technology (NIST)	69
4.5.6	North American Electric Reliability Corporation (NERC)	70
4.5.7	World Wide Web Consortium (W3C)	70
4.5.8	German Standards Institute DIN (<i>Deutsches Institut für Normung</i>)	71
4.6	Users groups and collaborative efforts within the power industry	71
4.6.1	UCA International Users Group	71

4.6.2	National Rural Electric Cooperative Association (NRECA)'s MultiSpeak	72
4.6.3	Cigré	72
4.6.4	GridWise™ Alliance	72
4.6.5	Electric Power Research Institute (EPRI)'s IntelliGrid program	73
4.6.6	Vendor collaborations	74
4.6.7	Utility Standards Board	76
4.7	Summary	77
	References	77
5	Smart Grid communication system and its cyber security	81
5.1	Introduction	81
5.2	Classification of power system communication according to their functional requirements	81
5.2.1	Real-time operational communication systems	81
5.2.2	Administrative operational communication systems	82
5.2.3	Administrative communication systems	83
5.3	Existing electric power system communication infrastructure and its limitation	83
5.4	Smart Grid communication system infrastructure	86
5.4.1	Fundamental functions of the Smart Grid communication infrastructure	87
5.4.2	Architecture of Smart Grid communication infrastructure	87
5.4.3	Smart Grid communication infrastructure challenges	87
5.4.4	Standardization efforts by industry	88
5.5	Cyber security of power systems	89
5.5.1	Basic definitions	89
5.5.2	Security of power systems and cyber attacks	90
5.5.3	Smart Grid cyber security	91
5.6	Summary	99
	References	99
6	International standard IEC 61850 and its application to Smart Grid	103
6.1	Introduction and historical background	103
6.2	Aim and objectives of IEC 61850	105
6.3	The structure of IEC 61850	105
6.4	The process bus	107
6.4.1	Practical implementation of the process bus	108
6.5	Merging unit	109
6.6	Comprehensive modeling approach of IEC 61850	110
6.7	Mapping process approach of IEC 61850 to protocols	114
6.8	IEC 61850 substation configuration language	115
6.9	IEC 61850 substation architecture	116

6.10	Smart Grids and IEC 61850	117
6.10.1	Example of Smart Grid demonstration projects using IEC 61850	118
6.11	Summary	119
	References	119
7	Power system protection under Smart Grid environment	121
7.1	Introduction	121
7.2	Protection prior to the Smart Grid era	122
7.3	Protection systems under Smart Grid environment	122
7.3.1	Operating concepts of Smart Grid protection relays	122
7.3.2	Fault circuit indicator	123
7.4	Smart Grid communication infrastructure that suits protection requirements	125
7.5	Smart Grid requires smarter protection	126
7.6	Architecture of Smart Grid protection system	128
7.7	Examples on development of smart adaptive protection systems	131
7.7.1	Smart adaptive protection for microgrids	132
7.7.2	Adaptive protection for smart distribution networks	135
7.8	Protection system architecture based on IEC 61850	137
7.8.1	Traditional practices	138
7.8.2	New opportunities offered by the introduction of IEC 61850 standard	138
7.9	Summary	140
	References	140
8	Application of Smart Grid concept to distribution networks	143
8.1	Introduction	143
8.2	Smart distribution networks versus conventional distribution networks	143
8.3	Why distribution networks need to be smart?	144
8.4	Basic building blocks of a smart distribution network	144
8.4.1	Agents	145
8.4.2	Characteristics of agents	145
8.4.3	PowerMatch	146
8.4.4	E-terra trade	146
8.4.5	E-terra control	146
8.5	Evolution of distribution networks into Smart Grids	147
8.5.1	Flexible Electricity Networks to Integrate the eXpected Energy Evolution (FENIX)	147
8.5.2	Active Distribution network with full integration of Demand and distributed energy RESourceS (ADDRESS)	152
8.6	Summary	159
	References	160

9	Smart Grid enables the integration of electric vehicles	163
9.1	Introduction	163
9.2	Types of electric drive vehicle	164
9.3	Benefits of transportation electrifications	165
9.4	The driving factors toward transportation electrification	165
9.5	Challenges to EV adoption	166
9.5.1	Challenges faced by customers	166
9.5.2	Challenges faced by utilities	167
9.6	Types of EV charging systems	169
9.6.1	L1 AC charging systems	169
9.6.2	L2 AC charging systems	169
9.6.3	L3 DC Charging stations	169
9.7	Smart Grid enables smart charging	170
9.7.1	Robust, reliable, and secure connectivity	170
9.7.2	Integration of EV charging infrastructure into demand side management (DSM) system	170
9.7.3	Provision of distributed intelligence	171
9.7.4	Provision of a separate meter at the EVSE integrated into AMI	171
9.7.5	Integration of EV charging infrastructure into DR system	171
9.7.6	Integration of EV charging infrastructure into distributed automation (DA) system	172
9.7.7	Coordination with renewable energy-based generation	172
9.8	Load management of EVs using Smart-Grid technologies	172
9.8.1	The difference EVs make to electricity load	172
9.8.2	Optimizing scheduling of EV charging using Smart-Grid technologies	172
9.8.3	EVs can help in meeting peak load	173
9.8.4	Management of intermittent renewable energy-based generation using EVs	173
9.8.5	Effect of regulation, electricity pricing business models for EVs charging stations on load management of EVs	174
9.9	Flexibility of electric vehicles and their integration into Smart Grid	175
9.9.1	Definition of flexibility in relation to EV	176
9.9.2	Components related to EV-Smart-Grid integration	177
9.9.3	Management of the flexibility provided by EVs stored energy	180
9.10	Coordination of multiple plug-in electric vehicle charging in Smart Grids using real-time smart load management (RT-SLM) algorithm	181
9.10.1	Background and assumptions	182
9.10.2	RL-SLM coordination algorithm	184

9.10.3	Automation of scheduling PEVs charging using RT-SLM algorithm	187
9.11	Summary	188
	References	188
10	Smart Grid and energy storage systems	193
10.1	Introduction	193
10.2	Characteristics of energy storage devices/systems	193
10.3	Types and characteristics of EES systems	194
10.3.1	Mechanical storage systems	195
10.3.2	Electrochemical storage systems (batteries)	196
10.3.3	Chemical ESS	201
10.3.4	Electrical storage systems	204
10.3.5	Thermal energy storage systems	205
10.4	Benefits of ESSs	208
10.5	Applications of ESSs	209
10.5.1	Electrical network energy storage applications	210
10.5.2	Transport and mobility energy storage applications	210
10.6	Energy storage systems and integration of wind power-based plants	211
10.6.1	Mitigation of power fluctuation	211
10.6.2	Improvement in LVRT capability	216
10.7	Summary	218
	References	218
11	Smart transmission grid	223
11.1	Introduction	223
11.2	Why transmission grids need to be smart?	223
11.3	Challenges and requirements of future STG	224
11.3.1	Environmental challenges	224
11.3.2	Market/customer requirements	224
11.3.3	Infrastructure challenges	224
11.3.4	Adaptation of innovative technologies	225
11.4	The essential aspects of the STG	225
11.4.1	Integration of synchrophasor measurements technology into transmission system operation and control	225
11.4.2	Compatibility of ICT infrastructure	227
11.4.3	Operational and coordination issues	227
11.5	Vision of future STG	228
11.5.1	Characteristics of future STG	228
11.5.2	Basic components of STG	230
11.5.3	Smart transmission network	231
11.5.4	Smart transmission substations	232
11.5.5	Smart control centers	237

11.6	Current research activities on STG	243
11.6.1	Smart transmission grid research in Europe	243
11.6.2	Smart transmission grid research in USA	248
11.6.3	Smart transmission grid research in China	253
11.7	Summary	256
	References	256
Index		259

This page intentionally left blank

About the author

Salman K. Salman is Professor Emeritus at Robert Gordon University (RGU) – Aberdeen. He was the Head of Renewable Energy and Power Systems Group at RGU. His research interest includes integration of renewable energy sources into electrical distribution networks, modeling of wind turbines, protection of distribution networks with integrated distributed generation, and substation automation. He worked closely with industry including ALSTOM, ScottishPower, Cruickshank and Partners, National Grid, and SiGen. His work has resulted in developing a prototype energy system consisting of two-wind turbine 15 kW each, fuel cell, hydrogen storage system, and small electric vehicle. It was installed at Unst isle, Shetland, north of Scotland, UK. Another example of his work is the development of a very sophisticated voltage control system in collaboration with Cruickshank and Partners and national grid, which was adopted by national grid for controlling their 400 kV substations. He is the co-author of the book titled “Digital protection for power systems,” published by the IEE. He is the author of more than 120 papers.

This page intentionally left blank

Preface

In recent years, it has been recognized that conventional electrical networks cannot meet the requirements of the twenty-first century in terms of reliability, efficiency, meeting the requirements of liberalization of electricity market, effective and seamless integration of various types of renewable energy sources, integration of electric vehicles (EVs), and inclusion of customers as players to support the grid to which they are connected. This has led to seriously consider the necessity to modernize electrical supply networks and hence the Smart Grid concept has emerged. Additionally, the emergence of new technologies such as distributed control, monitoring devices, computing and tremendous advances in information and communication technologies has paved the way to the realization of Smart Grid concept.

Hence, the idea of writing a book on Smart Grid has come about. The aim is to explain the evolution of Smart Grid. The book is intended for professionals, academia and research communities. The book therefore focuses on discussing the tools, drivers, technologies that are necessary to realize Smart Grid concept. The subject of the book is covered under 11 chapters as outlined below.

Chapter 1. In this chapter, the concept of Smart Grids and background are introduced. This is followed by an extensive literature survey related to the definition of the “Smart Grid.” A comprehensive definition of the Smart Grid may read: “A smart grid is an electricity network that uses digital and other advanced technologies, such as cyber-secure communication technologies, automated and computer control systems, in an integrated fashion to be able to monitor and intelligently and securely manage the transport of electricity from all generation sources both traditional and renewable to economically meet the varying electricity demands of end-users.”

Chapter 2. In this chapter, the motives behind the development of the Smart Grid concept have been identified. Such motives include aging of conventional electrical networks, political and environmental factors, economical factors, and motivation and inclusion of customers connected to Smart Grid. The evolution of the Smart Grid concept is then discussed. The advanced metering infrastructure (AMI), which is also known in Europe as smart metering system (SMS), was then introduced. AMI is considered a fundamental and first step to the overall modernization of conventional electrical networks which eventually has led to the development of the Smart Grid vision. AMI is viewed as an important tool for providing the essential link required between the grid, consumers and their loads, and generation and storage resources. Definition of AMI is given followed by

discussing its main components, AMI communication infrastructure, and the adopted communication technologies for AMI. This is followed by giving a brief overview of the Smart Grid infrastructure and its characteristics.

Chapter 3. In this chapter, the compositions of Smart Grid and the basis on which such compositions are defined have been discussed. This includes composition of Smart Grid based on standards adaptation, composition of Smart Grid based on technical components' perspective, composition of Smart Grid based on technical perspective, and composition of Smart Grid based on conceptual perspective.

Identification of the basic components of Smart Grid that are currently in use is then covered. It has been recognized that new components are continued to be developed as the Smart Grid evolves.

Chapter 4. In this chapter, the tool required to ensure the interoperability among the various digitally based components of the Smart Grid, which is considered a key requirement of the Smart Grid realization, is identified and discussed. Such tool is represented by the internationally recognized communication and interface standards. An analogy between the interoperability of a digitally based device and human interoperability is introduced. Cyber-interoperability standards are discussed highlighting their aim, type, and characteristics. Standards development organizations of power industry and the key interoperability standards that they are involved with are discussed. Additionally, the input of users groups and collaborative efforts within the power industry toward developments of interoperability standards is also discussed.

Chapter 5. This chapter is devoted to Smart Grid communication system and its cyber-security. A classification of power system communication (PSC) systems according to their requirements is given. They are classified into real-time operational communication systems, administrative operational communication systems, and administrative communication systems. This is followed by discussing the existing electric PSC infrastructure and highlighting its limitation. In particular, the following topics have been covered: overview of current PSC systems and their characteristics, shortcomings of current PSC systems, and characteristics of future PSC systems that suit Smart Grid requirements

Smart Grid communication system infrastructure was then discussed. This includes fundamental functions of the Smart Grid communication infrastructure, architecture of Smart Grid communications infrastructure, Smart Grid communications infrastructure challenges and standardization efforts by industry

Finally, cyber-security of power systems/Smart Grid was then discussed. It begins with giving definition of cyber-infrastructure and cyber-security. This is then followed by discussing security of power systems and cyber-attacks. The Smart Grid cyber-security was then discussed, which covered Smart Grid cyber-security challenges, emerging Smart Grid cyber-security technologies, compliance versus security, and Smart Grid cyber-security standards.

Chapter 6. This chapter is devoted to the application the international standards IEC 61850 to Smart Grid. An overview of the standards IEC 61850 is given highlighting its relevance to the development of the Smart Grid concept.

The discussion is started by giving an introduction and background of IEC 61850, its aim and objectives and its structure. The concept of “Process Bus” is then introduced followed by discussing its practical implementation. This is followed by discussing the comprehensive modeling approach of IEC 61850 and mapping process approach of IEC 61850 to protocols. Substation configuration language (SCL) as specified in IEC 61850 is then discussed followed by developing an IEC 61850 substation architecture model. Finally, an explanation as how IEC 61850 can be used to transform conventional electrical power network into Smart Grid is given. This is followed by covering an EU-funded project known as “Web2Energy” that uses IEC 61850-based communication system. In this project, the use of IEC 61850 by self-healing grid and distributed generation plants to communicate with the control center over various communication channels was highlighted.

Chapter 7. Development of Smart Grid concept could profoundly affect the way the relaying and protection of power systems are implemented. This chapter is therefore devoted to discuss power system protection under Smart Grid environment. Initially an overview of the protection prior to the Smart Grid era is given. This is followed by discussing relaying protection under Smart Grid environment highlighting the expected benefits. The operating concepts of Smart Grid protection relays and intelligent fault circuit indicator for Smart Grid applications are then covered. This is followed by discussing the communication infrastructure that suits protection requirements. How Smart Grid requires smarter protection is then explained. This is followed by discussing the architecture of Smart Grid protection system highlighting the application of multiagent technology and the relationship between multiagent systems and IEC 61850. Examples on development of smart adaptive protection systems are then given. These include smart adaptive protection for microgrids and adaptive protection for smart distribution networks. The chapter is concluded by presenting protection system architecture based on IEC 61850 under which two topics were covered: smart adaptive protection for microgrids and new opportunities offered by the introduction of IEC 61850.

Chapter 8. An overview of the application of Smart Grid concept to distribution networks is covered in this chapter. It begins by outlining the main differences between conventional distribution networks and their counterpart smart distribution networks. This is followed by explaining as why distribution networks are needed to be smart. The basic building blocks from which a smart distribution network consists of are then covered. Finally, the evolvement of conventional distribution networks into smart distribution networks is discussed. In this context and in order to achieve this objective, two EU projects, namely FENIX and ADDRESS, have been initiated which are briefly covered respectively.

In FENIX project, the concept of a virtual power plant (VPP) has been introduced as way forward to ensure the flexibility of distribution networks with regard to the integration of distributed energy resource/renewable energy source (DER/RES) units. The aim of ADDRESS project is to develop a comprehensive commercial and technical framework suitable for the development of “Active Demand” and to exploit its market-based benefits.

Chapter 9. This chapter is devoted to discussing how the integration of EVs is enabled by the Smart Grid. It begins by highlighting the benefits gained from the electrification of transportation and the factors that drive toward transportation electrification. The challenges to EV adoption faced by both customers and utilities are then discussed. This is followed by discussing the types of EV charging stations, which is also known as EV supply equipment (EVSE). Smart charging enabled by Smart Grid is then covered. The load management of EVs using Smart Grid technologies was then discussed. Under this title, several topics were covered including the difference EVs can make to electricity load, optimizing EV charging scheduling using Smart Grid technologies, explaining the use of EVs to help meet peak load, use of EVs combined with application of relevant regulations to manage the intermittency of renewable energy-based generation, and electricity pricing business models for EVs charging stations on load management of EVs. This is followed by discussing the flexibility of EVs and their integration into Smart Grid, whereby the definition of flexibility in relation to EV was introduced followed by discussing the components related to EV-Smart Grid integration and then the management of the flexibility provided by EV stored energy was covered. Finally, automatic charging scheduling of multiple plug-in EV to be connected to a Smart Grid using real-time smart load management (RL-SLM) algorithm was discussed. Among other things covered under this title include the basic components of RL-SLM algorithm, outlining the formulation of the optimization algorithm used to minimize generation and losses during PEVs charging and automation of scheduling PEVs charging using RT-SLM algorithm, whereby the operating principles of RT-SLM algorithm and its implementation were explained.

Chapter 10. This chapter is devoted to energy storage systems (ESS). The characteristics of energy storage devices/systems are discussed. This is then followed by discussing types and characteristics of electrical ESS. The types covered include mechanical storage systems, electrochemical storage systems (batteries), chemical ESS, electrical storage systems and thermal ESS. The potential benefits of ESS to Smart Grids in terms of enhancing their performance, operability, and security as well as reducing the cost of energy production and delivery are highlighted. Applications of ESS are then introduced. Such applications may be broadly divided into electrical network energy storage and transport and mobility energy storage. The application of ESS to facilitate effective and efficient integration of wind power-based generation (WPBG) into Smart Grid distribution networks is discussed. The discussion has focused on mitigation of power fluctuation caused by WPBG and on the improvement in low-voltage-ride-through (LVRT) capability.

Chapter 11. This chapter concerns with the development of smart transmission grid (STG). The reasons for the need of STG are discussed. This is then followed by discussing the challenges and requirements of future STG, which include environmental challenges, market/customer requirements, infrastructure challenges, and adaptation of innovative technologies. The essential aspects of the STG are then highlighted. These include integration of synchrophasor measurements technology into transmission system operation and control, the necessity of having compatible ICT infrastructure, and resolving the operational and coordination issues.

The vision of future STG is then discussed in which various topics have been covered including the characteristics of future STG, the basic components of STG that consist of smart transmission network, smart transmission substations, and smart control centers. An example of a 500 kV practical smart transmission substation is given. The discussion covered includes the applied architecture of IEC 61850 SAS using station and process buses, IEEE 1588 standard for precise time synchronization, and the communication network used inside the substation.

The smart control centers are discussed covering a review of the development of the control centers over the period expanding from the 1950s till the 1990s. Then the vision of functions that future smart control centers should have was highlighted. Such functions include monitoring/visualization, analytical capability, controllability, and electricity market interface.

Finally this chapter is concluded by discussing research activities at the time of writing this book that are conducted in Europe, the USA, and China aiming specifically at the development of STG.

Salman K. Salman
December 2016

This page intentionally left blank

Acknowledgments

The author thanks Robert Gordon University (RGU)-Aberdeen for providing access to RGU's library facilities. He also thanks Paul Deards (Publisher – Academic Books, The IET) for his help in clarifying the matter related to securing permission to reuse materials.

The author thanks NIST, OECD, Xanthus Consulting International, the European Parliament, and Springer for permission to reproduce information from their publications.

Finally, the author thanks the International Electrotechnical Commission (IEC) for permission to reproduce information from its international publications. All such extracts are copyright of IEC Geneva, Switzerland. All rights reserved. Further information on the IEC is available from www.iec.ch. IEC has no responsibility for the placement and context in which the extracts and contents are reproduced by the author, nor is IEC in any way responsible for the other content or accuracy therein.

This page intentionally left blank

Terminologies and abbreviations

4G	Fourth generation. It is the fourth generation of mobile telecommunication technology, succeeding 3G and preceding 5G technologies.
AAM	Advanced asset management
ACL	Agent communication language
AD	Active demand, which means the active participation of domestic and small commercial consumers (and prosumers) in the electricity markets and in the provision of services to the other electricity system participants
ADO	Advanced distribution operations
AGC	Automatic generation control
AMI	Advanced metering infrastructure
AMM	Automated meter management
AMM	Advanced meter management
AMR	Automated meter reading
ASAP-SG	Advanced security acceleration project for the Smart Grid
ATO	Advanced transmission operations
BMS	Battery management system
BMS	Business management system
CAPS	Centralized adaptive protection system
CB	Circuit breaker
CIM	Common information model
CIS	Customer information system
CCVT	Capacitance coupled voltage transformer
CSP	Concentrated solar power
DAR	Delayed auto reclosing
CCP	Common coupling point
CPC	Constant power control
DAS	Data acquisition system
DER	Distributed energy resources

DFIG	Doubly fed induction generator
DHS	Department of Homeland Security
DSO	Distributed system operator
TSO	Transmission system operator
DMS	Distribution management systems
DNP	Distributed Network Protocol
DR	Demand response
DSM	Demand side management
ED	Economic dispatch
EISA	Energy Independence and Security Act
EMS	Energy management systems
ESS	Energy storage system
EV	Electric vehicle
EVSE	EV supply equipment
EU	European Union
ECT	Electronic current transformer
EVT	Electronic voltage transformer
FAN	Field area networks
FAT	Factory acceptance test
FERC	Federal Energy Regulatory Commission
FM agents	Function management agents
Gencos	Generation companies
GIS	Geographic information system
GOMSFE	General object models for substation and field equipment
GOOSE	Generic object-oriented substation events
GPS	Global positioning system
GSC	Grid-side converter
GSE	Generic substation event
GSSE	Generic substation state events
HAN	Home area network
HEV	Hybrid electric vehicle
ICT	Information and communication technology
IEDs	Intelligent electronic devices
IoT	Internet of things
IP	Internet Protocol
ISO/RTO	Independent System Operator/Regional Transmission Organization

ISO	International Standards Organization
LAN	Local area networks
LFC	load frequency control
LMP	Location marginal prices
LN	Logical node
LSE	Load serving entity
LOM	Loss-of-mains
LTE	Long-term evolution
LVRT	Low-voltage ride through
MAC	Media access control
MDMS	Meter data management systems
MGCC	Microgrid central controller
MMS	Manufacturing message specification
MU	Merging unit
MUC	Multiutility communication
NAN	Neighbourhood Area Network
NETL	National Energy Technology Laboratory (USA)
NERC	North American Electric Reliability Corporation
NERC CIP	North American Electric Reliability Corporation Critical Infrastructure Protection
NCIT	Nonconventional instrument transformer
NIST	National Institute of Standards and Technology of North America
NTP	Network Time Protocol
OC	Over current
OMS	Outage management systems
OPF	Optimal power flow
OSI	Open system interconnect
PDC	Phasor data concentrator
PCM	Phase change material
PHEV	Plug-in hybrid electric vehicle
PHY	Physical layer
PLC	Power line carrier
PMU	Phasor measurement unit
PPS	Pulse per second
PTP	Precise Time Protocol
PV	Photovoltaic

QOS	Quality of service
RAS	Remedial action scheme
RF	Radio frequency
RES	Renewable energy sources
ROI	Return on investment
RSC	Rotor-side converter
RTO	Regional Transmission Organization
RTU	Remote terminal unit
SAN	Substation area networks
SAT	Site acceptance test
SBO	Select before operate
SCADA	Supervisory control and data acquisition
SCD file	System configuration description file
SCE	Southern California Edison
SCED	Security-constrained ED
SCL	Substation configuration language
SCSM	Specific communication service mapping
SCUC	Security-constrained unit commitment
SDM	Supply and demand matching
SDOs	Standards development organizations
SGCB	Setting group control block
SGIP	Smart grid interoperability panel
SMES	Superconducting magnetic energy storage
SMV	Sampled measured value
SNTP	Simple Network Time Protocol
SOA	Service-oriented architecture
SOC	State of charge
SPS	Special protection schemes
Transcos	Transmission companies
SSO	Standards (or specifications)-setting organization
SVC	Sampled value control
SVCB	Sampled value control block
TCP	Transmission Control Protocol
TSO	Transmission system operator
UC	Unit commitment
UCA	Utility communication architecture

UCAIug	Utilities Communication Architecture (UCA) International Users Group (UCAIug)
UDP	User Datagram Protocol
UML	Unified Modelling Language
WAMS	Wide Area Measurement System
WAN	Wide area networks
WFSC	Wind farm supervisory controller
WSDL	Web Service Description Language
WTG	Wind turbine generator
WiMAX	Worldwide Interoperability for Microwave Access
XML	Extensible Markup Language
XSD	XML Schema Definition

This page intentionally left blank

Chapter 1

Introduction to the Smart Grid concept

1.1 Background and history of Smart Grid evolution

In an article published in *Wired Magazine* [1] in July 2001 a precise description of the future network, which later on was known as a Smart Grid, states “The best minds in electricity R&D have a plan: Every node in the power network of the future will be awake, responsive, adaptive, price-smart, eco-sensitive, real-time, flexible, humming, and interconnected with everything else.”

The Smart Grid concept has recently been promoted in Europe [2–4], North America [5,6], and worldwide in countries such as India, China [7–10], and South Africa [11].

In Europe, the European Technology Platform for the Electricity Networks of the Future has been created following a proposal by industrial stakeholders and the research community during the first International Conference on the Integration of Renewable Energy Sources and Distributed Energy Resources held in December 2004. The work on Smart Grids was then started in 2005 by the SmartGrids European Technology Platform for Electricity Networks of the Future. The aim was to formulate and promote a vision for the development of European electricity networks in 2020 and beyond [12].

In the USA, Smart Grid concept has been promoted officially by the publication of the US Energy Independence and Security Act of December 2007 whereby it is stated [13]:

To move the United States toward greater energy independence and security, to increase the production of clean renewable fuels, to protect consumers, to increase the efficiency of products, buildings, and vehicles, to promote research on and deploy greenhouse gas capture and storage options, and to improve the energy performance of the Federal Government, and for other purposes.

Under Title XIII-Smart Grid, Sec. 1301 of this Act, the following statement of policy defined the Smart Grid:

It is the policy of the United States to support the modernization of the Nation’s electricity transmission and distribution system to maintain a reliable and secure electricity infrastructure that can meet future demand

growth and to achieve each of the following, which together characterize a Smart Grid:

1. Increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid.
2. Dynamic optimization of grid operations and resources, with full cyber-security.
3. Deployment and integration of distributed resources and generation, including renewable resources.
4. Development and incorporation of demand response, demand-side resources, and energy-efficiency resources.
5. Deployment of “smart” technologies (real-time, automated, interactive technologies that optimize the physical operation of appliances and consumer devices) for metering, communications concerning grid operations and status, and distribution automation.
6. Integration of “smart” appliances and consumer devices.
7. Deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal-storage air conditioning.
8. Provision to consumers of timely information and control options.
9. Development of standards for communication and interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid.
10. Identification and lowering of unreasonable or unnecessary barriers to adoption of smart grid technologies, practices, and services.

The Smart Grid definition given above is very broad. It covers many aspects of electric grid operation and management [14]. The Smart Grid vision embedded in this definition aims at improving reliability, efficiency, and security of all aspects of the power system, including generation, transmission, distribution, and customer sites. Many entities, however, focus their vision of the Smart Grid almost exclusively on the potential customer services enabled by advanced metering infrastructures (AMI). The latter will be discussed in detail in Chapter 2.

Advancements made over many decades in automation, protection, control, power dispatch, and communication used particularly in transmission networks have paved the way to the development of the Smart Grid concept. Some of these technologies have been in use since the early stage of electrical power industry while others have gradually been incorporated into electrical grids over several generations. For example, the earliest or first generation control equipment used in substations that was best described as automatic control. Their basic function is to de-energize the protected circuit when it is subjected to a fault condition, reclosing it once to test whether the fault to which the circuit is subjected to is momentary [6]. This function was initially performed by electromechanical relays but later on was taken over by digital/numerical relays [15]. The second generation is based on the automatic telephone switchboard equipment of the 1950s. It may be considered as one of the first uses of communication equipment in a grid substation. Using this equipment, the

operator at a remote location could read and have control of the local substation. This equipment was called supervisory control equipment. In the late 1960s the supervisory control and data acquisition system (SCADA) was introduced to replace supervisory control equipment. The SCADA system slowly expanded in the 1970s and 1980s whereby a minimum monitoring of the majority of the transmission systems operating at voltages of 220 kV or higher and some distribution substations were included. This system was also used to centrally support control rooms and remote terminal units (RTUs) for data collection and control in the substations. Latter on RTUs are connected through hardwires to programmable logic controllers (PLCs). The latter are originated from manufacturing industries. As technology progressed, communication links took the place of the hardwired inputs. The RTU/PLC configuration was then replaced with different network architecture in the mid-1990s. This network architecture consists of protection relays/intelligent electronic devices (IEDs), PLCs, and other devices talking to each other over a network and coordinating operations. Number of utilities has already moved to the second generation of this system and they are currently contemplating to transform the backbone communication protocol to International Electro-technical Commission (IEC) 61850. The IEC 61850 will be introduced in Chapter 6.

In the context of Smart Grid, historically distribution networks are usually controlled manually. However, manually operated switches and fuses do not lend themselves easily to the Smart Grid concept. For this reason, many utilities embarked on developing programs aiming at deployment of intelligence, primarily to enhance the voltage profiles of distribution networks and to speed up isolation of faults.

1.2 Definition of the Smart Grid

Smart Grid concept has been vision/initiated by different organizations and authors. Likewise, development of an acceptable definition of the Smart Grid has been attempted by different organizations and authors. In general, two different approaches have been adopted to define the Smart Grid. It is defined based on either (i) identifying the advantages offered by the grid (solution prospective) or (ii) what components the grid is consisted of (components' prospective) [16]. However, Asea Brown Boveri Ltd (ABB), in an internal white paper, based the definition of the Smart Grid on **its capabilities and operational characteristics** rather than the use of any particular technology. They took the view that deployment of Smart Grid technologies will occur over a long period of time, adding successive layers of functionality and capability onto existing equipment and systems. ABB argued that although technology is the key, it is only a means to an end; therefore, the Smart Grid can and should be defined by broader characteristics. A selection of definitions for the Smart Grid reported in literature is given below:

In 2003, the Department of Energy in USA has developed a vision of the grid in 2030 which states [17]:

Grid 2030 is a fully automated power delivery network that monitors and controls every customer and node, ensuring a two-way flow of electricity and information between the power plant and the appliance, and all points

in between. Its distributed intelligence, coupled with broadband communications and automated control systems, enables real-time market transactions and seamless interfaces among people, buildings, industrial plants, generation facilities, and the electric networks.

In 2005, the Electric Power Research Institute (EPRI) has developed an initiative for the Smart Grid called **IntelliGrid** which states [18]:

EPRI's IntelliGridSM initiative is creating the technical foundation for a smart power grid that links electricity with communications and computer control to achieve tremendous gains in reliability, capacity, and customer services.

A definition of the Smart Grid proposed by Cisco states [19]:

A Smart grid is the term generally used to describe the integration of all elements connected to the electrical grid with an information infrastructure, offering numerous benefits for both the providers and consumers of electricity.

An alternative definition of the Smart Grid proposed by European Technology Platform states [20]:

A SmartGrid is an electricity network that can intelligently integrate the actions of all users connected to it—generators, consumers and those that do both—in order to efficiently deliver sustainable, economic and secure electricity supplies.

The IEC development organization defines the Smart Grid as [21]:

The Smart Grid is integrating the electrical and information technologies in between any point of generation and any point of consumption.

In a recent publication, Gharavi and Ghafurian define the Smart Grid as follows [22]:

The Smart Grid can be defined as an electric system that uses information, two-way, cyber-secure communication technologies, and computational intelligence in an integrated fashion across electricity generation, transmission, substations, distribution and consumption to achieve a system that is clean, safe, secure, reliable, resilient, efficient, and sustainable.

In an article published in IET *Engineering and Technology (E&T)* magazine, Davies defined the Smart Grid as [23]:

A smart grid is an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end-users. Smart grids co-ordinate the needs and capabilities of all generators, grid operators, end-users and electricity market stakeholders to operate all

parts of the system as efficiently as possible, minimizing costs and environmental impacts while maximizing system reliability, resilience and stability.

A possible concise definition of the Smart Grid may be given as follows:

A smart grid is an electricity network that uses digital and other advanced technologies, such as cyber-secure communication technologies, automated and computer control systems, in an integrated fashion to be able to monitor and intelligently and securely manage the transport of electricity from all generation sources to economically meet the varying electricity demands of end-users.

Therefore, the Smart Grid ensures the coordination of the needs and capabilities of all generating facilities, grid operators, end-users, and electricity market stakeholders so that all parts of the system operate as efficiently as possible, minimizing costs and environmental impacts while maximizing system safety, reliability, resilience, and stability.

1.3 Characteristics of the Smart Grid

Similar to the definition of the Smart Grid, its characteristics have been identified by different organizations/authors using different approaches. Table 1.1 gives a selection of Smart Grid characteristics reported in literature by various sources. The widely adopted approaches for identifying Smart Grid characteristics are based on (i) functionality approach [24,25] and (ii) broad approach [22,26].

Smart Grid characteristics based on functionality approach [24,26] include seven principal characteristics as listed below:

1. ***Optimize*** asset utilization and operating efficiency.
2. ***Accommodate*** all generation and storage options.
3. ***Provide*** power quality for the range of needs in a digital economy.
4. ***Anticipate and respond*** to system disturbances in a self-healing manner.
5. ***Operate resiliently*** against physical and cyber-attacks and natural disasters.
6. ***Enable*** active participation by consumers.
7. ***Enable*** new products, services, and markets.

While those based on the broad approach [22,26] are as follows:

- ***Adaptive*** and ***self-healing***: Smart Grid being adaptive means it has less reliance on operators, particularly in responding rapidly to changing conditions. However, the Smart Grid being self-healing means it has the capability of automatically repair or remove potentially faulty equipment from service before it fails, and has the ability of reconfiguring the system in such a way to ensure continuity of the energy to all customers.
- ***Flexible***: The Smart Grid has the ability to rapid and safe interconnection of distributed generation and energy storage at any point on the system at any time.

Table 1.1 A selection of the Smart Grid characteristics as reported in literature

Reference [13]	Reference [22]	Reference [16]	Reference [26]	Reference [24]
The characteristics of the Smart Grid according to this reference include: 1. Extensively use digital information and controls technology in order to improve reliability, security, and efficiency of the electric grid. 2. Dynamically optimize grid operations and resources with full cyber-security. 3. Ensures the deployment and integration of distributed energy resources and generation, including renewable energy resources. 4. Ensures the development and incorporation of demand response, demand-side resources, and energy-efficiency resources.	According to this reference, a fully realized Smart Grid will have the following characteristics: 1. Self-healing: This means (a) automatically repairing or removing of potentially faulty equipment from service before it fails and (b) reconfiguration of the system to reroute supplies of energy to ensure sustainability of power to all customers. 2. Flexible: This implies the rapid and safe interconnection of distributed generation and energy storage at any point on the system at any time. 3. Predictive: This means predictions of the next most likely events so that appropriate actions are taken to reconfigure the system before next worst	This reference suggests that from a solution perspective, the Smart Grid is characterized by: 1. Self-healing: As in [22], this means, the ability of the grid to: (a) automatically repair or disconnect potentially faulty equipment from service before it fails and (b) reconfigure the system to reroute supplies of energy to ensure sustainability of power to all customers. 2. More efficient energy routing: Thus, the Smart Grid optimizes the energy usage, reduces the need for excess capacity and increases power quality and security. 3. Enhance monitoring and control of energy and grid components.	According to this reference, ABB focuses on broad characteristics rather than specific functions. Based on this concept, the Smart Grid is characterized as being: 1. Adaptive: This means that the Smart Grid is less dependence on operators, particularly in responding rapidly to changing conditions. 2. Predictive: The Smart Grid is predictive in terms of applying operational data to equipment maintenance practices as well as identifying potential outages before they occur. 3. Integrated: This means, in Smart Grid real-time communications and control functions are integrated.	The principal characteristics of the Smart Grid according to this reference include: 1. Enable active participation by consumers. 2. Accommodate all generation and storage facilities. 3. Enable new products, services, and markets. 4. Provide power quality for the digital economy. 5. Optimize asset utilization and operate efficiently. 6. Anticipate and respond to system disturbances (self-heal). 7. Operate resiliently against attack and natural disaster (Secure). Similarly, in a meeting organized by the U.S. Department of Energy in June 2008, industry leaders identified the following

5. Ensures the deployment of “smart” technologies for metering, communications concerning grid operations and status, and distribution automation. These include real-time, automated, interactive technologies that optimize the physical operation of appliances and consumer devices.
 6. Ensures the integration of ‘smart’ appliances and consumer devices.
 7. Ensures the deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal-storage air conditioning.
 8. Enables consumers to gain access to timely information and control options.
- events can happen. This can be achieved by using machine learning, weather impact projections, and stochastic analysis.
4. **Interactive:** This means allowing all key participants in the energy system to play an active role in optimal management of contingencies. This is achieved by providing appropriate information regarding the status of the system not only to the operators but also to the customers.
 5. **Optimized:** This is achieved by knowing the status of every major component in real or near real time and having control equipment that provides optional routing paths, which provides the capability for autonomous optimization of the flow of electricity throughout the system.
4. **Improved data capture:** This would improve outage management.
 5. **Two-way flow of electricity and real-time information:** This would help in incorporating green energy sources, demand-side management and real-time market transactions.
 6. **Highly automated, responsive, and self-healing:** This ensures seamless interfaces between all parts of the energy network.
4. **Interactive:** This refers to the interaction between customers and markets.
 5. **Optimized:** This is to maximize reliability, availability, efficiency, and economic performance.
 6. **Secure:** Smart Grid is expected to be secure from attack and naturally occurring disruptions.
- seven characteristics of Smart Grid [26]:
1. **Optimize** asset utilization and operating efficiency.
 2. **Accommodate** all generation and storage facilities.
 3. **Provide** power quality for the range of needs in a digital economy.
 4. **Anticipate and respond** to system disturbances in a self-healing manner.
 5. **Operate resiliently against** physical and cyber-attacks and natural disasters (Secure).
 6. **Enable** active participation by consumers.
 7. **Enable** new products, services, and markets.

(Continues)

Table 1.1 (Continued)

Reference [13]	Reference [22]	Reference [16]	Reference [26]	Reference [24]
9. Ensures the development of standards for communication and interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid.	6. Secure: Due to the two-way communication capability of the Smart Grid that covers the end-to-end system, it is extremely important to ensure the physical as well as cyber-security of all critical assets.			
10. Identifies and reduces unreasonable or unnecessary barriers to adoption of Smart Grid technologies, practices, and services.				

- **Predictive:** The Smart Grid has the ability to apply operational data to equipment maintenance practices and even identify potential outages before they occur. This may be achieved with the help of using machine learning, weather impact projections, and stochastic analysis to provide predictions of the next most likely events, so that appropriate actions can be taken to reconfigure the system before the next worst events can happen.
- **Integrated:** This is particularly important in terms of real-time communications and control functions.
- **Interactive:** The Smart Grid should have the capability of providing appropriate information regarding the status of the system not only to the operators, but also to the customers, that is, both consumers and prosumers, to allow all key participants in the energy system to play an active role in optimal management of contingencies and also to facilitate the interaction between customers and markets.
- **Optimized:** This is achieved by knowing the status of every major component in real or near real time and having control equipment to provide optional routing paths that provide the capability for autonomous optimization of the flow of electricity throughout the system with the aim of maximizing reliability, availability, efficiency, and economic performance.
- **Secure:** Since the two-way communication capability covering the end-to-end system is considered as a fundamental and basic requirement of the Smart Grid, the need for physical as well as cyber-security of all critical assets is essential. This is extremely important to ensure that the Smart Grid is secured from attack and naturally occurring disruptions.

1.4 Smart Grid benefits

The benefits obtained from the full implementation of the Smart Grid are enormous [27–29]. This includes technical, environmental, and electricity marketing benefits:

(a) Technical benefits

Full deployment of Smart Grid would result in several technical benefits that include:

- (i) **Energy efficiency improvement:** This is achieved through loss reduction, peak shaving, that is, peak demand control, implementation of AMI and automated energy system operation.
- (ii) **Grid reliability improvement:** This is achieved by reducing the frequency and duration of power interruptions.
- (iii) **Operational efficiency improvement:** Achieved through active control, automation, and management services in distribution grids and by empowering customers through home automation and use of smart appliances.
- (iv) **Security and safety improvement:** Security improvement can be achieved by using sensors and automated operations that will reduce the threats of blackouts and by properly coordinating the operation of transmission and distribution with intelligent preventive and emergency

control and coordinated restoration. Safety improvement, however, can be achieved by reducing the vulnerability of the grid to unexpected hazards and promoting a safer system for persons whether workers or general public.

- (v) **Quality of supply:** Quality of supply in terms of maintaining voltage magnitude within their statutory limits can be achieved by Smart Grid technologies such as sensors, two-way information, and communication technologies.
- (vi) **Improved connection and access of the grid:** Improved connection and access of the grid is particularly important to distributed energy sources (DERs), including renewable energy sources (RESs) and plug-in hybrid electric vehicles (PHEVs).

(b) **Environment benefits**

Environment benefits gained from deployment of Smart Grid include:

- (i) **Reduction in carbon emissions:** This is achieved due to reduction in grid losses, integration of renewable and distributed generation, and by supporting efficient end-use by plug-in electricity vehicles.
- (ii) **Climate change benefits:** Reduction in grid losses resulted from deployment of Smart Grid, as stated above, together with facilitating generation of electricity from renewable energy sources, such as wind, solar, and hydro has major implications on reduction in CO₂ emission which in turn improve the prospect of climate change.

(c) **Electricity marketing benefits**

Under the Smart Grid environment, the electricity price can be reduced compared with that of conventional grid, due to the dynamic interaction of the demand side of the market (consumers) with electricity supply side (suppliers/providers). The information made available under such an environment about electricity price from different suppliers would naturally let consumers choose the least electricity price supplier. Consequently this creates healthy electricity market competition, which benefits consumers and also plays part in optimizing the operation of the power system network.

1.5 Smart Grid vision and its realization

Two types of Smart Grid visions can be identified in literature; an overall vision and a relatively detailed vision as detailed below.

1.5.1 Definition of Smart Grid vision

Based on the discussion covered in previous sections, particularly with reference to the vision of the grid in 2030 that has been developed by the Department of Energy in the USA [17], the overall Smart Grid vision may be defined as:

Smart Grid is an electrical power network, which is fully automated as a result of equipping it with communication and information system

and other technological devices and systems such as distributed control systems, distributed intelligent systems that enable it to monitor and control every electrical load and node, ensuring a two-way flow of electricity and information between generating plants and the appliances, and all points in between. Its distributed intelligence, coupled with broadband communications and automated control systems, enables real-time market transactions and seamless interfaces among people, buildings, industrial plants, generation facilities, and the electric networks.

1.5.2 The IEEE Computer Society Smart Grid Vision

In 2013, the IEEE Computer Society Smart Grid Vision Project (CS-SGVP) has developed a relatively detailed Smart Grid vision that focuses on smart devices and various computational intelligence techniques for the next 30 years [30]. According to the outcome of this project, a Smart Grid is expected to be complex and will have huge number of intelligent connected devices and systems and computational intelligence techniques. According to this vision, the complexity of such a Smart Grid can be tackled by adopting top-down to the lowest levels of architectures approach and ensuring an interactive cooperation between smart components, each with a level of autonomy. The proposed Smart Grid vision is based on a three-layered approach: architectural, functional, and technological concepts layers as shown in Figure 1.1.

The architectural concepts level details Smart Grid goals and characteristics, general grid types, and computing concepts that are considered common across the Smart Grid, while functional concepts level explains how the Smart Grid will

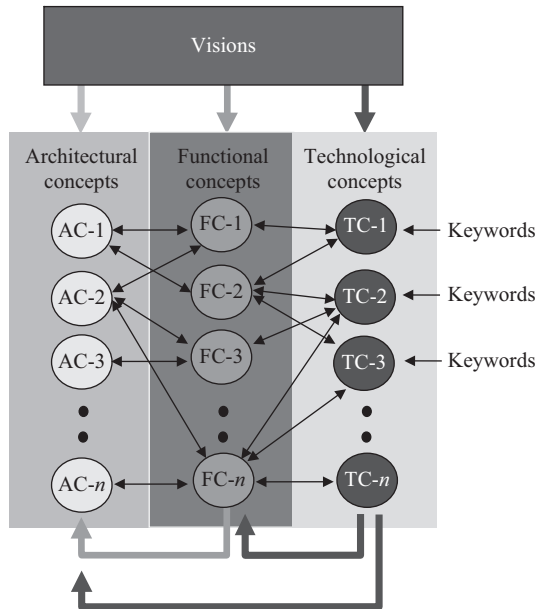


Figure 1.1 Smart Grid vision based on a three-layer approach [after 30]

operate, and the technological concepts level explains the roles of certain technologies within the Smart Grid.

The following subsections will be devoted to discuss these three levels.

1.5.2.1 Architectural concepts layer 1

The architectural concepts layer 1 sits at the top level. It consists of architectural concepts (AC- i) related to electrical grid configurations and operations, where $i = 1, 2, 3, \dots n$. Architectural concepts explain Smart Grid goals and characteristics, general grid types, as well as computing concepts that are considered common across grid types. They also explain Smart Grid business case goals and objectives, various supply side and demand side Smart Grid concepts, and system concepts that apply to this vision approach. The proposed visionary architectural concepts have introduced important concepts in the following areas:

- Evolution of energy supply mix
- Enhancement of transmission networks
- Coexistence of electrical network configurations
- End-use as an active component
- Advancement of enabling technologies
- Control methodologies

1.5.2.2 Functional concepts layer 2

Functional concepts layer 2 is placed underneath the architecture concept layer 1. It consists of large number of FC- i , where $i = 1, 2, 3, \dots n$ that are required to support any Smart Grid vision. According to [30], many functional concepts are currently in operation, while many others are at the stage of research and development. Additionally, some functional concepts represent an imagined capability but without clear idea as how such a capability will be achieved. Functional concepts under layer 2 cover high-level electrical power system infrastructure functions as well as functions at end-user sections of the system, including end-use devices and systems.

It has been acknowledged by [30] that despite the huge importance of the Smart Grid and its expected support of sustainable energy systems to the global economy and energy security, development of the basic functions needed for understanding and operating the power system, which includes optimizing and securing its performance, represents an overwhelming functional challenge. It has also been pointed out that at the time at which the Smart Grid vision under consideration was proposed, there were serious computational intelligence challenges in safety and security, communications, autonomy, and enterprise business solutions. This is especially true if it is recognized that required solutions must cover previously unconsidered interactions with other devices and systems, which include uncertainties related to cyber-security as well as social, economic, and environmental codependencies. The functional areas considered for the development of this proposed Smart Grid vision may be broadly defined as follows:

- Communications networks
- Cyber-security

- Markets and economics
- Operations, monitoring, and control
- Planning, analysis, and simulation
- Systems engineering
- Visualization and data management

1.5.2.3 Technological concepts layer 3

Technological concepts layer 3 consists of technological concepts (TC- i), where $i = 1, 2, 3, \dots n$. These technological concepts take the advantage of advancements in computational hardware and software technologies, including information systems, interaction protocols, networks, frameworks, middleware, resource management, and operating systems. Technological concepts enable the functional concepts described in the previous section. Since computing technologies continue to contribute to the advancement of all sectors of society's activities, including industry, commerce, finance, health, agriculture, and infrastructure, they will evolve along abstract ideas of methodology and tools that will be applied to realize new capabilities in all these sectors. As it has been discussed previously, computer and information technologies constitute an important component of the Smart Grid. Therefore, advances in these technologies would result in reducing the cost of their application to deliver a more efficient and secure electric system. For this reason the technological concepts in the CS-SGVP explore computer science disciplines and capabilities, including computational intelligence that technology developers must keep in mind when developing specific Smart Grid functional requirements.

Under this vision, the intention is that each technological concept must be independent from other technological concepts and must support multiple functional concepts. In addition, each functional concept that is derived by assembling the capabilities expressed in multiple technological concepts must also be independent. According to this vision, the technological concept areas include:

- Computer applications
- Cyber-security
- Distributed systems architectures
- Information science

1.6 Examples of Smart Grid projects/initiatives

As mentioned earlier, the Smart Grid concept has recently been promoted in many countries which led to the initiation of several research projects/initiatives aiming at practically realizing this concept. Examples of such projects/initiatives planned/executed in the USA, Europe, and China will be briefly discussed below.

1.6.1 US Smart Grid efforts

In the USA, several organizations have been engaged in Smart Grid initiatives/projects. EPRI's IntelliGridSM initiative and DOE's GridWise vision outlined below are two important examples of works on Smart Grid issues.

1.6.1.1 IntelliGridSM

The EPRI in the USA has initiated [31–33] a research program called “IntelliGridSM,” involving several electrical utility members, aiming at establishing the best way that ensures the creation of a Smart Grid and incorporating it into the operations of individual electrical utilities. This is based on creating technical foundation for a smart power grid that links electricity with communications and computer control to enhance reliability, capacity, and customer services.

An important early achievement of this initiative is the IntelliGrid Architecture. The aim of the IntelliGrid Architecture was to integrate two systems in the power industry, that is, the electrical power and energy delivery system and the information system that support it. The information system consists of communication, networks, and intelligence equipment. This is achieved by developing of open standards, advanced communications, and networking technologies capable of ensuring interoperability between various system components from different vendors so that it can work with intelligent equipment and algorithms to execute increasingly sophisticated electric utility system functions.

In 2007, the IEC has recognized the EPRI’s IntelliGrid methodology as a standard.

Utilities members of the IntelliGrid program are provided with the methodologies, tools, proposed standards, and unbiased assessments of technologies when implementing new system-wide technology solutions for advanced metering, distributed automation, demand response, and wide-area monitoring and control. The program also provides utilities with independent and unbiased testing of technologies and equipment from different vendors.

The IntelliGrid program addresses several key industry issues that include:

1. Understanding what does a Smart Grid mean for a particular utility.
2. Developing an industry architecture that enables interoperable systems and components.
3. Conducting technology assessments for the potential components that can make up a Smart Grid.

1.6.1.2 GridWise

The GridWise vision [34] is based on the assumption that information technology has the ability to revolutionize planning and operation of conventional power systems just as it has changed business, education, and entertainment. It is, therefore, perceived that information technology acts as the “nervous system” that integrates new distributed technologies (demand response, distributed generation, and storage) with conventional power system’s generation, transmission, and distribution networks. According to the GridWise vision the responsibility for managing the resulting new grid is shared by a “society” of devices and system entities. According to the same vision the new grid is expected to be highly intelligent and interactive electric system; one with decision-making information exchange capability and market-based opportunities. Such high-level perspective can be

achieved by providing guidelines for interaction between participants and interoperability between technologies and automation systems. Therefore, the vision grid is expected to:

1. Allow electric devices, enterprise systems, and their owners to interact and adapt as full participants in the grid operations.
2. Have the connectivity for intelligent interactions and interoperability across all automation components of the electric system from end-users, such as buildings or high voltage alternating current (HVAC) systems, to distribution, transmission, and bulk power generation.
3. Address issues of open information exchange, universal grid access, decentralized grid communications and control, and the use of modular and extensible technologies that are compatible with the existing infrastructure.

1.6.2 European Smart Grid efforts

European Smart Grid project is explained in detail in three-series documents. The first document [2], “Vision and Strategy for Europe’s Electricity Networks of the Future,” established the need to have a vision for the future European electricity networks. The second [3], “Strategic Research Agenda,” consolidated the views of stakeholders on the research priorities necessary to deliver these networks. The third [4], “The SmartGrids Strategic Deployment Document for Europe’s Electricity Networks of the Future,” concluded the series and focused on the deployment of new network technologies and the delivery of the SmartGrids vision.

According to the first document, Europe’s electricity networks have successfully provided the vital links between electricity producers and consumers for many decades. The fundamental architecture of these networks has been developed to meet the needs of large and predominantly carbon-based generation technologies, located remotely from demand centers. The change of the electricity generation landscape in recent years, due to market liberalization which led to the introduction of low-carbon generation technologies in a form of distributed generation (DG), including RES and storage generation, has created new energy challenges that Europe need to resolve.

The drive for low-carbon generation technologies, coupled with greatly improved efficiency on the demand side, enables customers to become much more interactive with the networks. This in turn has led to foresee customer-centric networks that are way forward. These fundamental changes, however, will significantly influence the way networks are designed and controlled.

In this context, the European Technology Platform (ETP) SmartGrids was established in 2005 aiming at creating a SmartGrids vision for the European networks for 2020 and beyond. The platform includes representatives from industry, transmission and distribution system operators, research bodies, and regulators. It has identified clear objectives and proposes an ambitious strategy to realize this vision for the benefits of Europe and its electricity customers.

This vision was based on a solid program of research, development, and demonstration that was expected to lead to an electricity of supply network that would meet the needs of Europe's future. Such envisioned network should be:

- **Flexible:** It must fulfill customers' needs and at the same time responding to the changes and challenges ahead;
- **Accessible:** It should be able to grant connection access to all network users, particularly for renewable energy sources and high efficiency local generation with zero or low carbon emissions;
- **Reliable:** It should have the ability of assuring and improving security and quality of supply, consistent with the demands of the digital age with resilience to hazards and uncertainties;
- **Economic:** It should have the capability of providing best value through innovation, efficient energy management, and "level playing field" competition and regulation.

The second document explains that the ETP has set the milestone for the establishment of a common strategy for the development of future Europe's electricity networks that can meet the challenges of the twenty-first century in its paper titled "Vision and Strategy for Europe's Electricity Networks of the Future" published in April 2006. This vision has highlighted that Europe's future electricity markets and networks must provide all consumers with a highly **reliable, flexible, accessible, and cost-effective** power supply, fully exploiting the use of both large centralized generators and smaller distributed power sources across Europe. It has also emphasized that end-users should become significantly more interactive with both markets and grids; electricity would be generated by centralized and dispersed sources; and grid systems would become more interoperable at a European level to enhance security and cost-effectiveness. This new concept of electricity networks is described as the "SmartGrids" vision. Such a vision is expected to enable a highly effective response to the rising challenges and opportunities, bringing benefits to all network users and wider stakeholders.

In order to realize this objective, the European Technology Platform SmartGrids has focused its efforts on the development of a **Strategic Research Agenda** (SRA). Four working groups that represent a wide range of European industrial and academic expertise have contributed to this effort. Member State governments have also provided valuable advice and comment through the Mirror group. The SRA is a reference document that consolidates the views of the stakeholders on research priorities that address the key elements of the vision document.

The aim of the SRA is to provide a resource for European and national programs. It is meant to be non-prescriptive and strategic in nature; it is designed to encourage competitive activity; and it is intended to be an inspiration for new thinking in important policy areas. The goals of the framework for a future research program proposed by the SRA can be summarized as follows:

- To ensure that Europe's electricity networks develop in such a way that enhances Europe's competitive position provided that environmental objectives or the commitment to sustainability are not compromised.

- To capture the benefits of collaboration and cooperation to address challenges that are common across all member states.
- To encourage imaginative solutions that may require community-wide adoption to be successful, including new approaches to energy efficiency and demand side participation.
- To build on previous R&D to maximize the benefit and eliminate duplication.
- To fully utilize the current infrastructure to ensure that the most efficient use is made of existing assets that are not age expired, thereby delivering innovative and competitive solutions for European customers.
- To provide a clear framework, goals and objectives on which the research community can focus, encouraging innovative solutions where this will add value.
- To generate the momentum and support necessary to convert good ideas to adopt products and solutions through catalyst projects, demonstration projects, and knowledge transfer.

A key principle in the development of the proposed SRA is that network users should be at the focus of developments. To achieve this, an integrated approach to technical, commercial, and regulatory aspects has been undertaken, aiming at delivery of added-value solutions and services to all stakeholders and end-users. It recognizes the complex factors inherent in achieving successful technology transfer from research to deployment, and also the new dimensions created by a liberalized market and its regulatory frameworks.

The third document embodied the aims set out by the strategic deployment document (SDD), which include (i) reinforcement of the need for and benefits of SmartGrids technologies and solutions, (ii) highlight the barriers that are currently constraining deployment of SmartGrids, and (iii) make recommendations that will address these barriers.

The SDD was also intended to engage with all stakeholders in the electricity supply chain, including governments, regulators, network operators, network users (both generators and consumers), network equipment manufacturers, consultants, suppliers of household appliances and information communication technology (ICT), and other service providers. To ensure the success of SmartGrids deployment, each stakeholder must play its part in the competitive environment of the electricity market.

As far as the need of SmartGrids is concerned, it has been recognized that it is vitally important that Europe's electricity networks must have the capability of integrating all low carbon generation technologies as well as encouraging the demand side to play an active role in the supply chain. This can be achieved by upgrading and evolving the networks efficiently and economically. This in turn involves network development at all voltage levels. For example, substantial offshore and improved onshore transmission infrastructure must be made in order to facilitate the development of wind power across Europe. However, distribution networks are required to embrace active network management technologies in order to efficiently integrate DG, including residential microgeneration, on a large scale. There are many other examples all of which require connectivity to the networks to ensure that the targets for energy security and environmental sustainability are achieved.

In order to achieve these developments in a timely manner, a combination of effective legislation and regulation must be put in place. The key challenges for SmartGrids that have been identified as follows:

- **Strengthening the grid:** This is necessary to ensure that there is sufficient transmission capacity to interconnect energy resources, especially renewable energy resources, across Europe.
- **Moving offshore:** This requires developing the most efficient connections for offshore wind farms and for other marine technologies.
- **Developing decentralized architectures:** This is vital for enabling smaller scale electricity supply systems to operate harmoniously with the whole system.
- **Communications:** This means delivering the right communications infrastructure that allows potentially millions of parties to operate and trade in a single electricity market.
- **Active demand side:** This is important to enable all consumers, whether they have their own generation or not, to play an active role in the operation of the system.
- **Integrating intermittent generation:** This means finding the best possible ways of integrating intermittent generation, including residential microgeneration.
- **Enhancing the application of intelligence:** This should be applied to generation, demand, and most importantly to the grid.
- **Capturing the benefits of DG and storage:** This may include, for example, the use of DG to support the network.
- **Accommodating electric vehicles:** While it is vital that SmartGrids should accommodate the needs of all consumers, accommodating electric vehicles are particularly important due to their mobile and highly dispersed character and their possible massive deployment in the near future. This will impose a major challenge to the future electricity networks.

1.6.3 China's Smart Grid efforts

Recently the Smart Grid has become a hot topic in China [7–10]. It is viewed as a sophisticated control system that can efficiently manage resources and consumptions. It is also perceived as a concept that can (i) enhance grid reliability, (ii) supply capacity, and (iii) help reduce grid losses. Accordingly, on May 21, 2009, China has announced the “Strong Smart Grid” plan during the 2009 International Conference on Ultra High Voltage (UHV) Power Transmission. This plan has focused on the transmission networks rather than the distribution networks. This is due to the fact that coal constitutes China’s main energy source and coal mines are far away from the main load centers. Under this scheme, a project was initiated known as the “West-East Electricity Transfer Project,” which includes construction of three major West–East transmission corridors. The transmission capacity of each corridor is 20 GW planned to be completed by 2020. The aim of building these transmission grids is to interconnect regional power grids in different areas of the country together and thereby improve cross-regional electricity transmission ability. This in turn helps balance power generation disparities in different regions of the country.

The main driver behind this effort is the state grid corporation of China (SGCC), which is the largest transmission company in China. SGCC has also undertaken the task of developing Chinese Smart Grid. SGCC has planned investing a total of US\$601 billion into a nationwide transmission network out of which US\$101 billion is dedicated to developing Smart Grid technology. SGCC has been involved in deploying several technologies such as wide area measurement system (WAMS) and information system integration project. WAMS uses the phasor measurement unit (PMU) based on the global positioning system (GPS) to develop a method that ensures the stability of power grids. SGCC is aiming at building a WAMS and by 2012 plans to have PMU sensors at all generators of 300 MW and above and all substations of 500 kV and above. SGCC has also been deploying extensive fiber optic network throughout China high voltage (HV) substations. This network covers 1,000,000,000 km of fiber-optic channels. The main features of Smart Grid technology that is planned to be implemented in China are:

- Development of policy and strategy for Smart Grid.
- Upgrade and development of latest transmission and distribution (T&D) to improve grid connectivity, capacity, and efficiency.
- Development of interoperability and standards to improve the connectivity of the grid components.
- Preparing the engineering workforce for the emergence of the Smart Grid technologies.
- Development of smart metering and AMI.
- Management platforms, integration, and security of Smart Grid technologies.
- Integration of renewable energy and environmental issues related to it.
- Identifying grid requirements for large-scale electric vehicle (EV) integration.

According to SGCC, China's Smart Grid plan can be divided into three phases:

Phase 1: Planning and pilot projects (2009–2010): Under this phase, the focus was on planning Smart Grid construction by outlining technical standards, developing technology and equipment, and implementing pilot projects.

Phase 2: Construction and development (2011–2015): The plan under this phase was to build a reliable nationwide ultra-high voltage (UHV) transmission system, including operational Smart Grid management systems, wide spread deployment of smart meters, and enough PHEV charging stations to facilitate the use of PHEVs.

Phase 3: System upgrades (2016–2020): The aim under this final phase is to complete the execution of China's nationwide UHV transmission system by connecting all planned coal, nuclear, hydroelectric, and wind power generation facilities to areas of high demand in a reliable and intelligently managed transmission network.

Specific Smart Grid projects in China include:

- Long-distance, large-capacity, low-loss **UHV core technology**, and localization of power equipment
- ± 800 kV UHV DC converter station

- Power system digital real-time simulation device
- Electric vehicle charging stations

1.7 Summary

In this chapter, the concept of Smart Grids is introduced. The background of this concept is covered in Section 1.1. This is followed by an extensive literature survey of the definition of the “Smart Grid” which is given in Section 1.2. A comprehensive definition of the Smart Grid may read:

A smart grid is an electricity network that uses digital and other advanced technologies, such as cyber-secure communication technologies, automated and computer control systems, in an integrated fashion to be able to monitor and intelligently and securely manage the transport of electricity from all generation sources both traditional and renewable to economically meet the varying electricity demands of end-users.

The characteristics of the Smart Grid as reported by important players in this field are discussed in Section 1.3. The identified Smart Grid’s characteristics depend on the approach used by different organizations/authors. The widely adopted approaches for identifying Smart Grid characteristics are based on (i) functionality approach and (ii) broad approach.

The benefits of Smart Grids as reported in literature are covered in Section 1.4. This includes technical benefits, environment benefits, and electricity marketing benefits. Section 1.5 is devoted to the Smart Grid vision and its realization. Two types of Smart Grid visions have been identified in literature; an overall vision and a relatively detailed vision developed by the IEEE Computer Society. In this context, the definition of Smart Grid vision, based on the vision of the grid in 2030 that has been developed by the Department of Energy in the USA, has been adopted. Finally, examples of Smart Grid projects considered/executed in different parts of the world, including Europe, the USA, and China are outlined in Section 1.6.

References

- [1] Silberman S. *The energy web* [Online]. *Wired Magazine*. July 2001. Available from http://www.wired.com/wired/archive/9.07/juice_pr.html [Accessed 22 August 2015]
- [2] European Commission (European Technology Platform). *SmartGrids: vision and strategy for Europe’s electricity networks of the future* [Online]. 2006. Available from http://ec.europa.eu/research/energy/pdf/smartgrids_en.pdf [Accessed 28 August 2015]
- [3] European Technology Platform SmartGrids. *Strategic research agenda for Europe’s electricity networks of the future* [Online]. 2007. Available from ftp://ftp.cordis.europa.eu/pub/fp7/energy/docs/smartgrids_agenda_en.pdf [Accessed 28 August 2015]

- [4] European Technology Platform. *SmartGrids: strategic deployment document for Europe's electricity networks of the future* [Online]. 2010. Available from http://www.smartgrids.eu/documents/SmartGrids_SDD_FINAL_APRIL2010.pdf [Accessed 7 September 2015]
- [5] Utility Standard board. *Smart Grid: interoperability and standards – an introductory review* [Online]. 2008. Available from http://xanthus-consulting.com/Publications/documents/Smart_Grid_Interoperability_and_Standards_White_Paper.pdf [Accessed 7 September 2015]
- [6] Johnson A.P. 'The history of the Smart Grid evolution at Southern California Edison'. *IEEE Conference on Innovative Smart Grid Technologies (ISGT)*; Gaithersburg, MD, 2010, pp. 1–3
- [7] Hashmi M. *Survey of smart grids concepts worldwide* [Online]. Finland: VTT Technical Research Centre of Finland; 2011. Available from <http://www.vtt.fi/inf/pdf/workingpapers/2011/W166.pdf> [Accessed 14 September 2015]
- [8] Li J. *From strong to smart: the Chinese Smart Grid and its relation with the globe* [Online]. Asia Energy Platform – Article 00018602; 2009. Available from http://assets.fiercemarkets.net/public/smartgridnews/AEPN_Sept.pdf [Accessed 14 September 2015]
- [9] Zpryme Research & Consulting. *China: rise of the smart grid – special report by Zpryme's smart grid insights* [Online]. 2011. Available from https://www.smartgrid.gov/files/China_Rise_Smart_Grid_201103.pdf [Accessed 14 September 2015]
- [10] IEEE. *China's strengthened smart grid* [Online]. Available from <http://www.smartgrid.ieee.org/resources/public-policy/china> [Accessed 18 June 2012]
- [11] Bipath M. *Proposed smart grid vision for South Africa* [Online]. 2012. Available from <http://africasmartgridforum2014.org/fr/expert/sessionb2/minnesh-bipath-sg-vision-presentation-to-the-asgf-en.pdf> [Accessed 21 November 2015]
- [12] EU. *Background – SmartGrids: European technology platform* [Online]. Available from <http://www.smartgrids.eu/?q=node/27> [Accessed 21 March 2011]
- [13] U.S. Government. *H.R. 6 (110th): US Energy Independence and Security Act of 2007* [Online]. 2007. Available from <http://www.gpo.gov/fdsys/pkg/BILLS-110hr6enr/pdf/BILLS-110hr6enr.pdf> [Accessed 16 September 2015]
- [14] Utility Standard Board. *Smart grid: interoperability and standards – an introductory review* [Online]. 2008. Available from http://xanthus-consulting.com/Publications/documents/Smart_Grid_Interoperability_and_Standards_White_Paper.pdf [Accessed 18 September 2015]
- [15] Johns A.T. and Salman S.K. *Digital protection for power systems*. Peter Peregrinus Ltd, IEE Power Series 15, 1995
- [16] OECD. *Smart sensor networks: technologies and applications for green growth* [Online]. 2009. Available from <http://www.oecd.org/sti/44379113.pdf> [Accessed 18 September 2015]

- [17] U.S. Department of Energy. *Grid 2030—a national vision for electricity's second 100 years* [Online]. 2003. Available from http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/Electric_Vision_Document.pdf [Accessed 19 September 2015]
- [18] EPRI [Online]. 2012. Available from <http://intelligrid.epri.com/> [Accessed 21 September 2015]
- [19] Cisco. *Why Cisco and Smart Grid?* [Online]. 2009. Available from http://www.cisco.com/cisco/web/UK/solutions/strategy/energy/pdfs/sGrid_qa_c67_532319.pdf [Accessed 21 September 2015]
- [20] European Technology Platform. *SmartGrids: strategic deployment document for Europe's electricity networks of the future* [Online]. European Commission; 2010. Available from http://www.smartgrids.eu/documents/SmartGrids_SDD_FINAL_APRIL2010.pdf [Accessed 16 November 2015]
- [21] IEC. *IEC Smart Grid standardization roadmap* [Online]. IEC; 2010. Available from http://www.iec.ch/smartgrid/downloads/sg3_roadmap.pdf [Accessed 16 November 2015]
- [22] Gharavi H. and Ghafurian R. 'Smart grid: the electric energy system of the future'. *Proceedings of the IEEE*. 2011;99(6):917–21
- [23] Davies S. 'Network evolution: developing a modern, intelligent power grid'. *E&T Magazine*. 2012;7(4):52–5
- [24] Miller J. *Structuring the smart grid framework: application of complex systems engineering* [Online]. US DOE/NETL Modern Grid Team; 2009. Available from http://www.smartgrid.gov/sites/default/files/pdfs/structuring_smart_grid_framework_05-2009.pdf [Accessed 16 November 2015]
- [25] Hamilton B.A., Pullins S., Miller J., Renz B., and Hanley M. *Smart grid principal characteristic enables new products, services, and markets* [Online]. US DOE/NETL; 2010. Available from http://www.smart-gridinformation.info/pdf/1267_doc_1.pdf [Accessed 16 November 2015]
- [26] ABB. *Towards a Smarter Grid—ABB's vision for the power system of the future* [Online]. USA: ABB; 2009. Available from http://www02.abb.com/db/db0003/db002698.nsf/0/e30fc9d5f79d4ae8c12579e2002a4209/%24file/Toward_a_smarter_grid_Jul+09.pdf [Accessed 16 November 2015]
- [27] Council of European Energy Regulators (CEER). *Smart grids scope, history and prospects update on smart metering activities – note to the GA* [Online]. Europe: CEER; 2009. Available from www.ure.gov.pl/download.php?s=1&id=2456 [Accessed 16 November 2015]
- [28] Smart Grid GB (SGGB). *Smart grid benefits* [Online]. Available from <http://smartgridgb.org/smart-grid/smart-grid-benefits.pdf> [Accessed 7 June 2012]
- [29] Center for Neighborhood Technology (CNT). *Illinois smart grid initiative: summary of smart grid benefits and issues* [Online]. Available from <http://www.cnt.org/news/media/isgi-summary-of-benefits-and-issues-6-08.pdf> [Accessed 7 June 2012]
- [30] Cartes D., Chow J.H., McCaugherty D., Widergren S., and Venayagamoorthy G.K. 'The IEEE Computer Society Smart Grid Vision Project opens

- opportunities for computational intelligence'. *IEEE Conference on Evolving and Adaptive Intelligent Systems (EAIS)*; Singapore, 2013, pp. 144–50
- [31] EPRI. *Intelligrid* [Online]. Available from <http://intelligrid.epri.com/publications.html> [Accessed 21 June 2012]
 - [32] EPRI. *IntelliGridSM architecture report* [Online]. Available from <http://intelligrid.epri.com/deliverables.html> [Accessed 21 June 2012]
 - [33] EPRI. *IntelliGrid[®] Research Program Media Brief* [Online]. USA: EPRI; 2008. Available from <http://mydocs.epri.com/docs/CorporateDocuments/MEDIAKITS/IntelliGridmediabrief9-23-08.pdf> [Accessed 16 November 2015]
 - [34] The GridWise Architecture Council. *GridWise interoperability context-setting framework* [Online]. USA: GridWise Architecture Council; 2008. Available from http://www.gridwiseac.org/pdfs/interopframework_v1_1.pdf [Accessed 16 November 2015]

This page intentionally left blank

Chapter 2

Smart Grid versus conventional electrical networks

2.1 Introduction

The aim of this chapter is to give the reader a comparison between conventional electrical networks and future Smart Grid. The infrastructure of conventional electrical networks will be reviewed followed by highlighting their main characteristics. The motives behind modernizing conventional electrical networks which led to the development of the Smart Grid concept will be discussed. This is followed by discussing evolution of the Smart Grid concept. Finally, the advanced metering infrastructure (AMI), which is considered as the fundamental and first step to the overall modernization of conventional electrical networks, will be covered.

2.2 Conventional electrical networks

2.2.1 Infrastructure of conventional electrical networks

Conventional electrical supply network usually consists of **generation**, **transmission**, **distribution**, and **consumer (load)** systems. Generation system normally consists of a combination of large-scale centralized generation plants. A typical modern generating unit has rated value of over 1,000 MW. A transmission system is specifically designed to transfer bulk of power from generating plants to distribution systems at high- and extra-high voltage levels over long distances. Typical operating voltages of transmission systems include 765 kV, 500 kV, 400 kV, and 275 kV. Distribution systems, however, are specifically designed to receive electric power from transmission system to be distributed to load centers. It is therefore important to note that the role of a distribution network is *passive*, that is, its role is confined to transferring electricity from generation and transmission systems to load centers. The operating voltage of distribution networks includes 132 kV, 110 kV, 66 kV, 33 kV, 20 kV, and 11 kV.

Conventional electrical supply networks normally have vertical structure whereby the electric power generated by the generation system is passed to transmission system which is then transferred to distribution network for feeding it to connected loads. Figure 2.1 shows the principle of vertical structure of electrical supply networks whereby electricity flows in one direction, starting from generation system, through transmission system to distribution networks and finally to loads.

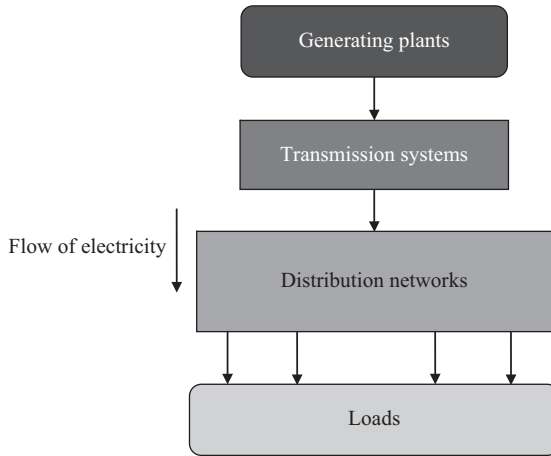


Figure 2.1 Principles of vertical structure of conventional power systems whereby the flow of electricity is unidirectional

2.2.2 Main characteristics of conventional electrical networks

The main characteristics of conventional electrical networks include:

- (i) Conventional electrical network has vertical structure (see Section 2.2.1)
- (ii) Power flow is unidirectional. This is particularly true for distribution networks.
- (iii) The price of electricity is dictated by the utility to which the consumer is connected. In other words, consumers have no choice of opting from where they buy their electricity, that is, consumers are considered passive.

2.3 Motives behind developing the Smart Grid concept

It has been recognized that the changes to which electrical networks are subjected in recent years have made the grid of today unable to meet the challenges of the future [1]. This has led to urgent need to modernizing electrical networks, which in turn has evolved into the development of the Smart Grid concept. The Smart Grid concept is widely perceived as way forward to solve problems related to growing energy consumption, integration of distributed generation, energy efficiency, power supply reliability, and power quality [2].

The factors that led to the development of the Smart Grid concept may be summarized as follows:

- Aging of conventional electrical networks coupled with the emergence of new applications
- Political and environmental factors
- Liberalization of electricity market
- Motivation and inclusion of customers as players to support the grid

2.3.1 *Aging of conventional electrical networks coupled with the emergence of new applications*

Conventional electrical networks in many countries were designed in 1950s and built in 1960s and 1970s, well before the microprocessor era and huge advancements in areas such as communications and automatic control and smart appliances. In addition to this, totally new applications have emerged that are likely to affect the management and operation of electrical networks. Examples of such applications include electrical vehicles (EVs) and heat pumps which will have a considerable impact on the electricity grid [3]. Therefore, it has been recognized that electrical networks have become very old and out-of-date and consequently their modernization has become essential. In this context, upgrading the current European electricity grid with “smarter” technologies was made one of the key priorities in the effort to overcome the infrastructural and operational challenges posed by the newly adapted EU energy-climate legislative package with its triple targets for 2020 [4]. The EU’s triple commitment aims at:

- Reducing CO₂ emissions by 20%
- Sourcing 20% of the EU’s total energy, including transport, heating and lighting, and electricity from renewable sources
- Improving energy efficiency by 20%

All targets must be completed by 2020. This represents a considerable challenge for the energy sector of today. As far as the electricity grid, the triple commitment is even more challenging as this means that approximately 35% of all electricity must be generated from renewable energy sources (RESs).

2.3.2 *Political and environmental factors*

Sharp increase in oil prices following the Arab–Israeli conflict in October 1973 has led the industrial nations to multiply their efforts to harness RESs, including wind, solar, hydro, etc. Subsequent years have witnessed the development of mature technologies to generate electricity from RESs such as solar energy, using photovoltaic (PV), and wind power, which are perceived as environment friendly and they do not emit the greenhouse gas, CO₂, associated with generation of electricity using fossil fuels. It is claimed that the electricity generated from fossil fuels causes approximately 25% of global greenhouse gas emissions [3] which prompted utilities to redefine the electricity system of the future in terms of how it should look like. However, the majority of electrical generators powered by RES are normally integrated into electrical networks at distribution level. This process has led to transforming distribution networks from being **passive** into **active** networks and consequently the flow of power in these networks has become **bidirectional**. This in turn has created several technical difficulties which in turn have affected the proper operation of protection relays [5] and voltage control devices [6,7]. All these factors have adversely affected the overall management of the networks.

2.3.3 *Liberalization of electricity market (economic factors)*

Liberalization of electricity market in the USA, Europe [4], and elsewhere has made it necessary that the reliability and quality of energy supply must be ensured while adapting the structure and processes to take on board the new market approach and new legal obligations, integrating RESs into the system and increasing the efficiency of both transmission and distribution networks in order to limit the grid tariffs.

2.3.4 *Motivation and inclusion of customers*

Traditionally, customers are perceived as “**passive users of electricity**” while utilities as providers of electricity commodity with fixed tariffs [8]. Recently, this situation has changed due to (i) making it possible to customers, through legislations and various incentives, to generate electricity and feed it back partially or totally to the grid using electrical network’s transmission and distribution systems and (ii) empowering customers, through the use of combination of advanced technologies in association with recently developed smart appliances, to choose electricity provider based on the price on offer and/or decide the most suitable time to operate their appliances.

The inclusion of customers can be facilitated by the implementation of the Smart Grid concept. The price of electricity can be used as the key motivator by customers. This is achieved through customer choices that they can make with their smart appliances and energy management systems to actively respond instantaneously, hourly, daily, and even seasonally, in order to closely match their energy usage to the actual cost of producing that electricity or in response to emergency situations. Under this situation, utilities are required to respond more interactively to customer needs in order to meet their reliability and efficiency requirements in a more timely and comprehensive manner.

2.4 **Comparison between Smart Grid and conventional electrical networks**

Future Smart Grid is expected to differ from the current conventional networks in several ways. Table 2.1 summarizes the fundamental differences between the Smart Grid and conventional electrical networks, particularly distribution network [1].

2.5 **Evolution of Smart Grid concept**

Apart from being old and out-of-date, conventional electrical networks have recently been subjected to many changes. The most important of these that proved to be difficult for the networks to accommodate include:

- (i) The integration of distributed energy resources (DERs) based-generators, including RESs based-generators and storage systems into electrical networks, particularly at distribution voltage levels.

Table 2.1 *Fundamental differences between the Smart Grid and conventional electrical networks*

Feature/component	Conventional network	Smart Grid
Communications	None or one-way, typically not real-time	Two-way, real-time
Customer interaction	Limited	Extensive
Metering	Electromechanical	Digital (enabling real-time pricing and net metering)
Operation and maintenance	Manual equipment checks	Remote monitoring, predictive, time-based maintenance
Generation	Centralized	Centralized and distributed
Power flow control	Limited	Comprehensive, automated
Reliability	Prone to failures and cascading outages, essentially reactive	Automated, proactive protection, prevents outages before they start
Restoration following disturbance	Manual	Self-healing
Topology of distribution networks	Radial, generally one-way power flow	Network, multiple power flow pathways

- (ii) Accommodating the recent new development in transport industry in terms of EVs will be presented as a new type of load which puts further stress on the network.
- (iii) Dealing with the dynamic situation between electricity market stakeholders and electrical utilities due to liberalization of electricity market in recent years that require the implementation of new tools and methodologies with the help of new and advanced technologies.

These changes have adversely affected the operation, management, and protection of networks in a number of ways. Additionally the advancement in digital, communication, automatic control, and other technologies has opened new windows and opportunities to find solutions and tackle network's problems. This in turn has led to initially contemplate on modernizing conventional electrical networks and eventually to the development of the Smart Grid concept.

2.5.1 *Characteristics of Smart Grid as defined by EU and US Smart Grid visions*

Modernizing conventional electrical networks has particularly been considered in the EU and the USA, which led to the development of the Smart Grid concept. The Smart Grid vision set up by the EU, which includes both transmission and distribution networks, was driven by the combined effects of market liberalization, the change in generation, storage, and electricity consumer technologies to meet environmental targets and the future uses of electricity [9]. To achieve the vision laid down by the EU, an intensive program of research, development, and

demonstration was drawn with a goal toward developing an electricity supply network that meets the needs of Europe's future, which later on was known as the Smart Grid. According to this vision, the Smart Grid must be [9,10]:

- **Flexible:** The Smart Grid must be designed to fulfill customers' needs and at the same time has the ability to respond to the changes and challenges ahead.
- **Accessible:** The Smart Grid must have the ability to grant connection access to all network users, particularly for renewable power sources and high efficiency local generation with zero or low carbon emissions.
- **Reliable:** The Smart Grid must have the capability to ensure and improve security and quality of supply, consistent with the demands of the digital age with resilience to hazards and uncertainties.
- **Economic:** The Smart Grid must have the ability to provide best value through innovation, efficient energy management, and "level playing field" competition and regulation.

Similarly, in the USA, a program was set up to develop the Smart Grid with the following principal characteristics that define the vision of the Smart Grid [11,12]:

- Enable active participation by consumers
- Accommodate all generation and storage options
- Enable new products, services, and markets
- Provide power quality for digital economy
- Optimize assets utilization and operate efficiently
- Anticipate and respond to system disturbances (self-heal)
- Operate resiliently against attack and natural disaster

These principal characteristics will be discussed as follows.

2.5.1.1 Enable active participation by consumers

It is expected that active participation of consumers in electricity markets would bring several benefits to the grid as well as the environment. By fully implementing the Smart Grid concept, consumers will get access to the necessary information, control, and options that allow them to engage in "electricity markets." However, grid operators will consider willing consumers as resources in the day-to-day operation of the grid as will be discussed later on in the following chapters. Additionally well informed consumers will have the ability to modify their consumption based on balancing their demands and resources with the electric system's capability to meet those demands. Dedicated demand response (DR) programs will help satisfying basic consumers' need, i.e., the ability and flexibility in deciding when and where from energy is purchased. Such participation of consumers would help in reducing or shifting peak demand that allows utilities to minimize capital expenditures and operating expenses. It would lead to reducing line losses and minimizing the operation of inefficient peaking power plants. This in turn would result in substantial environmental benefits.

2.5.1.2 Accommodate all generation and storage options

Under the Smart Grid environment it will be much easier to integrate all types and sizes of electrical generation and storage systems using simplified interconnection processes and universal interoperability standards to support what is called a “plug-and-play” approach. It is expected that large central generation plants, including advanced nuclear plants and RESs, such as wind and solar farms which are considered environment friendly, will continue to play a major role despite the expected deployment of large number of smaller distributed resources, including plug-in EVs. It will also be possible to interconnect generators with capacities ranging from small to large at essentially all voltage levels. This will include DERs such as photovoltaic, wind, advanced batteries, plug-in hybrid vehicles, and fuel cells. Commercial users will find it much easier and more profitable to install their own generation such as highly efficient combined heat and power installations and electric storage facilities.

2.5.1.3 Enable new products, services, and markets

Realizing the Smart Grid will facilitate linking buyers and sellers together, starting from consumers to generators and all those in between. It will also support the creation of new electricity markets and tools that ensure efficient electricity trading. This will range from the home energy management system at the consumers’ premises to the technologies that allow consumers and third parties to bid their energy into the electricity market. This will help in making consumers feel price fluctuations through real-time pricing. The reaction of consumers to price increases will inevitably lead to mitigate demand and energy usage. This in turn will drive lower-cost solutions, which will lead to new technology development. New and clean energy-related products will also be offered as market options. The Smart Grid is also expected to support consistent market operation across regions.

2.5.1.4 Provide power quality for digital economy

It is expected that implementing the Smart Grid concept will help in monitoring, diagnosing, and responding to power quality deficiencies. This in turn will lead to a substantial reduction in the business losses currently experienced by consumers due to low power quality. Adapting new power quality standards will balance load sensitivity with delivered power quality. The Smart Grid will facilitate the supply of varying grades of power quality at different pricing levels. Additionally, power quality events that originate in the transmission and distribution elements of the electrical power system can be minimized. The irregularities caused by certain consumer loads can also be isolated and consequently preventing the adverse effect on the electrical system and other consumers.

2.5.1.5 Optimize asset utilization and operate efficiently

It is anticipated that implementing the Smart Grid concept will greatly improve the operation of power system as a result of improving load factors, reducing system losses, and the expected dramatic improvement in the outage management performance. It is also anticipated that as a consequence of fully implementing the Smart

Grid concept the grid will be equipped with additional intelligence. This in turn will provide planners and engineers with extra knowledge to build “*what is needed when it is needed*,” extend the life of assets, repair equipment *before* it fails unexpectedly, and more importantly manage the work force responsible for maintaining the grid. This will result in reducing the operation, maintenance, and capital costs and thereby reducing the pressure on electricity prices.

2.5.1.6 Anticipate and respond to system disturbances (self-heal)

Under the Smart Grid environment the grid will have the ability to heal itself. This is achieved by continuously performing self-assessments to detect and analyze the status of the grid and its components, take corrective action to mitigate the effect of defective components and, if needed, rapidly restore grid components or network sections. It will also have the capability to handle problems that are too large or too fast-moving to be handled by human. Grid’s self-healing is considered as the grid’s “immune system.” It will help maintain grid reliability, security, affordability, power quality, and efficiency. This will result in minimizing disruption of service. Self-healing can be achieved by employing modern technologies that can acquire data, execute decision-support algorithms, prevent or limit interruptions, dynamically control the flow of power, and restore service quickly. For example, probabilistic risk assessments based on real-time measurements can be used to identify the equipment, power plants, and lines most likely to fail. A second example, real-time contingency analyses can be used to determine overall grid health, trigger early warnings of trends that could result in grid failure, and identify the need for immediate investigation and action. A third example is the use of communication system to communicate with local and remote devices to analyze faults, low voltage, poor power quality, overloads, and other undesirable system conditions. Based on these analyses, appropriate control actions will be taken, automatically or manually as the need determines.

2.5.1.7 Operate resiliently against attack and natural disaster

A system-wide solution that ensures the reduction of physical and cyber vulnerabilities and enables a rapid recovery from disruptions will be incorporated under the Smart Grid environment. This will result in the Smart Grid being resilience which will deter any attack that would be committed from even those who are determined and well equipped. However, its decentralized operating model and self-healing features will also make it less vulnerable to natural disasters than today’s grid. Additionally, security protocols will be designed such that they will contain elements of deterrence, detection, response, and mitigation to ensure minimizing the impact on the grid and the economy. This particular characteristic of the Smart Grid makes it less susceptible and more resilient, which will in turn make it a more difficult target for terrorists.

2.5.2 Advanced metering infrastructure

Development of AMI is considered as the milestone of modernizing conventional electric power system and its evolvement to the Smart Grid. A key benefit of AMI

is, it provides customers real-time (or near real-time) pricing of electricity and it also helps utilities to achieve necessary load reductions. In this section, a definition of the AMI will be given followed by discussing the components/technologies from which AMI consists of.

2.5.2.1 Definition of AMI

AMI is defined as [13] “an integration of many technologies that provides an intelligent connection between consumers and system operators.”

An alternative definition refers to AMI as [14] “a measurement and collection system that includes smart meters, communication networks, and data management systems that make the information available to the service provider.”

An AMI therefore is an integration of several technologies that provides an intelligent connection between consumers and system operators. It facilitates the supply to consumers with the necessary information they need to make intelligent decisions, the ability to execute those decisions and a variety of choices leading to substantial benefits they do not enjoy under conventional electrical network environment. Additionally, AMI enables system operators to greatly improve consumer service by refining utility operating and asset management processes based on the data provided by AMI.

Technologies involved in such integration include smart metering, home area networks, integrated communications, data management applications, and software interfaces with existing utility operations and asset management processes. The system resultant from the integration of these technologies enables AMI providing the required link between the grid, consumers and their loads, and generation and storage resources. Such a link is considered fundamental and the first step to the overall modernization of conventional electrical networks and eventually development of the Smart Grid vision.

2.5.2.2 Main components of AMI

An AMI is a system which comprises of a number of technologies and applications that are integrated together to perform as a single system [13]. The three main components of AMI systems are as follows as shown in Figure 2.2 [14,15].

(i) Smart meters

Smart meters are typically digital programmable devices that record customer consumption of electric energy in intervals of an hour or less and communicate that information, daily or more frequent, back to the energy supplier for monitoring and billing purposes. Other functions of smart meters include [10] (i) time-based pricing, (ii) net metering, (iii) loss of power and restoration notification, (iv) remote turn on/turn off operations, (v) load limiting for “bad pay” or demand response purposes, (vi) energy prepayment, (vii) power quality monitoring, (viii) tamper and energy theft detection, and (ix) communications with other intelligent devices in the home.

A smart meter may be labeled as a “green meter” because it enables the demand response that can lead to reduction in carbon emission. It also

- Wireless (radio frequency), either centralized or a distributed mesh
 - Internet
 - Combinations of the above
- (iii) **Data reception and management system**

The meter data transferred over the communication network are received at utility/third party site by the AMI host system [15], which is then sent to the meter data management system (MDMS) as shown in Figure 2.2.

MDMS plays an important role in realizing the full potential functions of AMI, particularly when implemented prior to a large-scale residential AMI installation [16]. The major functions of MDMS system include (i) automating and streamlining the complex process of collecting meter data from multiple meter data collection technologies, (ii) evaluating the quality of the collected data and generating estimates where errors and gaps exist, and (iii) delivering the collected data in a format that suits utility billing systems.

In the context of AMI system, smart meters are usually located at customer premises outside residential buildings while MDMS are located at the utility side as shown in Figure 2.2. Therefore, smart meters and MDMS communicate with each other within a neighborhood through neighborhood area network (NAN) [14]. For a comprehensive discussion of this topic, interested readers are advised to refer to references [17,18].

In addition to the above three main components, home area networks (HANs) and operational gateways are also considered as constituents of an AMI system [13].

HANs

HANs have emerged and were intensively used in the late 1990s and early 2000s as a consequence of the growth of the Internet [19]. The Internet and the technologies that are initially developed for an HAN aimed at moving large amounts of data (high bandwidth) with high speed through a network at somewhat intermittent intervals. This applies to applications, including graphics, music, and video. However, the needs of the Smart Grid applications are significantly different. It requires relatively low bandwidth but regular communications. These devices that are to be used in consumer premises to manage their energy consumption as well as enable them to interact with electricity market include thermostats, HVAC systems, major appliances, home automation systems, home energy management systems, lighting, gas meters, water meters, and electric meters. All these devices are characterized by having low bandwidth but regular and consistent data stream requirements.

The purpose of an HAN is to interface with the consumer portal so that it links smart meters to controllable electrical devices. The energy management functions of HANs include [13] (i) in-home displays to make the consumer aware about the energy being used and its cost, (ii) responsiveness to price signals based on consumer-entered preferences, (iii) set points that limit utility or local control actions to a consumer specified band, (iv) automatic control of loads, i.e., without the need of continued consumer involvement, and (v) consumer override capability.

The HAN/consumer portal acts as the consumer's "agent" because it provides a "smart interface" to the market. It can also support new value added services such as security monitoring.

Implementation of an HAN may be made in different ways. For example it may be done with the consumer portal located in any of several possible devices, including the meter itself, the neighborhood collector, a stand-alone utility-supplied gateway, or even within customer-supplied equipment.

Operational gateways

AMI interfaces with several system-side applications, as discussed in MDMS above, to support:

- (a) Advanced distribution operations
Advanced distribution operations include (i) distribution management system with advanced sensors (including real and reactive powers (PQ) data from AMI meters), (ii) advanced outage management (real-time outage information from AMI meters), (iii) DER operations using Watt and VAR data from AMI meters, (iv) distribution automation including Volt/VAR optimization and fault location, isolation, sectionalization, and restoration, (v) distribution geographic information system, and (vi) application of AMI communications infrastructure for microgrid operations, including both AC and DC, high-speed information processing, advanced protection and control and advanced grid components for distribution.
- (b) Advanced transmission operations
Advanced transmission operations include (i) substation automation, (ii) high-speed information processing, (iii) advanced protection and control, including distribution control to improve transmission conditions, (iv) modeling, simulation, and visualization tools, (v) advanced regional operational applications, and (vi) electricity markets.
- (c) Advanced asset management (AAM) system
AMI data will be required to support AAM in areas, including (i) system operating information, (ii) asset "health" information, (iii) operations to optimize asset utilization, (iv) transmission and distribution planning, (v) condition-based maintenance, (vi) engineering, design, and construction, (vii) consumer service, and (viii) work and resource management.

It will be noted that equivalent term to the AMI used in Europe is "Smart metering system (SMS)" [20]. Figure 2.3 shows a typical SMS architecture that has been contemplated in various US and European standards such as ZigBee and ETSI machine to machine [21]. In this figure, it can be seen that home automation system, for example, a home building energy system (HBES) or a home energy management system (HEMS), may be interfaced with the smart meter or the gateway within the HAN. The in-home display (IHD) unit shown in the figure, often called as customer display unit, is a special device that provides a visualization of data received from smart meter(s), which may include electricity, gas, water, and heat meters and optional submeters attached to specific appliances.

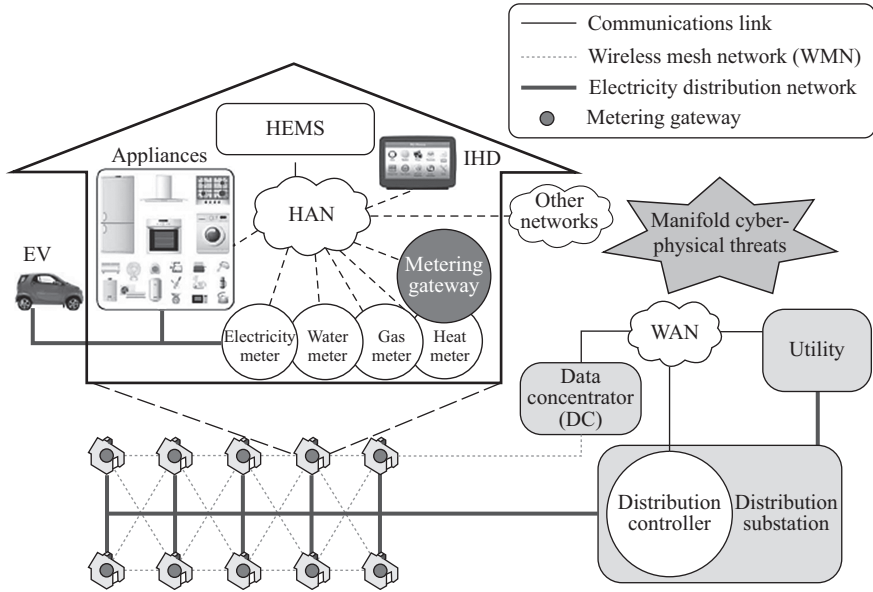


Figure 2.3 Typical SMS architecture contemplated in various US and European standards [20]. Reproduced with permission of IEEE

Several home sensors and actuators can be integrated together to control and optimize energy consumption. This functionality may further be used to optimize renewable power generation and to reach carbon saving targets.

2.5.2.3 AMI communication infrastructure

In general terms the AMI communication infrastructure may be considered to consist of two layers; lower layer and upper layer as shown in Figure 2.4 [14]. The lower layer is the smart meter network that connects smart meters, which may include local concentrator(s). This network is typically a mesh network whose function is to collect consumption information from end-users and subsequently upload them to the backhaul network directly or through local concentrators. It also helps to propagate commands/price signals among smart meters. The most important requirements of such network are its cost effectiveness and reliability.

The upper layer is the backhaul network that connects backbone concentrators and a control center or MDMS. It is the function of backbone concentrators to collect consumption data from smart meters or local concentrators. They are also used to transmit information and receive commands from the control center. It is important to ensure the main requirements of the backhaul network of high reliability and low latency.

2.5.2.4 Communication technologies adapted for AMI

Communication technologies that can be adapted to support AMI deployment include both wired and wireless technologies. The commonly communication

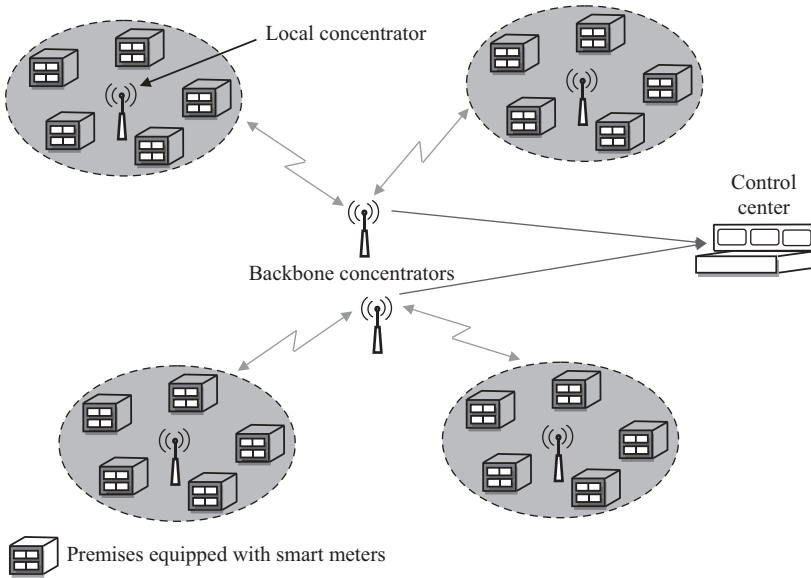


Figure 2.4 Typical two-layer AMI communication network [after 14]

wired technologies used for AMI deployment include power line communication (PLC) and fiber optic. However, the commonly wireless communication technologies used for AMI deployment include cellular (4G (the fourth generation of wireless mobile telecommunication technology), LTE (Long-Term Evolution, which is a standard for high-speed wireless communication for mobile phones and data terminals), and WiMAX (Worldwide Interoperability for Microwave Access)), WLAN (Wireless Local Area Network), Zig-Bee (a specification for a suite of high level communication protocols used to create personal area networks built from small, low-power digital radios), and RF (Radio Frequency) mesh (900 MHz). Each of these communication technologies has advantages and disadvantages as discussed below.

(i) **Wired communication technologies**

- **PLC**

As the name implies, this type of technology uses existing power lines as a medium to transmit data. PLC is conceived as a promising communication technology for Smart Grid applications because of the availability of existing infrastructure represented by power lines. It suits many control applications, including smart metering, home automation, and others. This is particularly true for rural areas which have access to power but do not have communication infrastructures. However, PLC has several disadvantages due to noisy channel, low-bandwidth, and difficulty for signals to be transmitted through power distribution devices. Security concerns represent another drawback of PLC.

- **Fiber optic communications**
Fiber optic is characterized by having high data rate and immunity to noise. This makes it a popular communication technology to be adopted as backbone communications to support various Smart Grid applications. Fiber optic communication technology particularly suits long distance network that has limited number of access points. The major drawback of this technology is its high installation cost.

(ii) **Wireless communication technologies**

- **Cellular communication (4G, LTE, and WiMAX)**
A utility can save the time and cost that are needed to set up the network for Smart Grid applications if a cellular network infrastructure exists. Thus an existing cellular network can be a good opportunity for setting up an AMI system, particularly to support data communications between concentrators and the control center. One of the advantages of adopting cellular network is its very strong security. However, the disadvantages include (i) network congestion in certain emergency situations due to sharing cellular networks with other customers and (ii) the possibility of not providing a guaranteed service by cellular networks during abnormal conditions, such as a wind storm. Among all cellular technologies, WiMAX is considered the most promising 4G wireless technology based on the IEEE 802.16 series of standards. It has a data rate of up to 75 Mbps and a coverage distance of up to 50 km. WiMAX has also low communication latency. Such good qualities make WiMAX a good candidate for Smart Grid applications. However, the main disadvantages of WiMAX are its high power consumption and its relatively high deployment cost.
- **ZigBee**
ZigBee is considered as the most popular industry wireless mesh networking standard for connecting sensors, instrumentation, and control systems [22]. It is a personal area network protocol based on the IEEE 802.15.4 standard [14]. The coverage distance of ZigBee is up to 100 m while that of ZigBee pro is up to 1,600 m. The range of ZigBee pro suits AMI applications. Its data rate extends from 20 Kbps to 250 Kbps. ZigBee is characterized as a low-cost, low-power consumption, and secure technology. However, the drawback of ZigBee is that it suffers from severe interference problems with other networks because of sharing the same channel spectrum. It also suffers from low processing capabilities. This is why implementation of ZigBee must be based on a well-designed network structure and well organized communication traffic. Hence the mesh topology is commonly used to support large-scale applications.
- **WLAN**
WLAN is also known or marketed as Wi-Fi. It is considered as a type of high-speed wireless network technology. It is based on the IEEE 802.11 standards and operates on 2.4 GHz, 3.6 GHz, and 5 GHz bands. The main advantage of WLAN is its reliability, security, and high-speed

communication. However, it has the drawback of relatively high implementation cost and power consumption compared to other short-range (100 m) technologies, such as ZigBee. Access points are usually required to set up the network. Similar to ZigBee, WLAN commonly uses mesh networking topology.

- 900 MHz band

The 900 MHz band is unlicensed industrial, scientific, and medical (ISM) RF band. 900 MHz has a range approximately two times that at 2.4 GHz. Additionally, the protocol mostly implemented for 900 MHz technology is the mesh protocol. Consequently, it inherits mesh network properties, which are self-healing, highly reliable, and cost effective with wide coverage range. These properties make them suitable for deployment in urban as well as suburban areas. Thus the RF (900 MHz) mesh network can be a good option for setting up AMI mesh network connecting smart meters. However, as it is the case for all other networks using mesh protocol, 900 MHz has many drawbacks. The drawbacks include high bandwidth consumption, lack of interoperability, and privacy protection issues.

2.6 An overview of the Smart Grid infrastructure

The Smart Grid is considered to consist of electricity system, communication and information system, and protection, automation, and control system. Similar to conventional electrical networks (CENs), Smart Grid's electricity system consists of four key subsystems namely generation, transmission, distribution, and consumer or load [23]. Unlike conventional electrical networks, consumers in the Smart Grid are **“active”** as discussed above. A consumer, in the Smart Grid, may be a generator supplying electricity to the grid which is referred to as “prosumer” or it may be a consumer who dynamically uses the electricity supplied from the grid with the help of his smart appliances in association with communication networks and other advanced technologies. Another major difference from CENs is that the four main electricity subsystems of the Smart Grid are linked together by highly advanced and secured communication infrastructure. Details of Smart Grid infrastructure will be discussed in Chapter 3.

2.7 Summary

In this chapter, the infrastructure of conventional electrical networks and their main characteristics have been reviewed. The motives behind the development of the Smart Grid concept have also been identified. Such motives include (i) aging of conventional electrical networks, (ii) political and environmental factors, (iii) economical factors, and (iv) motivation and inclusion of customers connected to Smart Grid. The evolution of the Smart Grid concept is then discussed. The AMI, which is also known in Europe as SMS, was then introduced. AMI is considered a fundamental and first step to the overall modernization of conventional electrical

networks which eventually has led to the development of the Smart Grid vision. AMI is viewed as an important tool for providing the essential link required between the grid, consumers and their loads, and generation and storage resources. Definition of AMI is given followed by discussing its main components, AMI communication infrastructure, and the adopted communication technologies for AMI.

Finally a brief overview of the Smart Grid infrastructure and its characteristics is given.

References

- [1] ABB. *Towards a Smarter Grid, ABB's vision for the power system of the future* [Online]. USA: ABB Inc. Report; 2009. Available from http://www02.abb.com/db/db0003/db002698.nsf/0/e30fc9d5f79d4ae8c12579e2002a4209/%24file/Toward_a_smarter_grid_Jul+09.pdf [Accessed 27 October 2015]
- [2] Makkonen H., Tikka V., Kaipia T., Lassila J., Partanen J., and Silventoinen P. *Green Campus – Smart Grid* [Online]. Available from http://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&frm=1&source=web&cd=1&ved=0CDEQFjAA&url=http%3A%2F%2Fwww.cleen.fi%2Fen%2FSitePages%2Fpublic%2Fdeliverables.aspx%3FfileId%3D1677%26webpartid%3Dg_e6ff1fc0_9a94_40af_8aae_e1274f853ff6&ei=_K5vUvy3CYXwhQeC54HICg&usg=AFQjCNGTv4o42-SJSpmY3Lf2A_AaPuBcFg&bvm=bv.55123115,d.d2k [Accessed 27 October 2015]
- [3] Hashmi M. *Survey of smart grids concepts worldwide* [Online]. Finland: VTT Technical Research Centre of Finland; 2011. Available from <http://www.vtt.fi/inf/pdf/workingpapers/2011/W166.pdf> [Accessed 27 October 2015]
- [4] Hallberg P., Bergerland C., Blanquet A., *et al.* *Smart Grids and Networks of the Future* [Online]. Belgium: Union of the Electricity Industry – EURELECTRIC – A.I.S.B.I.; 2009. Available from http://www.eurelectric.org/media/43723/smart_grids_-_eurelectric_views_v21_ffinal-2009-030-0440-01-e.pdf [Accessed 27 October 2015]
- [5] Salman S.K. and Rida I.M. 'Investigating the impact of embedded generation on relay settings of utilities electrical feeders'. *IEEE Transaction on Power Delivery*. 2001;**16**(2):246–51
- [6] Salman S.K., Jiang F., and Rogers W.J.S. 'Effects of wind power generators on the voltage control of utility's distribution networks'. *Wind Engineering*. 1994;**18**(4):181–7
- [7] Jiang F. and Salman S.K. 'Effect of integration on wind farms into utility networks on voltage control due to the co-ordination of AVC relays'. *Wind Engineering*. 1999;**23**(4):205–13
- [8] Cleveland F., Small F., and Brunetto T. *Smart Grid: interoperability and standards – an introductory review* [Online]. USA: Utility Standard Board; 2008. Available from http://xanthus-consulting.com/Publications/documents/Smart_Grid_Interoperability_and_Standards_White_Paper.pdf [Accessed 27 October 2015]

- [9] Bacher, R. *Europäische Technologieplattform (ETP) SmartGrids* [Online]. Switzerland: 2009. Available from <http://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&ved=0CCgQFjABahUKEwi25riQIOPIAhVH1BoKHQftDIM&url=http%3A%2F%2Fwww.bfe.admin.ch%2Fphp%2Fmodules%2Fenet%2Fstreamfile.php%3Ffile%3D000000010297.pdf%26name%3D0000000290121&usg=AFQjCNHsFT-9jQ778Xo9pz38D0cQdNNGYw&bvm=bv.106130839,d.d2s> [Accessed 27 October 2015]
- [10] European Commission (European Technology Platform). *SmartGrids: vision and strategy for Europe's electricity networks of the future* [Online]. 2006. Available from http://ec.europa.eu/research/energy/pdf/smartgrids_en.pdf [Accessed 27 October 2015]
- [11] Hamilton B.A., Pullins S., Miller J., and Renz B. *Smart grid principal characteristic enables new products, services, and markets* [Online]. USA: Report DOE/NETL-2010/1401; 2010. Available from http://www.netl.doe.gov/File%20Library/research/energy%20efficiency/smart%20grid/whitepapers/Appendix-A6—Enables-Markets-v3_0.pdf [Accessed 29 October 2015]
- [12] National Energy Technology Laboratory (NETL). *The modern grid strategy: a vision for the smart grid* [Online]. USA: Report; 2009. Available from https://www.smartgrid.gov/files/The_Modern_Grid_Strategy_Vision_for_Smart_Grid_200910.pdf [Accessed 29 October 2015]
- [13] National Energy Technology Laboratory (NETL). *Advanced metering infrastructure* [Online]. USA: Report; 2008. Available from https://www.netl.doe.gov/File%20Library/research/energy%20efficiency/smart%20grid/whitepapers/AMI-White-paper-final-021108-2-APPROVED_2008_02_12.pdf [Accessed 29 October 2015]
- [14] Bian B., Kuzlu M., Pipattanasomporn M., and Rahman S. 'Analysis of communication schemes for advanced metering infrastructure (AMI)'. *IEEE PES General Meeting Conference and Exposition*; National Harbor, MD, USA, 2014, pp. 1–5
- [15] Electric Power Research Institute (EPRI). *Advanced metering infrastructure (AMI)* [Online]. February 2007. Available from <http://www.ferc.gov/event-calendar/Files/20070423091846-EPRI%20-%20Advanced%20Metering.pdf> [Accessed 8 September 2015]
- [16] Moore S. *Key features of meter data management systems* [online]. 2008. Available from https://www.itron.com/na/PublishedContent/Key%20MDM%20Features%20Whitepaper_FINAL.pdf [Accessed 10 September 2015]
- [17] Kuzlu M. and Pipattanasomporn M. 'Assessment of communication technologies and network requirements for different smart grid applications'. *Proceedings of the IEEE Innovative Smart Grid Technologies (ISGT) PES Conference*; Washington, DC, USA, February 2013, vol. 1, no. 6, pp. 24–7
- [18] Bian D., Kuzlu M., Pipattanasomporn M., and Rahman S. 'Assessment of communication technologies for a home energy management system'. *Proceedings of the IEEE Innovative Smart Grid Technologies (ISGT) PES Conference*; Washington, DC, USA, 2014, pp. 1–5

- [19] Clements S.L., Hadley M.D., and Carroll T.E. *Home area networks and the smart grid* [Online]. Report PNNL-20374. USA: Department of Energy; April 2011. Available from http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-20374.pdf [Accessed 30 October 2015]
- [20] Kalogridis G., Sooriyabandara M., Fan Z., and Mustafa M.A. 'Toward unified security and privacy protection for smart meter networks'. *IEEE System Journal*. 2014;**8**(2):641–54
- [21] ETSI. *Machine-to-machine communications (M2M); smart metering use cases* [Online]. 2010. TR 102 691, v1.1.1 Cedex, France. Available from http://www.etsi.org/deliver/etsi_tr/102600_102699/102691/01.01.01_60/tr_102691v010101p.pdf [Accessed on 27 February 2016]
- [22] Tomar A. *Introduction to ZigBee Technology* [Online]. 2011. Available from <https://www.element14.com/community/servlet/JiveServlet/previewBody/37177-102-1-219424/Introduction%20to%20Zigbee%20Technology.pdf> [Accessed 13 October 2015]
- [23] Gunther E.W., Snyder A., Gilchris G., and Highfill D.R. *Smart grid standards assessment and recommendations for adoption and development* [Online]. USA: EnerNex Corporation; February 2009. Available from <http://www.osgug.org/Shared%20Documents/Smart%20Grid%20Standards%20Landscape%20White%20Paper%20v0%2083.doc> [Accessed 31 October 2015]

This page intentionally left blank

Chapter 3

Smart Grid infrastructure

3.1 Introduction

An overview of the composition of the Smart Grid will be discussed in this chapter. Literature review has revealed that the composition of the Smart Grid is defined using four different methods. These methods defined the composition of Smart Grid based on (i) standards adaptation, (ii) technical components' perspective, (iii) technical perspective, and (iv) conceptual reference model perspective.

According to the standards adaptation-based method, Smart Grid is considered as a "System of Systems." Its main components include electric power system, other entity systems comprised of the many unique customer systems, services provider systems, and an overall macro-system such as a wide area control system and Regional Transmission Organization/Independent System Operator (RTO/ISO) systems.

The technical components' perspective-based method considers the Smart Grid as a highly complex combination and integration of multiple digital and nondigital technologies and systems. Its main components include new and advanced grid components, smart devices and smart metering, integrated communication technologies, software programs for decision support and human interfaces, and advanced control systems.

According to the technical perspective-based method, Smart Grid is considered to consist of three major systems. These are smart infrastructure system, smart management and control system, and smart protection system.

The conceptual reference model perspective-based method considers the Smart Grid to consist of seven domains. These domains are bulk generation, transmission, distribution, customers, service providers, operations, and markets. This model helps to identify the interfaces between domains and actors. It also includes applications necessary for exchanging information, for which interoperability standards are needed.

As the Smart Grid continues to evolve, totally new components, including hardware and software, as well as new standards will continue to be developed and adapted. It will therefore be difficult to precisely identify the components from which a future Smart Grid will be made of. However, after re-examining the definitions and characteristics of Smart Grid covered in Chapter 1 and after

reviewing Smart Grid composition given in this chapter, basic components of a Smart Grid have been identified.

Finally, the infrastructure of the Smart Grid has been defined. Basically, it consists of electrical power system, communication and information system, intelligent protection, automation, and distributed control system and marketing system.

3.2 Composition of the Smart Grid

Composition of the Smart Grid is highly complex. Several attempts have been made to define the composition and components of the Smart Grid as will be discussed below. According to these attempts, composition of the Smart Grid has been defined using the following basis:

- Standards adaptation
- Technical components' perspective
- Technical perspective
- Conceptual reference model perspective

A review of the composition of the Smart Grid will be discussed in the following subsections.

3.2.1 Composition of Smart Grid based on standards adaptation

It has been recognized by electrical utilities that development and adaption of open standards are essential for a Smart Grid to ensure interoperability and security. In this context, the Smart Grid is assumed to comprise of [1,2]: (i) a “utility electric system” which consists of several individual systems, including generation, transmission, distribution, and customer systems within the utility, (ii) other entity systems comprised of the many unique customer systems, services provider systems, systems, and resources supplier systems, and (iii) an overall macrosystem such as a wide area control system and RTO/ISO systems. Linking “utility systems,” other entity systems and macrosystems together results in the Smart Grid which is a “System of Systems” as illustrated in Figure 3.1.

Identifying the components of the Smart Grid in this way helps in distinguishing between two types of interfaces as follows:

- (i) Intersystem interfaces: These are the interfaces linking the various systems. Strictly speaking, they are the interfaces between the boundary of the utility's transmission, distribution, and customer systems and the boundary of another entity's systems or devices. For example, this could be the interface between a utility meter and customer device, or between utility grid management system and RTO system.
- (ii) Intrasytem interfaces: These are the interfaces within a utility system. In other words, these are the interfaces within the boundary of the utility's system of transmission, distribution, and customer systems. For example, this could be the interface between a utility meter and a utility communication network or a utility fault detector and distribution management system.

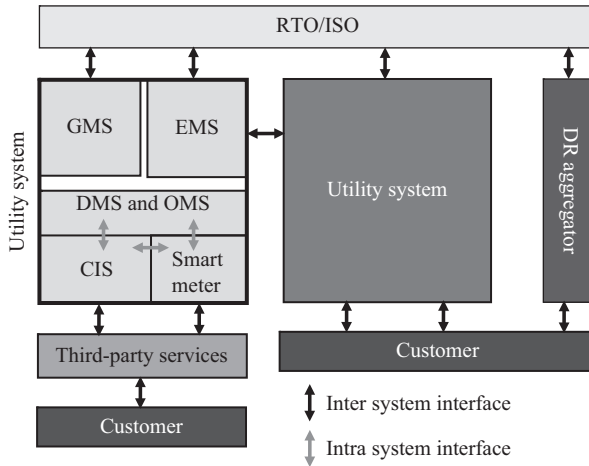


Figure 3.1 Composition of the Smart Grid as a “System of Systems” based on standards adaptation. Adapted from [1]

The most significant customer value that can be derived from standards application in interoperability is that related to “inter-system” interfaces. This may be illustrated by the following examples:

- The interface between the smart meter and plug-in electric vehicle (PEV) requires the adaptation of an “inter-system” standard.
- Service providers must have a standard “inter-system” interface to be able to access customer data from utility back-office systems for web presentation through an application programming interface (API).
- It is essential to have “inter-system” standards adoption to enable in-home energy displays, energy smart appliances, smart thermostats, and energy smart home automation.

3.2.2 Composition of Smart Grid based on technical components’ perspective

According to this approach, the Smart Grid is viewed as a highly complex combination and integration of multiple digital and nondigital technologies and systems. Its main components, as illustrated in Figure 3.2, consist of [3]: (i) new and advanced grid components, (ii) smart devices and smart metering, (iii) integrated communication technologies, (iv) software programs for decision support and human interfaces, and (v) advanced control systems.

(i) *New and advanced grid components*

Example of such components include advanced conductors and superconductors, improved electric storage components, new materials, advanced power electronics, and distributed energy generation. Introduction of such

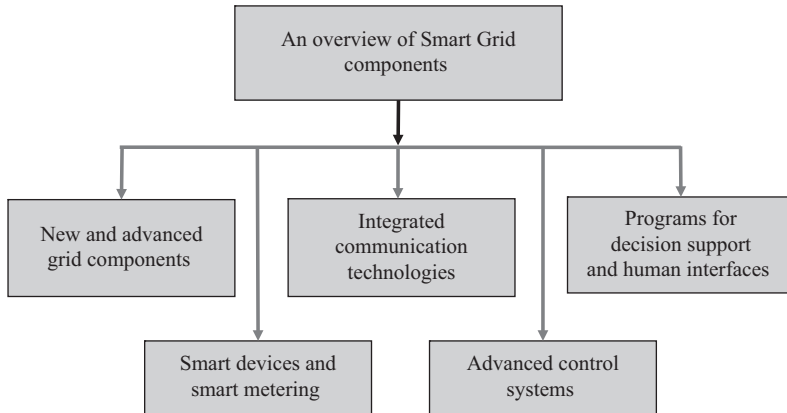


Figure 3.2 Main components of a Smart Grid based on technical components' perspective [after 3]

components would improve the efficiency of energy supply and increase the reliability and availability of power.

(ii) **Smart devices and smart metering**

Smart devices and smart metering include **sensors and sensor networks**. Sensors are usually fitted at different locations on the grid. For example, they may be fitted at transformers and substations or at customers' homes. Sensors play an extremely important role in the area of remote monitoring and consequently facilitate demand-side management. This in turn promotes new business processes such as real-time pricing.

As sensors and sensor networks are normally fitted all over the place along the grid, they are able to monitor the functioning and the health of grid devices, monitor temperature, detect outages, and power quality disturbances. This enables control centers receiving accurate information about the actual condition of the grid as soon as the grid is subjected to any change. Consequently, maintenance procedure can be carried out immediately after the occurrence of a disruption and therefore moving away from interval-based inspections.

Smart meters are normally fitted at customers' premises. They can play an important role. They provide real-time determination and information storage of energy consumption and also provide "the possibility to read consumption both locally and remotely." Additionally, they can detect power fluctuations and power outages, allow customers to remotely apply limits on energy consumption, and permit the meters to be switched off. This results in important cost savings and consequently enables utilities to prevent electricity theft.

Using smart meters help electricity providers to have a better picture of customers' energy consumption and consequently help them gaining accurate understanding of energy consumption at different points in time. This in turn enables utilities to establish demand-side management (DSM) and accordingly developing new pricing mechanisms. This makes it possible to

Table 3.1 An overview of Smart Grid communication applications and technologies [3]. Reproduced with permission from OECD

An expanded view of different Smart Grid communication application and technologies		
Core networking	• Protocols needed to provide interoperable connectivity in a network that may vary greatly in topology and bandwidth	e.g. HTTP, TCP
Security	• Security measures for consumer portal communications as portals directly deal with consumer information and billing process	e.g. IPSec, HTTPS
Network management	• Standard technologies for collecting statistics, alarms, and status information on the communications network itself	e.g. Basic IP, SNMP
Data structuring and presentation	• “Meter-data” for formally describing and exchanging how devices are configured and how they report data	e.g. HTML, XML
Power system operation	• Several of the key applications for portals involve integration with distribution system operations such as outage detection and power quality monitoring	e.g. DNP 3
Consumer applications	• Electrical metering and various aspects of building automation	e.g. ANSI/IEEE C12
Network technologies		
WAN technologies	• The problem of how to reach the consumer site represents the most rapidly changing area of portal technology, and the one that will have the most impact on its commercial viability	e.g. DSL, Cellular
LAN technologies	• Technology making a portal distant from being just a “smart meter” or “smart thermostat” is its stability to network with other devices locally	e.g. Ethernet, Wi-Fi

decide the price of energy according to real-time costs taking into account peak power loads. Also price signals can be transmitted to home controllers or customers’ devices which consequently enable evaluation of the information and power. This results in customers becoming more interactive with electricity suppliers and therefore benefits from an increased visibility into their energy consumption habits.

(iii) ***Integrated communication technologies***

Information generated by smart sensors and smart meters needs to be transmitted to processing locations via a communication network. Such a

communication network must be of a high-speed and two-way information flow. The communication network is formed from the integration of different communication applications and technologies. These can be classified into communication services groups. Table 3.1 provides an overview of these groups as well as brief descriptions and examples [3].

Utilities can choose between multiple and diverse technologies in the area of **communication network technologies**. Several network technologies that suit the Smart Grid applications have been deployed. Examples of such networks include wide-area networks (WAN), which aim at reaching the customer, and local-area networks (LAN), which are operated at customer sites.

In this context, the distinction made between WAN and LAN technologies to differentiate between networks used to reach the customer and those at customer sites.

WAN technologies are designed to handle a two-way information flow that suits Smart Grid environment. Different types of WAN technologies are available. They are capable of providing both broadband and narrowband solutions for the Smart Grid. Discussing the details of this subject is outside the scope of this book. Readers who are interested to know more about this subject are advised to refer to reference [3].

(iv) ***Programs for decision support and human interfaces***

Programs for decision support and human interface are considered as a key Smart Grid's component that is needed to handle the sheer volume of data that is expected to be generated under the Smart Grid environment. This constitutes a rather difficult challenge to utilities. The functionality of this component consists of two tasks: (i) properly handles the integration and management of the generated data and (ii) presents the data available to grid operators and managers in a user-friendly manner to support their decisions.

Example of tools and applications that help minimizing data volume as well as "creating a format most effective for user comprehension" include artificial intelligence methods and semi-autonomous agent software, whereby the software has the ability of learning from input and adapts accordingly [3,4]. To be able to integrate data from different sources that provides information on the status of the grid and power quality and providing quick information about instabilities and outages, new methods of visualization are needed. Geographic information systems that provide geographic, spatial, and location of sources of information to tailor such information to the specific requirements for decision support systems along the Smart Grid are also required.

(v) ***Advanced control systems***

The main function of advanced control systems is to monitor and control essential elements of the Smart Grid [3]. Such systems include distributed intelligent control systems, substation automation, distributed automation, and integration with enterprise systems [4].

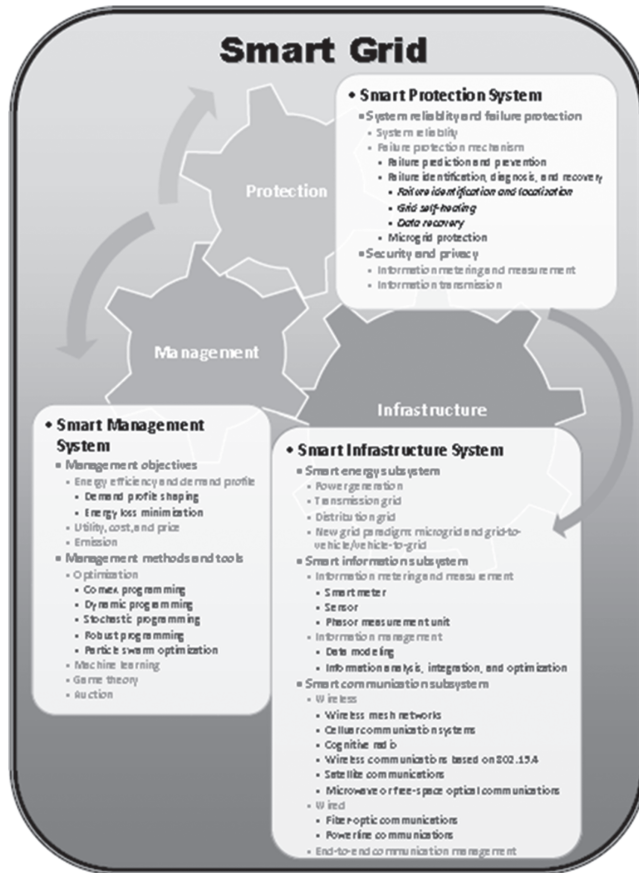


Figure 3.3 Details of the composition of Smart Grid according to the technical perspective approach [5]. Reproduced with permission of IEEE

3.2.3 Composition of Smart Grid based on technical perspective

From technical perspective point of view the Smart Grid is considered to consist of the following three major systems, the details of which are shown in Figure 3.3 [5]:

- (i) *Smart infrastructure system*
- (ii) *Smart management and control system*
- (iii) *Smart protection system*

(i) **Smart infrastructure system**

The smart infrastructure system consists of (i) electrical energy subsystem, whose function is to generate electricity, transmit it, and distribute it to load centers, (ii) information subsystem, whose function is to support advanced

information metering, monitoring, and management systems and (iii) communication infrastructure subsystem, whose function is to perform communication and information transmission between various subsystems, devices, and applications from which Smart Grid consists of.

Under Smart Grid environment, the smart infrastructure system supports two-way flow of electricity and information. Unlike conventional power system networks, in addition to central generating plants, the electricity may be generated at distribution voltage level by customers or otherwise and fed back to the grid. For example, customers may generate electricity using solar panels at homes and feed it back to the grid. Electric vehicles may also be used to help in “peak shaving,” a process whereby electric power is fed back to the grid to balance loads during peak demand periods (see Chapter 9).

(ii) ***Smart management and control system***

The smart management and control system of the Smart Grid provides advanced management and control services. The main objective of this system is to improve energy efficiency, ensure supply and demand balance, ensure greenhouse gas emission control, reduce operation cost, and maximize utility profit.

(iii) ***Smart protection system***

The smart protection system of the Smart Grid provides advanced grid reliability analysis, failure protection, and security and privacy protection services. The function of this system does not confine only to the protection of the grid from unintentional faults due to users, errors, equipment failures, and natural disasters, but it also includes protecting the grid from deliberate cyber-attacks that can be committed, for example, by disgruntled employees, industrial spies, and terrorists.

3.2.4 *Composition of Smart Grid based on conceptual reference model perspective*

The National Institute of Standard and Technology (NIST) in the USA proposed the Smart Grid conceptual reference model [6]. Such a model provides a high-level, overall view of the Smart Grid. It is considered as a useful tool for identifying actors and possible communications paths between various players in the Smart Grid. This model is also used to identify the interfaces between domains and actors. It also includes applications necessary for exchanging information, for which interoperability standards are needed. According to this model the Smart Grid is divided into seven domains, as briefly described in Table 3.2. Figure 3.4 shows a graphical representation of the Smart Grid conceptual model which is intended to help in analysis, that is, this diagram is ***not*** a design diagram that defines a solution and its implementation. In other words, the conceptual model is descriptive and not prescriptive. The main benefit of this approach is to help understanding the Smart Grid operational details and complexities and does not prescribe how the Smart Grid can be implemented.

Table 3.2 Domains and roles/services in the Smart Grid conceptual model [6].
Reproduced with permission from OECD

Domain	Actors in the domain
1 Customers	The end-users of electricity. May also generate, store, and manage the use of energy. Three customer types are considered, each with its own domain: residential, commercial, and industrial.
2 Markets	The operators and participants in electricity markets.
3 Service Providers	The organizations providing services to electrical customers and utilities.
4 Operations	The managers who control the flow of electricity.
5 Generation	Generators of electricity may also store energy for later distribution. This domain includes traditional generation sources (traditionally referred to as generation) and distributed energy resources (DER). At a logical level, “generation” includes coal, nuclear, and large-scale hydro generation usually attached to transmission. DER (at a logical level) is associated with customer- and distribution-domain-provided generation and storage, and with service-provider-aggregated energy resources.
6 Transmission	The carriers of bulk electricity over long distances may also store and generate electricity.
7 Distribution	The distributors of electricity to and from customers may also store and generate electricity.

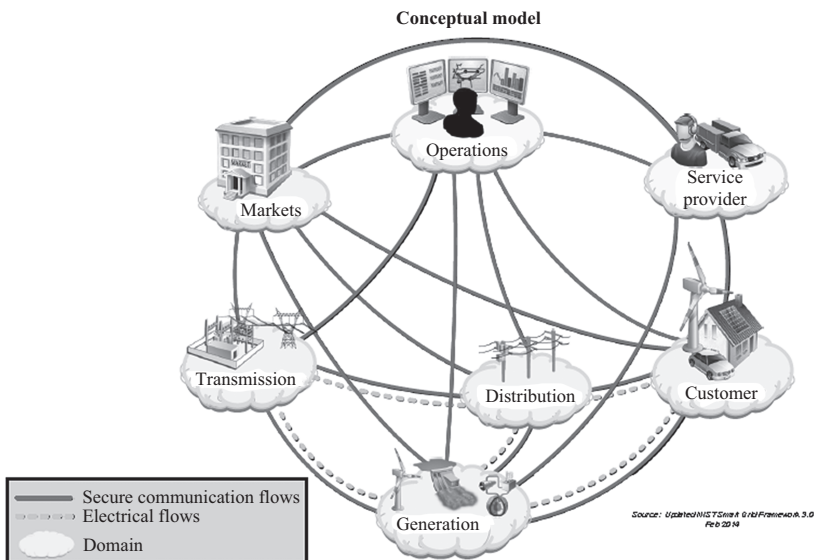


Figure 3.4 The Smart Grid conceptual model which shows the interaction of roles in different Smart Grid Domains through secure communication [6]

Each domain and its subdomains comprises Smart Grid **actors** and **applications**. An actor is a device, a system, or a program that makes decisions and exchange information necessary for performing applications. Examples of devices and systems include smart meters, solar generators, and control systems. However, applications are defined as tasks performed by one or more actors within a domain. Examples of applications include home automation, solar energy generation and energy storage, and energy management.

Actors in the same domain, in general, have similar objectives. To facilitate Smart Grid functionality, the actors in a particular domain frequently interact with actors in other domains, as shown in Figure 3.4. However, communications within the same domain may not necessarily have similar characteristics and requirements. Additionally, particular domains also may contain components of other domains. For instance, the ISOs/RTOs in the USA have actors in both the markets and operations domains. Similarly, a distribution utility is not entirely contained within the distribution domain. It is likely to contain actors in the operations domain, such as a distribution management system, and in the customer domain, such as meters.

Fundamentally the conceptual model is a legal and regulatory framework that includes policies and requirements that apply to various actors and applications and to their interactions. The adopted regulations are developed in such a way that they govern many aspects of the Smart Grid. They are intended to ensure that electricity rates are fair and reasonable and that security, reliability, safety, privacy, and other public policy requirements are met. The process of transferring to the Smart Grid is bound to introducing new regulatory considerations. The proposed conceptual model must be consistent with the legal and regulatory framework and must support the evolution of the Smart Grid over time. It is important that the standards and protocols identified in the framework must align with the existing and emerging regulatory objectives and responsibilities. The aim of developing the conceptual model is to use it as a useful and effective tool for regulators at all levels to assess how best to achieve public policy goals and at the same time maintain business objectives, motivate investments in modernizing conventional electric power infrastructure and building a clean energy economy.

3.2.4.1 Use cases

One of benefits of introducing the conceptual reference model is that it provides a useful tool for constructing use cases [6]. So what are the use cases? A use case may be defined as “*a method for describing the interaction between a Smart Grid actor and a system when the actor is using the system to accomplish a specified goal.*” Use cases are classified into a “*black box*” and a “*white box*.” The black box use case describes the user-system interaction and the functional requirements to achieve the goal. However, it leaves the details of internal operation of the system to the discretion of the implementer. However, a white box use case describes the internal details of the system in addition to the interaction and associated requirements. White box use cases are therefore prescriptive because they do not allow the implementer to change the internal system design.

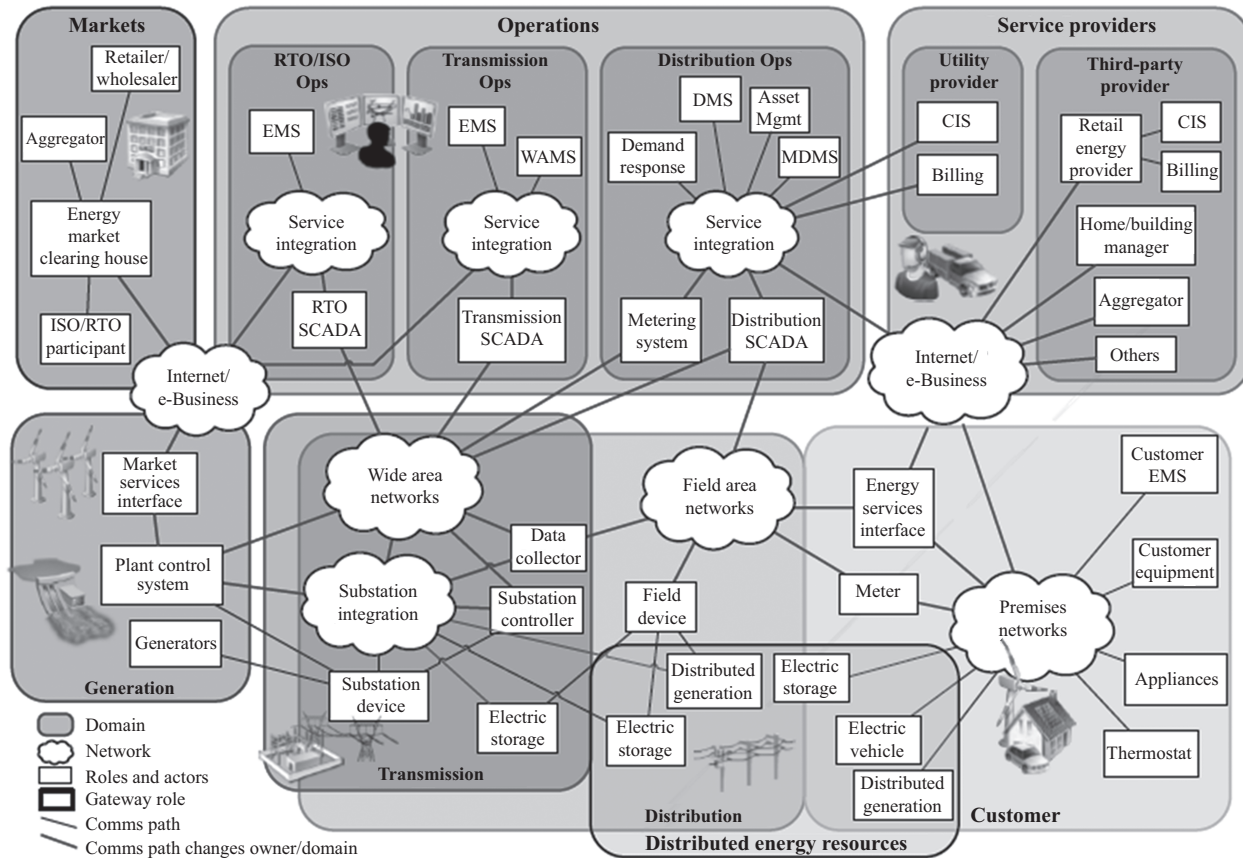


Figure 3.5 Logical model of conventional systems mapped onto conceptual domains for Smart Grid information networks [6]

For the purpose of developing interoperability standards framework and roadmap, the focus is placed on the black box use cases that describe how systems within the Smart Grid interact. White box use cases, however, are not covered by the framework and are left to the stakeholders to create as they describe the details of a particular solution and therefore they are prescriptive. The reason behind the focus on “black box use cases” is because they allow maximum innovation in the Smart Grid applications and at the same time ensure their ready deployment and interoperability within the Smart Grid as it evolves.

It has been recognized that “black box use cases,” both individually and collectively, are helpful when aiming at interoperability requirements for specific areas of functionality, such as on premises energy management or predictive maintenance for grid equipment. When viewed from a range of stakeholder perspectives and application domains, combining the actors and interactions from multiple use cases makes the Smart Grid as a collection of transactional relationships, within and across domains, as illustrated in Figure 3.5.

At this point of time, many Smart Grid intra- and interdomain use cases have already been developed, and the number will continue to grow as the Smart Grid evolves. The aim of the body of existing use cases also cover cross-cutting requirements, including cyber security, network management, data management, and application integration, as discussed in the *GridWise Architecture Council Interoperability Context-Setting Framework* [7].

A major activity covered at the second NIST Smart Grid interoperability standards public workshop held on May 19–20, 2009, was the development of black box use cases and interface requirements. This activity was focused on six Smart Grid functionalities, including wide-area situational awareness, demand response, energy storage, electric transportation, advanced metering infrastructure, and distribution grid management. The cross-cutting cyber security task group employed use cases in the priority areas; in addition to those, it is developing to supplement the priority area use cases.

Interested readers can find the detailed use cases on the NIST Smart Grid Collaboration Web site [8].

3.3 Basic components of Smart Grid and its technical infrastructure

Having reviewed the various attempts related to classifying the composition of the Smart Grid in the previous sections of this chapter, we shall try in this section to build up a vision of the technical infrastructure of the Smart Grid. But let us first identify the basic components of the Smart Grid.

3.3.1 Basic components of Smart Grid

The Smart Grid can be thought of as a concept by which electrical power system network getting smarter as a result of integrating different technologies/knowledge into it. As the Smart Grid continue to evolve, totally new components, including

hardware and software as well as new standards will continue to be developed and adapted. It is therefore difficult to precisely identify the components from which a future Smart Grid will be made of. However, by re-examining the definitions and characteristics of the Smart Grid covered in Chapter 1 and the attempts related to define the Smart Grid composition covered in the previous sections of this chapter, the following basic components of a Smart Grid may be identified:

- Generation facilities which may include a combination of bulk generation plants, distributed generation plants, and/or renewable energy based-generation plants such as wind, solar, and hydro.
- Transmission network, including transmission substations
- Distribution network, including distribution substations
- Consumer's load networks
- Information and communication technologies with provision of security to safely and reliably transmit data. The function of communication technologies is to ensure connectivity among systems, devices, and applications. Communication technologies consist of communication networks, media, and protocols.
- AMI: AMI is considered as a key component of the Smart Grid that implements residential demand response and also acts as the principal mechanism for implementing dynamic pricing [6]. See Chapter 2 for detailed discussion of the AMI.
- Intelligent electronic devices (IEDs)
- Control devices, computer control and distributed control systems
- Smart Grid-enabled home appliances: These are domestic appliances, such as Smart Grid-enabled clothes dryer, which are enabled by Smart Grid on the basis of electricity price and other demand signals and therefore help customers to benefit from the energy saving the Smart Grid environment offers. Ideally such appliances can be plug-in, registered with the appropriate service provider through a web portal or toll-free phone call. Such arrangement would particularly help customers who do not have the necessary expertise and who are not willing to spend time and money to configure their appliances. An energy services interface (ESI) should have the ability to communicate with the Smart Grid-enabled appliances both in the presence or absence of separate data network in the home. Such communication should require no expertise. It should work on the basis of "plug and play" and "auto-configuring" [6].
- Smart interfacing devices between the Smart Grid and customers: Such interfacing devices are particularly important as they represent the most visible part of the Smart Grid to customers [6]. An interfacing device consists of two distinct elements; a meter and an ESI. The main functions of the meter is to (i) measure, record, and communicate energy usage, (ii) communicate information for outage management, and (iii) enable automated provisioning and maintenance functions, such as connection or disconnection of service. In cases whereby customer's premises contain distributed generation or storage resources the meter's function is extended to also include measurement of the

flow of power from these facilities into the grid. As with regard to ESI, it is considered as the information management gateway through which the customer's network interacts with energy service providers. Its basic functions include (i) demand response signaling, for example, it communicates price of energy unit and critical peak period signals, and (ii) provision of customer energy usage information to residential energy management service or in-home display.

- Internet protocol (IP)-based networks: IP-based networks can be considered as a basic component of the Smart Grid. It serves as a fundamental element for the Smart Grid information networks. Existing IP-based networks may be adapted in the process of Smart Grid deployment. This offers several benefits, including the maturity of a large number of IP standards, the availability of tools and applications that can be applied to Smart Grid environments, and the widespread use of IP technologies in both private and public networks. Additionally, IP technologies may act as a bridge between applications and the main communication medium. A key advantage of adopting IP technologies is their flexibility to allow applications to be developed independent of both the communication infrastructure and the various communication technologies that are being used, whether wired or wireless [6].
- Standards models and protocols: Standards and protocols that support deployment of Smart Grid are important to ensure interconnection and interoperability [9]. Identification of existing standards and protocol documents and/or development of new documents that support the interoperability of Smart Grid are extremely important in the process of Smart Grid deployment [6]. In order to build safe and secure Smart Grid that is end-to-end and interoperable, hundreds of standards are required. Therefore a special effort is needed to identify and select those standards from the existing ones which are suitable for the Smart Grid deployment. A detail discussion of identifying and setting guidelines for selecting these standards are outside the scope of this book.
- Software and programs for decision support and human interfaces

3.3.2 *Smart Grid infrastructure*

The Smart Grid basic infrastructure can be thought to consist of the following four systems as shown in Figure 3.6:

1. Electrical power system
2. Communication and information system
3. Intelligent protection, automation, and distributed control system
4. Electricity marketing system

We shall focus our attention on systems 1, 2, and 3, which cover the technical aspects of the Smart Grid. System 4 related to electricity marketing system is outside the scope of this book and therefore will not be covered. However, it must emphasize that under Smart Grid environment interoperability among the various

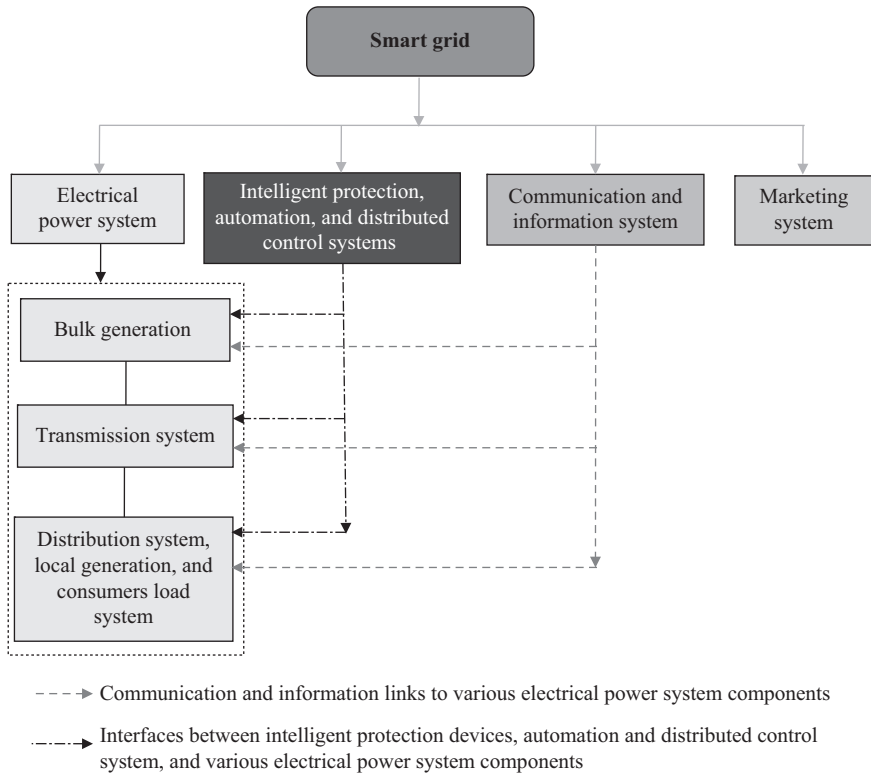


Figure 3.6 The Smart Grid basic infrastructure

devices within individual systems as well as among the four systems must be ensured.

3.3.2.1 Electrical power system

As discussed in Chapter 2, a conventional power system consists of (i) electrical generation system using large power plants that are normally located far away from load centers, (ii) transmission system for transferring electrical power from generating power plants to distribution system, (iii) distribution system whose role is to distribute the power received from transmission system to consumer's loads, and (iv) consumers' load. In case of Smart Grid, its electrical power system component can be similar to that of conventional power system described above but with an important difference in that generating plants known as "distributed generators (DGs)" are connected at different points on the power system. The size of DGs may vary from few kilowatts, normally located at the premises of consumers, to several hundreds of megawatts most of which are integrated into power system at distribution voltage level. In most cases, such plants use renewable energy sources, including wind, solar, and hydro, to generate electric power.

3.3.2.2 Communication and information system

Detailed discussion of the communication and information system related to Smart Grid will be covered in Chapter 5.

3.4 Summary

In this chapter, the compositions of the Smart Grid and the basis on which such compositions are defined have been discussed. This include (i) composition of Smart Grid based on standards adaptation, (ii) composition of Smart Grid based on technical components' perspective, (iii) composition of Smart Grid based on technical perspective, and (iv) composition of Smart Grid based on conceptual perspective. They are covered under Sections 3.2.1, 3.2.2, 3.2.3, and 3.2.4 respectively.

Identification of the basic components of the Smart Grid that are currently in use are then covered under Section 3.3.1. It has been recognized that new components are continued to be developed as the Smart Grid evolves.

Finally, a basic technical infrastructure of the Smart Grid has been covered under Section 3.3.2. Such infrastructure consists basically of (i) an electrical power system, (ii) communication and information system, (iii) intelligent protection, automation, and distributed control system, and (iv) marketing system.

References

- [1] American Electric Power (For Smart Grid Utility Executive Working Group and OpenSG Subcommittee). *Smart grid standards adoption—utility industry perspective* [Online]. USA: 2009. Available from <http://osgug.ucaiug.org> [Accessed 28 November 2015]
- [2] UCA International Users Group. *Smart grid standards adoption—utility industry perspective* [Online]. USA: 2009. Available from <http://osgug.ucaiug.org> [Accessed 28 November 2015]
- [3] OECD. *Smart sensor networks: technologies and applications for green growth* [Online]. 2009. Available from <http://www.oecd.org/sti/44379113.pdf> [Accessed 18 July 2016]
- [4] Science Applications International Corporation (SAIC). *San Diego Smart Grid Study – Final Report* [Online]. 2006. Available from https://lib.sandiego.edu/law/documents/centers/epic/061017_SDSGStudyES_FINAL.pdf [Accessed 18 July 2016]
- [5] Fang X., Misra S., Xue G., and Yang D. 'Smart grid—the new and improved power grid: a survey'. *IEEE Communications Surveys & Tutorials*. 2012; **14**(4):944–80
- [6] NIST. *NIST framework and roadmap for smart grid interoperability standards* [Online]. 2010. Available from http://www.nist.gov/public_affairs/

- releases/upload/smartgrid_interoperability_final.pdf [Accessed 18 July 2016]
- [7] The GridWise Architecture Council. *GridWise Interoperability Context-Setting Framework – v 1.1* [Online]. 2008. Available from http://www.gridwiseac.org/pdfs/interopframework_v1_1.pdf [Accessed 18 July 2016]
 - [8] <http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/IKBUseCases> [Accessed 18 July 2016]
 - [9] Miller J., Pullins S., and Bossart S. (NETL). *The modern grid* [Online]. 2008. Available from http://wpui.wisc.edu/programs/Institute%20Lunches/Smart_Grid/Presentations/Miller.pdf [Accessed 18 May 2012]

This page intentionally left blank

Chapter 4

Smart Grid interoperability standards

4.1 Introduction

The Smart Grid, as previously stated, is basically the resultant of the transformation of conventional electrical power system network to a fully automated network as a consequence of equipping it with distributed intelligence together with broadband communication and automated control systems. A key requirement of the Smart Grid is the interoperability among its various digitally based components which may be called “cyber systems.” Additionally it has been recognized that [1]:

To get from today’s electricity grid to tomorrow’s smart grid with inter-connection and full two-way communications connection to distributed energy sources such as wind, solar, and plug-in electric vehicles requires an interoperability framework of protocols and standards.

The only way to achieve interoperability requirements among the various components of the Smart Grid is through the use of internationally recognized communication and interface standards [2]. It is expected that Smart Grid standards will cover the entire grid. This means there is a need for two types of standards, these are: (i) interoperability standards (top down) and (ii) building block standards (bottom up) [1]. However, this chapter will address the issues related to interoperability standards as applied to the Smart Grid.

4.2 Analogy between the interoperability of a digitally based device and human interoperability

4.2.1 Definition

Interoperability defined by the IEEE [1,3] as “the ability of two or more systems or components to exchange information and to use the information that has been exchanged.” According to this definition it is vitally important to note that a digitally based device should not only have the ability to exchange information but it must also have the ability to understand the exchanged information so that it can use it properly and efficiently.

In order to highlight the importance of developing appropriate standards that enable the interoperability among digitally based devices/systems manufactured by different vendors (and therefore making them talking to each other), it would be

Table 4.1 Analogy between human interoperability and digitally based devices/systems interoperability

Human	Digitally based devices/systems
Establishment of a common “language” standard such as English that makes conversation among people talking different languages possible	Establishment of common cyber “language” standards that make exchange of information between digitally based devices of different vendors possible.
Human language components:	Cyber language components:
• Nouns • Verbs • Grammar	• Data • Messages: send, transmit an event, and acknowledgement • Rules for exchanging information: formatting, sending, and responding to messages
Time somebody at a meeting starts to speak: Guided by societal rules	Time a digitally based device starts to send a message: Defined by cyber standards
Security: Achieved by limiting the number attending the meeting	Security: Achieved by using passwords and encryption
What subject discussed during the meeting	What data can be exchanged and under what condition

useful to develop an analogy between interoperability of people (talking to each other) who speak different languages and digitally based devices/systems manufactured by different vendors. Such analogy is shown in Table 4.1 [2].

In this context, example of digitally based systems includes computer systems, and example of digitally based devices includes intelligent electronic devices (IEDs).

4.3 Cyber interoperability standards

The analogy between human interoperability and digitally based devices/systems interoperability detailed in Table 4.1 clearly shows that in order for digitally based devices/systems, produced by different vendors, to communicate with each other a common “cyber language” need to be developed specifically for this purpose, which is similar to the need of people, talking different languages, adopting a common language such as English. However, in order to develop a tested, effective, and efficient cyber language, an appropriate standard need to be developed with inputs from concerned industries. For the case under consideration this includes power industries, standards development organizations, and utilities.

4.3.1 Aim of interoperability standards

The aim of cyber interoperability standards [2] is to formulate **nouns** (data), **verbs** (messages), **grammar** (rules for exchanging information), and **societal rules for exchanging information** (cyber standards rules). Using cyber technical language,

this is expressed as formalizing the object model semantics, the messaging syntax, the communication profiles, and the network/security management.

4.3.2 Type and characteristics of interoperability standards for Smart Grid

4.3.2.1 Type of interoperability standards

There are different types of interoperability standards that are developed with different properties. Most of these standards focus only on specific levels, although there are no clear distinctions between such levels. The levels of cyber standards may be broadly classified into four levels as follows [2]:

- Media-related standards specific to fiber optics, microwave, Wi-Fi, CATV, wires, telephones, and cell-phones
- Transport-related standards such as Internet standards, including Ethernet, IP, TCP, HTTP, and OPC
- Application-related standards such as HTML, XML, IEC 61850, and common information model (CIM)
- Security-related standards such as AES 256, PKI, secret keys, and certificates

4.3.2.2 Characteristics of interoperability standards

Standards must not be too rigid. They should leave flexibility for systems to add new functionalities or select certain options. Flexible Smart Grid system interoperability design and operational standards will also help short and long terms Smart Grid evolution [1]. In many cases, standards have the provision of both mandatory requirements and optional selections, as well as with “extension rules” for expanding the standards in a consistent manner for new functions. Usually a rule of 80/20 is applied, that is, the standards address about 80 percent of the interoperability needs, while at least 20 percent must be left for vendor’s specific requirements or utility’s specific requirements, as well as the flexibility to meet unforeseeable future requirements [2].

It should be noted that most standards are developed by vendors and consultants. Utilities may have some input but experience has shown that such input is rather limited.

4.4 Interoperability standards development organizations

There are many standards bodies worldwide that are engaged in tackling interoperability issues for a wide range of industries, including the electrical power industry [2] (see Section 4.5). Many users groups and consortia (see Section 4.6) have also been involved in providing input and guidance for the development and implementation of these standards.

In real life, involvement of utilities, vendors, and other stakeholders of the Smart Grid is extremely important in speeding up the development of relevant standards.

4.5 Electrical power industry standards development organizations (SDOs) and key interoperability standards

There are several SDOs for electrical power industry worldwide. Additionally, several users groups and consortia such as the Utility Standards Board (USB) are working to provide input and guidance for the development and implementation of these standards. A brief coverage of the most active SDOs as well as users groups and consortia in Smart Grid-related issues and the key interoperability standards that have been handled by such organizations and users groups and consortia will be given in the following subsections.

4.5.1 *The International Electrotechnical Commission*

The International Electrotechnical Commission (IEC) is considered as the leading global organization. It has undertaken the task of preparing and publishing international standards for all electrical, electronic, and related technologies, primarily for the electrical power industry. It has also undertaken some electrical-related work in industrial processes.

The IEC Council is formed from the membership of national committees, one from each country. The international standards work is coordinated by the standards management boards (SMBs), which operate under the IEC Council. This standards work is executed by several technical councils (TCs), each targets specific area. For example, TC 57 aims at developing standards for communications and interoperability. It is also home to the working groups (WGs) which are developing many of the Smart Grid interoperability standards. These WGs consist of technical experts authorized by their national committee to participate in the two to four meetings per year, in addition to undertaking significant work between meetings.

Figure 4.1 illustrates the specialized communications standards for the electrical power industry that has been developed by the IEC TC 57 [4]. This is an ongoing work aiming at expanding and enhancing these standards, which include:

- IEC 61850 for substation automation, distributed generation that includes photovoltaics, wind power, and fuel cells, supervisory control and data acquisition (SCADA) communications, and distribution automation, plug-in hybrid electric vehicles (PHEV).
- IEC 61968 for distribution management and AMI back office interfaces
- IEC 61970 CIM for transmission and distribution abstract modeling
- IEC 62351 for security that focuses on IEC protocols, network and system management, and role-based access control

IEC TC 13 deals with issues related to metering. It may combine its effort with TC 57 to develop communications for metering, specifically for AMI.

4.5.2 *Institute of Electrical and Electronic Engineers (IEEE)*

The methodology used by the IEEE for developing draft and, ultimately, final standards is similar to that of the IEC. However, in case of the IEEE the voting is

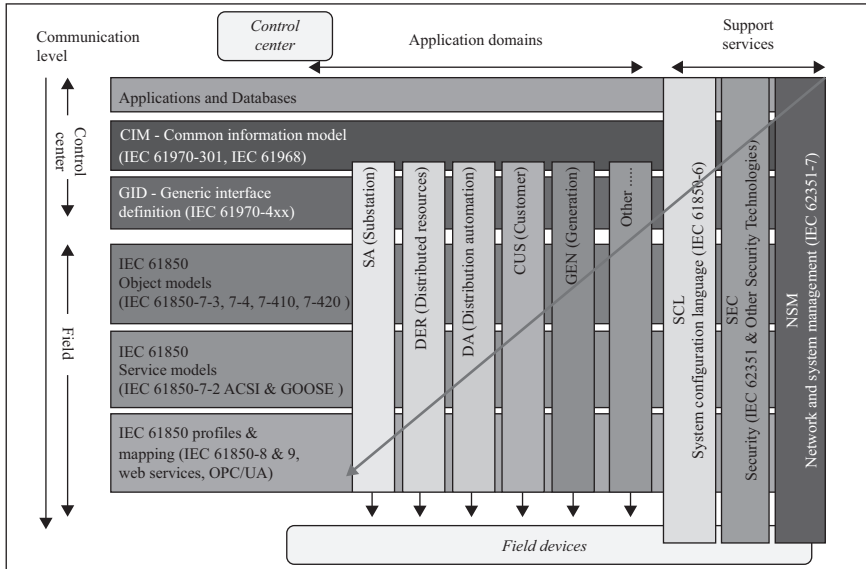


Figure 4.1 IEC communications standards for the electrical power industry that has been developed by TC 57 [4]. Reproduced with permission from IEC Smart Grid Standardization Road Map ed.1.0, © 2010 IEC Geneva, Switzerland. www.iec.ch

conducted only by members of the working groups, that is, national committees are not involved. Additionally, the IEEE working groups have been engaged in the development of many other types of documents. This includes recommended practices, technical reports, conference papers, and other nonstandard-oriented documents.

Many standards have been developed by the IEEE. The most appropriate ones for communications and interoperability are listed below:

- IEEE 802.3 (Ethernet)
- IEEE 802.11 (Wi-Fi)
- IEEE 802.15.1 (Bluetooth)
- IEEE 802.15.4 (ZigBee)
- IEEE 802.16 (WiMax)

4.5.3 Internet Engineering Task Force

The Internet Engineering Task Force (IETF) is responsible for Internet standards. The mechanism employed by the IETF to develop, send out for comment, and finalize standards is based on what is called “A Request for Comment (RFC) document.” In order to fully accept RFC specifications as standards they must be

implemented by more than one vendor. Some of the key IETF RFCs are listed below:

- RFC 791: Internet Protocol (IP)
- RFC 793: Transport Control Protocol (TCP)
- RFC 1945: HyperText Transfer Protocol (HTTP)
- RFC 2571: Simple Network Management Protocol (SNMP)
- RFC 3820: Internet X.509 Public Key Infrastructure (PKI) for security

4.5.4 *American National Standards Institute (ANSI)*

Similar to other standards organizations, ANSI has working groups who undertake the development of specific standards as well as updating them as necessary [2]. The most relevant ANSI standards for interoperability of AMI systems include:

- ANSI C12.18-2006: Protocol Specification for ANSI Type 2 Optical Port. This Standard establishes the criteria required for communications between a C12.18 Device and a C12.18 Client via an optical port [5]. In this context, the C12.18 Client may be a handheld reader, a portable computer, a master station system or some other electronic communications device.

This standard also provides details for a complete implementation of an OSI 7-layer model. The protocol specified in this document was designed to transport data in table format. The table definitions are in ANSI C12.19 Utility Industry End Device Data Tables (see below).

- ANSI C12.19: Utility Industry End Device Data Tables [6]: This standard defines a table structure for utility application data to be passed between an “end device” and any “other device.” In this context, the “end device” is typically an electricity meter, and the “other device” is typically a handheld device carried by a meter reader, or a meter communication module which is part of an automatic meter reading system.
- ANSI C12.21-2006: American National Standard Protocol Specification for Telephone Modem Communication.

ANSI C12.21 Standard was developed aiming at facilitating the communications between a C12.21 Device and a C12.21 Client via a modem connected to the switched telephone network [7]. In this context the C12.21 Client could be a laptop or portable computer, a master station system, or some other electronic communications device.

The protocol developed in this standard was specifically designed to facilitate the transportation of data in table format. Table formats are defined in ANSI C12.19.

- ANSI-ANSI C12.22-2008: Protocol specification for interfacing to data communication networks: This standard has been developed by extending the concepts of standards [8].

Communications with electronic devices, initially, involve transportation of memory data via proprietary protocols that are unique to the manufacturer that has

developed it. The recognition of the importance of interoperability and support of multiple manufacturers by reading and programming systems has led to recognize the need for standardization of data formats and transport protocols.

The first step that was taken to achieve this goal was standardization of data formats by abstracting internal data as a set of tables. Definition of a set of standard table contents and formats were detailed in ANSI C12.19, “Utility Industry End Device Data Tables.”

A point-to-point protocol was developed to transport table data over an optical connection in Standard ANSI C12.18, “Protocol Specification for ANSI Type 2 Optical Port.” An application language called Protocol Specification for Electric Metering (PSEM) was specifically developed in the ANSI C12.18 to make it possible for applications to read and write tables. Later on, Standard ANSI C12.21, “Protocol Specification for Telephone Modem Communication” was developed to make it possible for devices to use PSEM to transport tables over telephone modems.

Extending the concepts of the ANSI C12.18, ANSI C12.19 and the ANSI C12.21 standards, this Standard, that is, ANSI C12.22, was developed to make it possible transporting table data over any reliable networking communications system. Additionally, this standard describes an optionally exposed point-to-point interface between a C12.22 Device and a C12.22 Communications Module designed to be attached to “any” network. Additionally, this standard defines a methodology to capture, translate, and transmit one-way device messages.

It will be noted that ANSI C12.22 standard uses Advanced Encryption Standard (AES) to ensure strong and secure communications, including confidentiality and data integrity. ANSI C12.22 also defines message services which are components of an AMI.

4.5.5 National Institute of Standards and Technology (NIST)

In the context of Smart Grid, NIST has developed special publications in the 800 series [2]. They provide documents of general interest to the community that deals with computer security. These documents are more of guidelines rather than standards, but are very relevant to moving toward secure interoperability. As far as the Smart Grid is concerned the following two documents are of particular interest:

- NIST SP-800-53: Recommended Security Controls for Federal Information Systems [9]:

This publication provides guidelines for selecting and specifying security controls for the USA federal information systems in accordance with the security requirements in the USA Federal Information Processing Standard (FIPS) 200. This includes selecting an initial set of baseline security controls based on an FIPS 199 worst-case impact analysis, tailoring the baseline security controls, and supplementing the security controls based on an organizational assessment of risk. These guidelines apply to all components of an information system that process, store, or transmit federal information.

- NIST SP-800-82: Guide to Industrial Control Systems (ICS) Security [10]:
This document provides guidance for establishing secure ICS. Such systems include SCADA systems, distributed control systems (DCS), and other systems performing control functions.

4.5.6 *North American Electric Reliability Corporation (NERC)*

The NERC has issued security standards known as Critical Infrastructure Protection (CIP) Standards. These security standards are specifically developed for the bulk power systems. However, it has been recognized that many of the requirements can also be applied to distribution and AMI systems. Consequently, they may eventually become standards for these systems as well. NERC Standards CIP-002 through CIP-009 provide a cyber-security framework for the identification and protection of Critical Cyber Assets to support reliable operation of bulk electric power systems. These standards recognize the differing roles of each entity in the operation of bulk electric power systems, the criticality and vulnerability of the assets needed to manage the reliability of bulk electric power systems, and the risks to which they are exposed. Responsible entities should interpret and apply Standards CIP-002 through CIP-009 using reasonable business judgment. NERC CIP 002-009 Security Standards [1,11,12] cover:

- Critical Cyber Asset Identification
- Security Management Controls
- Personnel and Training
- Electronic Security Perimeter(s)
- Physical Security of Critical Cyber Assets
- Systems Security Management
- Incident Reporting and Response Planning and
- Recovery Plans for Critical Cyber Assets

4.5.7 *World Wide Web Consortium (W3C)*

The W3C was founded in October 1994. It is the main international standards organization for World Wide Web (abbreviated as WWW or W3). In context of Smart Grid the W3C has been involved in developing interoperable technologies in terms of specifications, guidelines, software, and tools for the World Wide Web, including [2]:

- HTML: HTML is the main markup language, which is used for web page design. HTML elements are the basic building-blocks of webpages.
- Extensible Markup Language (XML): It is a markup language that defines a set of rules for encoding documents in a format that is readable by both human and machine. XML is designed with emphasis on simplicity, generality, and usability over the Internet. XML is widely used for the representation of arbitrary data structures (e.g., in web services), although its design focuses on documents.
- Web services for application-to-application communications, such as Simple Object Access Protocol (SOAP) for transmitting data: SOAP is a protocol

specification specifically developed for exchanging structured information in the implementation of web services in computer networks. It relies on XML for its message format, and commonly relies on other application layer protocols, particularly HTTP and Simple Mail Transfer Protocol (SMTP) for message negotiation and transmission.

4.5.8 *German Standards Institute DIN (Deutsches Institut für Normung)*

Electricity metering is one of the Smart Grid issues that has been covered significantly and effectively by DIN [13].

4.6 **Users groups and collaborative efforts within the power industry**

Standards are normally developed such that they can only define exactly how a specific interface should be structured. However, they do not address which standards fit best for different requirements, or which optional parameters to implement. Real-world implementation requires continuous updating and corrections that need to be fed back to the various standards groups. Education and training on the capabilities of different standards are also important to effectively and correctly apply them.

These refinements, feedback, and educational programs are performed by several users groups, collaborative efforts, associations, alliances, and other non-standard organizations. Number of the key groups related to Smart Grid requirements will be briefly discussed in the following subsections.

4.6.1 *UCA International Users Group*

Utilities Communication Architecture (UCA) International Users Group (UCAIug) focuses its effort on assisting users and vendors in the deployment of standards for real-time applications for several industries with related requirements. The users group does not write standards, but works closely with those bodies who take the responsibility of completion of standards as their main objective [14].

Such bodies particularly include IEC TC 57: Power Systems Management and Associated Information Exchange.

UCAIug has several subgroups/subcommittees, the most active of them are [2]:

- IEC 61850 Users Group [15]:
International standards IEC 61850 and its application to the Smart Grid will be discussed in detail in Chapter 6.
- CIM Users Group (CIMug) [16]: This group was established in 2005 as a subgroup of the UCAIug. The aim is to provide a forum whereby users, consultants, and suppliers can cooperate and promote the IEC CIM international standards to advance interoperability across the utility enterprise. The main

purpose is to share technology basics, best practices, and technical resources while advancing interoperability for the utility enterprise.

- Open Smart Grid (OpenSG) Users Group (OSGug) [2,17]: The aim of this users group is to help users getting information on the progress of the OSG issues and to share their project experiences. Issues addressed by this group include AMI issues (OpenAMI), security for AMI (AMI-SEC), Home Area Networks (OpenHAN), and AMI Enterprise issues (AMI-Enterprise).

4.6.2 *National Rural Electric Cooperative Association (NRECA)'s MultiSpeak*

The MultiSpeak initiative is a collaborative work between the National Rural Electric Cooperative Association (NRECA), leading software vendors and electric utilities aiming at developing an interoperable communications protocol, called MultiSpeak [2,18,19]. According to this initiative, a MultiSpeak specification for interoperability has been developed and continues to be expanded. MultiSpeak specification defines standardized interfaces between software applications commonly used by electric distribution utilities. It is considered a key industry-wide standard that facilitates interoperability among wide-ranging business and automation applications used in electric distribution utilities. Applications with interoperability capability that have been enabled by MultiSpeak are already in place in many electric utilities which helped in integrating operation of previously stand-alone systems. It will be noted that MultiSpeak provide similar capabilities to those included in IEC 61968 distribution extensions to the CIM.

4.6.3 *Cigré*

The International Council on Large Electric Systems known as Cigré is a parallel organization to the IEC. However, Cigré' focuses on discussions and reports related to key issues related to electric power industry, which are normally authored by utility personnel [2].

Cigré has several working groups aiming at developing reports on communications, cyber security, and interoperability issues [20]. Some of these reports are used to propose the types of standards that should be developed, usually by the IEC.

4.6.4 *GridWiseTM Alliance*

The GridWise Alliance is a leading industry coalition whose members are from public and private stakeholders that promote the idea of a smarter grid for providing better services to the public. The aim of the Alliance is to facilitate effective collaboration among stakeholders, promote, educate, and advocate for the adoption of innovative Smart Grid solutions [2,21]. It is the belief of Alliance that such solutions will bring about economic and environmental benefits for customers, communities, shareholders, and society.

The GridWise Alliance has helped in sponsoring conferences and workshops such as the GridWise Architecture Council, Grid Interop, GridWeek, and EPRI's

IntelliGrid projects. It has also published reports related to transformation of conventional power systems to the Smart Grid. Examples of such reports include “The Future of the Grid,” “The 2014 Grid Modernization Index (GMI),” and “Grid of the Future Transitional Action Plan.”

The GridWise Alliance, founded in 2003, has developed into an organization that represents a broad range of the energy supply chain from utilities to large tech companies to academia to venture capitalists to emerging tech companies. This variety of stakeholders gives the Alliance a unique diversity of perspectives which enables interactive dialogue between members. Being a consensus-based organization, the assortment of opinions produces deliberate and highly reflected upon resolutions to key issues.

Since its foundation in 2003, the GridWise Alliance has developed into an organization that represents a broad range of the energy supply chain that encompasses utilities, large tech companies, academia, venture capitalists, and emerging tech companies.

It is worth mentioning that the GridWise Alliance is a founding member of the **Global Smart Grid Federation**.

4.6.5 Electric Power Research Institute (EPRI)’s IntelliGrid program

In an effort to develop guidelines on interoperability and standards, the EPRI in the USA has initiated the IntelliGrid program in 2003 [1]. Since then electric utilities continued to transform their systems toward Smart Grid by equipping them with technologies such as advanced monitoring, communications, computing, and information technologies to support “Smart Grid” applications such as wide area monitoring and control, integration of bulk or distributed renewable generation, distribution automation, and demand response. As a result of this, utilities find themselves facing many challenges, including [22]:

- Selecting technologies that best meet current and future business needs and regulatory requirements while minimizing the risk of early obsolescence and vendor lock-in
- Creating an overall architecture that integrates the many intelligent devices, communications networks and enterprise systems to utilize resources, and provide information to all users
- Managing the tremendous amount of data that are generated by the Smart Grid so that they can be converted into actionable information and effectively present the information to the people who need to take action
- Managing a growing network of intelligent devices that have different capabilities and that use different protocols and data formats in a way that optimizes performance
- Ensuring that the workforce has the skills necessary to design, operate, and maintain equipment and systems that use new technologies.

In order to address these challenges the IntelliGrid Program extended its activity to include:

- Tracking government and regulatory activities related to standards, cyber security, and communications, and interpret the impact that these actions may have on the electrical utility industry.
- Promoting interoperable systems by participating in the development of key Smart Grid standards, assessing emerging standards, conducting interoperability tests of products that implement key standards and providing information to utilities on how to implement standards.
- Defining requirements for utility communications networks and assesses key communications technologies.
- Facilitating Smart Grid demonstration projects around the world to better understand and advance the use of distributed energy resources in Smart Grids.

4.6.6 *Vendor collaborations*

Finalizing the details of the Smart Grid standards as well as reaching an agreement among various vendors on which aspects of the standards are to be implemented constitute important steps toward the implementation of the Smart Grid concept. To achieve this goal, several collaborations and alliances of vendors have been formed. Examples of relevant vendor alliances and collaborations are given below [1]:

- **ZigBee Alliance**

The ZigBee Alliance (ZA) considers itself as an organization “leading the global evolution of the Internet of Things and creating a time when you can Control Your World” [23]. Members of this Alliance work closely together in an open, global environment, sharing their expertise to create ZigBee innovative standards that offer reliable, secure, low-power, and easy-to-use wireless communication. The members also collaborate using globally recognized open standards development processes to guide their work.

ZA aims at simplifying the integration of wireless products and speeding up time to market, while reducing costs and risks for product manufacturers looking to introduce energy-efficient wireless control into their products.

ZigBee considered as the only global and standards-based wireless solution that can conveniently and affordably control the widest range of devices to improve comfort, security, and convenience for consumers [24]. ZigBee technology has become the choice of leading service providers, installers, and retailers who bring the benefits of the Internet of Things into the smart home. ZigBee serves as the language for a wide variety of smart home devices so companies can deliver an integrated ecosystem of home monitoring, energy management, heating and cooling, security, and convenience devices.

- **HomePlug Powerline Alliance**

HomePlug Alliance is an association formed from several companies [25]. The aim of this Alliance is to develop technology specifications and certification

and logo programs for power-line networking. To achieve its objectives, HomePlug Alliance brings together individual researchers, technologists, strategic thinkers, market experts, business decision-makers, and product developers, and unites them in a common goal to create a global environment where powerline communications can thrive.

An example of where HomePlug Powerline can be applied is the Smart Home, which is evolving rapidly. Smart Home has several characteristics that fit well with HomePlug technology [26]. Until recently, home automation and management used to be set up on a separate, home control network with its own communication protocols, control consoles, and applications. However, with the advent of the smart phone and connected tablets, consumers increasingly looking for controlling their Smart Homes via mobile devices and also monitoring the status of their homes when they are away from home. To achieve seamless connectivity among all devices, everywhere in a Smart Home, the home broadband network and the home control network need to be merged.

As the average home becomes a media hub, a robust home network is needed to support it. Streaming videos on TVs or computers, online gaming, HDTV, and multiple devices running high bandwidth applications throughout the house are becoming the norm. This in turn puts huge pressure on the home network. Although wireless offers great mobility around the home, it often struggles when it is located far from the router, particularly with demanding application such as online gaming or streaming videos.

HomePlug provides interoperability for the Smart and Connected Home. There are several HomePlug technologies available in the market. Examples of these include (i) HomePlug Green PHYTM technology, which is low cost and ideally suited for smart appliance and home control applications and (ii) HomePlug AV which has the benefits of providing a reliable communications technology for high bandwidth distribution of entertainment-grade HD video, gaming, and Internet. Mobile devices are continuously becoming the controllers for consumers' "digital life." To address this trend, HomePlug technologies seamlessly integrate with Wi-Fi to ensure whole home wired/wireless high-speed broadband and internet of things (IoT) connectivity.

- ISA SP-100 Standardization Committee for Wireless Systems for Automation
The International Society of Automation (ISA), which was created in 1945, has become a leading global organization. Activities of ISA include development of standards, certifying industry professionals, and providing education and training [27].

ISA 100 (previously known as ISA SP100 [28]) is ISA's Wireless Systems for Automation Standards Committee [29]. It was formed from end-users and technology suppliers aiming at establishing standards, recommended practices, technical reports, and related information that define procedures for implementing wireless systems in the automation and control environment with a focus on the field level (Level 0).

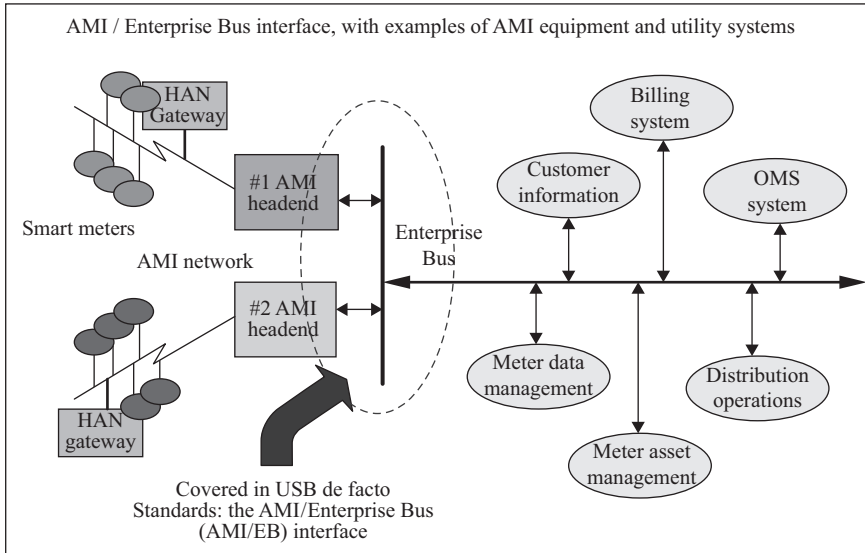


Figure 4.2 AMI/Enterprise Bus interface [2]. Reproduced by permission of Xanthus Consulting International

4.6.7 Utility Standards Board

The USB is a group formed from a number of major utilities in North America [1,30]. They join their effort to develop de facto interoperable standards to address the interface between the AMI systems and several utility systems. The latter includes back office metering, billing, and revenue protection, as well as distribution operations such as outage management, power quality, and load management, which are interconnected to the AMI via a generic “Enterprise Bus (EB).”

This joint effort has provided utilities with excellent forums for discussing AMI issues. It has also helped in providing significant input into the formal IEC standards-development process as the de facto standards are released through the UCA Users Group to the IEC.

Additionally, through their participation in the USB, utilities members have taken the lead in providing the business processes as a foundation for developing interoperability standards. Some of the work they involved with include:

- Meter/Headend Event Codes
- Remote Connect/Disconnect
- Outage Management

Figure 4.2 illustrates the AMI/EB interface. Its function is to establish an interface between AMI systems which are connected to the meters and customer gateways, and the EB which connects to utility systems, including back office systems and certain distribution operations systems. Although the implementation configurations of these systems may vary significantly, the basic architecture

remains the same, with the EB acting as the link between the AMI systems and any other systems.

4.7 Summary

This chapter is devoted as introduction to the Smart Grid interoperability standards. An analogy between the interoperability of a digitally based device and human interoperability is first introduced. This is followed by discussing cyber interoperability standards with emphasis on highlighting the aim, type, and characteristics of interoperability standards.

Major organizations of power industry that are engaged in standards development are then covered. These include (i) the IEC, (ii) IEEE, (iii) IETF, (iv) ANSI, (v) NIST, (vi) NERC, (vii) W3C, and (viii) DIN.

Finally, Users Groups and collaborative efforts within the power industry are discussed. These include (i) UCAIug, (ii) NRECA's MultiSpeak, (iii) Cigré, (iv) GridWiseTM Alliance, (v) Electric Power Research Institute's IntelliGrid, (vi) Vendor Collaborations, and (vii) USB.

References

- [1] DeBlasio R. and Tom C. 'Standards for the Smart Grid'. *IEEE Energy 2030 Conference*; Atlanta, GA, November 2008, pp. 1–7.
- [2] Utility Standard board (Cleveland F., Small F., and Brunetto T.). *Smart grid: interoperability and standards – an introductory review* [Online]. 2008. Available from http://www.xanthus-consulting.com/Publications/documents/Smart_Grid_Interoperability_and_Standards_White_Paper.pdf [Accessed 5 January 2016].
- [3] ISA. *Information sharing environment-information interoperability framework (I²F), Version 0.5* [Online]. March 2014. Available from http://www.ise.gov/sites/default/files/FINAL%20-%20ISE_I2F_v0%205.pdf [Accessed 26 November 2014].
- [4] IEC Smart Grid Strategic Group (SG3). *IEC smart grid standardization roadmap – Edition 1.0* [Online]. IEC; June 2010. Available from http://www.iec.ch/smartgrid/downloads/sg3_roadmap.pdf [Accessed 8 November 2016].
- [5] ANSI. *ANSI C12.18-2006: Protocol Specification for ANSI Type 2 Optical Port* [Online]. USA: American National Standard Institute, Inc.; May 2006. Available from <https://www.nema.org/Standards/ComplimentaryDocuments/ANSI-C12-18.pdf> [Accessed 4 December 2014].
- [6] ANSI. *ANSI C12.19-2008* [Online]. USA: American National Standard Institute, Inc.; February 2009. Available from <https://www.nema.org/Standards/ComplimentaryDocuments/ANSI-C1219-2008-contents-and-scope.pdf> [Accessed 4 December 2014].
- [7] ANSI. *ANSI C12.21-2006: Protocol specification for telephone modem communication* [Online]. USA: American National Standard Institute, Inc.;

- May 2006. Available from <https://www.nema.org/Standards/Complimentary Documents/ANSI-C12-21-2006.pdf> [Accessed 8 December 2014].
- [8] ANSI. *ANSI C12.22-2008: protocol specification for interfacing to data communication networks* [Online]. USA: American National Standard Institute, Inc.; January 2009. Available from <https://www.nema.org/Standards/ComplimentaryDocuments/ANSI-C1222-2008-Contents-and-Scope.pdf> [Accessed 23 November 2016].
- [9] NIST. *Guide for assessing the security controls in federal information systems and organizations: building effective security assessment plans, special publication 800-53A* [Online]. USA: NIST; June 2010. Available from http://csrc.nist.gov/publications/nistpubs/800-53-Rev3/sp800-53-rev3-final_updated-errata_05-01-2010.pdf [Accessed 23 April 2012].
- [10] NIST. *Guide to industrial control systems (ICS) security, special publication 800-82* [Online]. USA: NIST; June 2011. Available from <http://csrc.nist.gov/publications/nistpubs/800-82/SP800-82-final.pdf> [Accessed 23 April 2012].
- [11] Kropp T. *CIP-002 – CIP-009: a brief overview* [Online]. August 2009. Available from https://docs.google.com/viewer?a=v&q=cache:CdpXXzz1oDIJ:www.emct.net/documents/1BNexant-Kropp.pdf+The+NERC+CIP+002%E2%80%9090009+Security+Standards&hl=en&gl=uk&pid=bl&srcid=ADGEESj76Zwta4YfHPciJ3B-p1n7oR9g1GS1JekxU6-qrzomgpRyNw1X7gqFGH67HlcrV78wReEorrr6PtgDJ8kwDi9THeGFqtQFcoz8gqXd7XYoTn9PtJ_CHIXqHNpzR6ZbWzoZUDaP&sig=AHIEtbSomQn2pioN1t1MZ5ymfpdtRfCtRg [Accessed 23 April 2012].
- [12] CorreLog. *Navigate your way to NERC compliance, WhiteSheet* [Online]. USA: CorreLog Inc.; 2009. Available from http://www.infosec.co.uk/ExhibitorLibrary/1289/Whitesheet-CorreLog_for_NERC-HR_20.pdf [Accessed 23 April 2012].
- [13] <http://www.din.de>.
- [14] UCAIug. *UCA International Users Group* [Online]. USA: UCAIug. Available from <http://www.ucainternational.org/> [Accessed 28 April 2012].
- [15] <http://iec61850.ucaiug.org/default.aspx>.
- [16] CIMug. *CIMug Users Group* [Online]. USA: UCAIug. Available from <http://cimug.ucaiug.org/default.aspx> [Accessed 15 December 2014].
- [17] Knudsen C. *Open Smart Grid (OpenSG) Technical Committee* [Online]. USA: November 2011. Available from http://www.ucaiug.org/Meetings/Austin2011/Shared%20Documents/OpenSG-BootCamp-Nov_2011.pdf [Accessed 15 December 2014].
- [18] NRECA. *MultiSpeak* [Online]. Available from <http://www.multispeak.org/about/Pages/default.aspx> [Accessed 30 April 2012].
- [19] McNaughton G.A. and Saint R. *How NRECA's MultiSpeak specification supports interoperability of diverse electric grid automation systems* [Online]. USA: Grid-Interop Forum 2007; 2007. Available from http://www.gridwiseac.org/pdfs/forum_papers/118_paper_final.pdf [Accessed 30 April 2012].
- [20] <http://www.cigre.org/>.
- [21] <http://www.gridwise.org/>.

- [22] <http://smartgrid.epri.com/IntelliGrid.aspx>.
- [23] ZigBee. *The ZigBee Alliance* [Online]. Available from <http://zigbee.org/> [Accessed 20 December 2014].
- [24] ZigBee. *What is ZigBee?* [Online]. Available from <http://zigbee.org/> [Accessed 20 December 2014].
- [25] Homeplug. *Homeplug Alliance Overview* [Online]. Available from <http://www.homeplug.org/alliance/alliance-overview/> [Accessed 20 December 2014].
- [26] Homeplug. *Explore Homeplug-Smart Home* [Online]. Available from <http://www.homeplug.org/explore-homeplug/smart-home/> [Accessed 30 December 2014].
- [27] ISA. *International Society of Automation* [Online]. Available from <https://www.isa.org/> [Accessed 26 December 2014].
- [28] Caro D. *ISA SP100 keeps on its wireless path* [Online]. Available from <http://www.controlglobal.com/articles/2007/028/?start=1> [Accessed 27 December 2014].
- [29] ISA. *ISA100, Wireless systems for automation* [Online]. Available from <https://www.isa.org/isa100/> [Accessed 26 December 2014].
- [30] Cleveland F. *Utility Standards Board (USB): utilities develop business requirements for interoperable smart grid standards* [Online]. USA: Grid Interop Forum 2008; 2008. Available from <http://xanthus-consulting.com/Publications/USB%20Paper%20for%20Grid%20Interop%202008.pdf> [Accessed 3 May 2012].

This page intentionally left blank

Chapter 5

Smart Grid communication system and its cyber security

5.1 Introduction

As stated previously, power system communication (PSC) infrastructure is considered as a key component of the Smart Grid that enables it to fulfill the role that is expected to play. In this chapter, the characteristics and structure of Smart Grid communication system will be discussed. Under the Smart Grid environment, a huge amount of data information about the electrical power system is generated. Such information is normally collected at points on the power system along routes between generation plants and points of consumers' connection. The collected information is used for performing different tasks, which include [1] (i) making real-time operational decisions that ensure dispatching power efficiently, (ii) identifying certain aspects related to system planning, and (iii) identifying where the consumers' power comes from and how much it costs at a given time. Therefore, it is extremely important that any communication system that handles such data must be reliable, resilient, secure, and efficient.

5.2 Classification of power system communication according to their functional requirements

In recent years, capabilities of communication systems have developed from narrowband, low speed (range of 100 bit/s) to high-speed broadband "highways" (range of 100 Mbit/s) [2] for all sorts of communications.

Power system communication systems may be classified, based on their functional requirements, into three categories as follows [3]:

1. Real-time operational communication systems
2. Administrative operational communication systems
3. Administrative communication systems

5.2.1 Real-time operational communication systems

Real-time operational communication covers communication in real time that is necessary to maintain the operation of electric power system. This may be divided

into (i) real-time operational data communication and (ii) real-time operational voice communication.

(i) *Real-time operational data communication*

As the name implies, real-time operational data communication is characterized by the fact that interaction normally takes place in real time, with critical time requirements. The requirements for this type of communication define the design of the technical solutions. This type of communication is used to transmit (a) protection signals and (b) power system control signals.

As far as protection signals are concerned, they must be transmitted within a very short time interval. This depends on the type of protection scheme under consideration. However, the maximum allowed time is in the range of 12–20 ms. This requirement is due to the fact that fault current usually cleared within approximately 100 ms.

However, power system control signals are mainly due to supervisory control systems such as supervisory control and data acquisition (SCADA) systems and energy management systems (EMS). Operational data such as measured signals and circuit breaker status signals are mainly transmitted using dedicated operational data networks. The measured values of power system control signals must arrive the control center no later than 15 s, while circuit breaker signals must arrive no later than 2 s after the occurrence of an event.

(ii) *Real-time operational voice communication*

Real-time operational voice communication covers transmitting phone calls related to the operation of electric power system such as troubleshooting during abnormal conditions. Voice communication, which is normally conducted by operating staff such as those operating control centers, is considered as one of the most important tools, both during normal and abnormal operation conditions. Real-time operational voice communication also includes facsimile for switching sequence orders.

The means of using electronic mail (e-mail) for transmitting switching sequence orders is also considered.

5.2.2 *Administrative operational communication systems*

Administrative operational communication systems normally deal with transmitting detailed information that describes what has happened in minor and major power system disturbances following their occurrence. Examples include information due to interactions with local event recorders, disturbance recorders, and power swing recorders.

Unlike real-time operational communication, this class of communication does not require the interaction to take place in real time, and thereby, time requirements are not so critical.

The functions that are also included under this class include (i) asset management, (ii) fault location, (iii) metering and transmission of settlement information, (iv) security system, and (v) substation camera supervision.

5.2.3 Administrative communication systems

This class of communication is dedicated to the communication and facsimile between the offices of a company located at the same site as well as different geographical locations. It also covers the communication from/to the company, where the communication has only an administrative purpose.

5.3 Existing electric power system communication infrastructure and its limitation

Under this section, the followings will be discussed:

- (i) Overview of current PSC systems and their characteristics
- (ii) Shortcomings of current PSC systems
- (iii) Characteristics of future PSC systems that suits Smart Grid requirements

(i) *Overview of current PSC systems and their characteristics*

The PSC infrastructure that has been in use, prior to contemplating Smart Grid concept, has evolved several decades ago to meet the needs of the regulated electric power industry. Its structure is based on what is called “star topology” [4,5] whereby the functionality of PSC is based on communication between a control center and individual substations as shown in Figure 5.1. This figure illustrates a typical example of existing PSC systems. It shows two areas named as utility A and B. Each utility has (i) its own control center and (ii) remote terminal units (RTUs) installed at generation plants, transmission centers and distribution centers. The RTUs are linked, via PSC links, to SCADA systems and special protection schemes (SPSs), sometimes also called remedial action scheme (RAS) [6].

The main functions of such PSC systems include (i) carrying control signals between various components of control systems that are necessary for the operation of such systems and (ii) carrying protection signals that are usually generated by protection devices following fault conditions to open appropriate circuit breakers necessary for isolating the fault.

(ii) *Shortcomings of current PSC systems*

Several shortcomings associated with existing communication infrastructure (ECI) have been identified as explained below:

- Existing communication infrastructure such as that shown in Figure 5.1 used by the control centers results in slow automatic control to balance load and generation [5]. The manual control which is based on ECI used by operators to open and close circuit breakers is even slower [4]. Examples of control systems used in power systems are the SCADA systems. These systems are built using star topology-based communication infrastructure, which conveys power system status information as well as commands back and forth within a period of several seconds.
- Fast control systems including protection systems against short circuits, some voltage controls and special controls normally make decisions

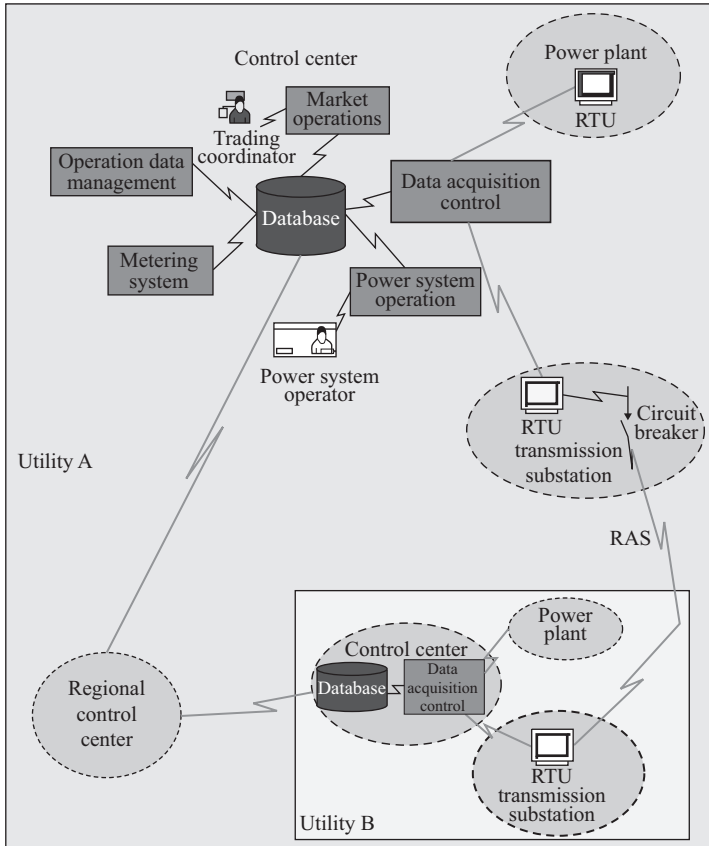


Figure 5.1 Existing power system communication infrastructure [4]. Reproduced by permission of IEEE

based on local measurements. Use of ECI by these control systems limits their ability to cope with grid-wide phenomena [4]. For example, in the event of a power outage, fast control systems such as the RAS protect lines against short-circuits and regulate line voltages, but they can neither detect nor correct rapidly occurring cascading failures in the power system. Therefore, it can be concluded that existing communication systems require complete updating in order to cater to the needs of the ever-growing power systems [5].

In this context, SPSs have been developed to meet some of the wide-area control needs that cannot be addressed by ECI. An SPS involves installing hardwired, point-to-point communication between two or more substations, which are in some cases separated by hundreds of miles. If an event or a measurement occurs in a certain location on the grid, installation of an SPS can help in triggering actions, such as breaker tripping at another location.

However, these schemes cannot be relied on as a solution to the long-term control requirements of the grid [4].

Additionally, the limitations of existing communications infrastructure may also cause utilities' operators to be unaware of disturbances in neighboring control areas. Under such circumstances the operators tend to resolve the situation by communicating in a hit-or-miss fashion using telephones, which could lead to miss the opportunity to limit the spread of disturbance [4].

In addition to what has been stated above, several developments have been made in recent years, which put the grid under stress and also highlight the limitation of ECI. Such developments include the following [4]:

- Low investment in transmission system while demand, including that for higher-quality power, keeps increasing.
- Introduction of deregulation, which led the introduction of regional transmission operator (RTO)-based operational structures, independent sellers and power producers, new requirements for ancillary services, increased separation of power producers and consumers (which results in increasing load on the transmission infrastructure), and many more participants involved in the system overall.
- Continued increase of penetration of distributed generation that has led to several protection and control challenges.
- Increased concern about the security of the grid including malicious attacks on the grid.

Additionally, over the same time period, the number of intelligent electronic devices (IEDs) deployed in substations, for monitoring and measurement, has continued to increase. These devices have the capability of monitoring grid operational parameters as well as independently protecting the grid at the substation level. The data they gather are usually recorded at the substation to be used for postincident analysis. Synchronous phasor measurement units (PMUs), which have the capability of gathering data several times per power cycle, are also deployed to help develop a much more detailed picture of the grid's dynamics for systems planning, control, and postincident analysis. However, due to the limitations of current communications infrastructure, these data cannot be used beyond the substation where they are generated.

(iii) ***Characteristics of future PSC systems that suits Smart Grid requirements***

Future PSC systems that suits Smart Grid requirements and also ensure overcoming the limitations of existing PSC systems need to be characterized as having an **evolvable** and **adaptable** communication architecture that enables it to meet the following requirements [4]:

- It must have the capability of easily making status information available to any legitimate participant at any location.
- It must have the ability to deliver the information to each and every participant in a timely and reliable manner. It is important to note that for many envisioned control applications (such as SPS replacement) the faster the signal is transmitted, the better. However, regardless of the

absolute speed requirement, there is a need for predictable latency in any control application despite any foreseeable communication failure or overload.

Security of PSC systems must be ensured in such a way that status information is protected against illegitimate use, and participants can trust the status information they receive. It is also important that participants must be assured about the trustworthiness of the data they receive from other parties with whom they communicate, to limit the risk of using inaccurate data or of disclosing information to unauthorized sites.

5.4 Smart Grid communication system infrastructure

The communication infrastructure is a key component of the Smart Grid. A scalable and pervasive communication infrastructure is crucial for both the realization and effective and intelligent operation of a Smart Grid [7]. Therefore, the infrastructure of Smart Grid communication system (SGCS) that suits Smart Grid environment must have the capability to support the expected Smart Grid functionalities and meets its performance requirements. Such a communication system is expected to connect a huge number of electrical devices and should also manage the complicated device communications. It should therefore be designed using a hierarchical architecture approach with interconnected individual subnetworks whereby each of them takes the responsibility of separate geographical regions [8]. Figure 5.2 shows an illustrative example of this architecture [7].

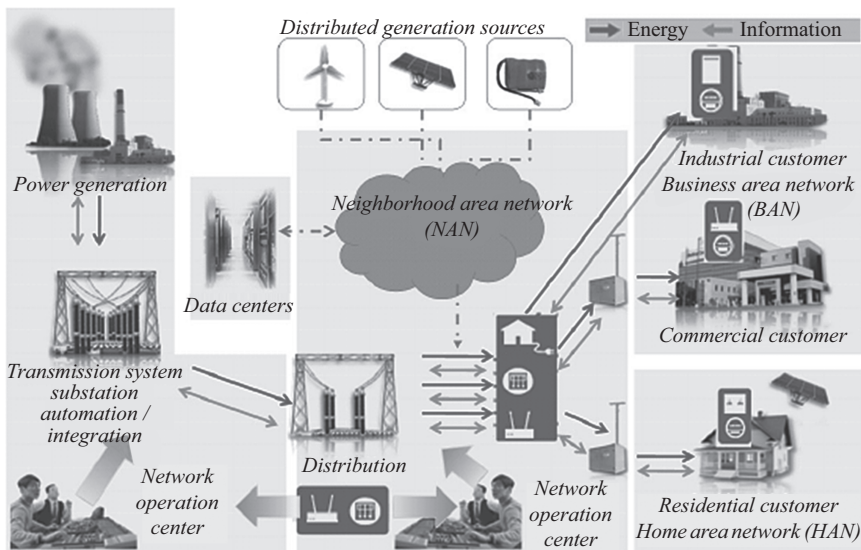


Figure 5.2 Architecture of Smart Grid communication infrastructure [7].
Reproduced by permission of IEEE

5.4.1 *Fundamental functions of the Smart Grid communication infrastructure*

The fundamental functions of the Smart Grid communication infrastructure are to ensure efficient, reliable, and secure data collection and transmission to support the operation of the following functionalities [9]:

- Sensing: This concerns with the data that are carried out by a large number of smart meters (SMs) or sensors to detect the status of the grid at various locations in a real-time manner.
- Two-way data transmission: This requires establishment of two-way transmission links to make it possible to transport data between the sensors and the control centers.
- Control: This is related to control instructions that are usually delivered from/to SMs, sensors, or control devices located at different places to support efficient operations of the Smart Grid and reliable access to grid components.

5.4.2 *Architecture of Smart Grid communication infrastructure*

In order to meet the fundamental requirements of Smart Grid communication infrastructure identified above, its architecture must be designed such that it helps to integrate enabling networking technologies. It must also cover the entire geographical area occupied by the Smart Grid to connect all relevant sets of nodes. To fulfill these goals the architecture of communications infrastructure need to be of a multilayer structure [9] that extends across the whole Smart Grid from the home area to the neighborhood area and the wide area. Figure 5.2 shows a general architecture for smart grid communication infrastructure that satisfies these requirements [7]. As can be seen from this figure, it includes home area networks (HANs), business area networks (BANs), neighborhood area networks (NANs), data centers, and substation automation (SA) integration systems.

The role of HANs is to communicate with various smart devices to provide energy efficiency management and demand response. While NANs connect multiple HANs to local access points. However, BANs provide communication links between the NANs and the commercial and industrial customers. This multilayered structure of the communication networks provides a potential operation of the Smart Grid to work economically, efficiently, reliably, and securely.

5.4.3 *Smart Grid communication infrastructure challenges*

The design of the Smart Grid communication architecture faces several challenges as discussed below [9]:

Dealing with huge volume of data: It is expected that the growth of data generated by SMs and intelligent sensors in the Smart Grid will explode in the next few years [9]. The volume of Smart Grid data that electrical utilities need to handle over the next few years is going to surge from 10,780 terabytes (TB) of new data created in 2010 to over 75,200 TB in 2015 [10]. The volume of the data would obviously continue to grow in the coming years. Managing, analyzing, and visualizing such huge volumes of data places considerable challenge on the Smart Grid communication architecture.

Energy sources: The second challenge placed on the Smart Grid communication architecture is the diversity of energy sources characterizing the Smart Grid whereby distributed renewable energy sources (e.g., solar and wind power) are integrated into the grid in addition to traditional fossil-based power sources. In a NAN, there is a possibility of having two power sources: namely, the power from the utility and the distributed renewable energy. These two power sources have two distinct differences: price and availability. Balancing the usage of different energy sources will be very important for power grid stability, availability, and operational cost.

Highly varying traffic: Smart Grid generates large amounts of real-time and archival operational data. The volume of such data varies considerably during the day, and consequently, traffic conditions change rapidly. For example, solar power is normally available only during a certain period of time during the day. Consequently, switching instructions of equipment related to solar energy source are transmitted dynamically according to the availability of this type of energy source. This means that during peak hours, the data communications system needs to deal with higher data rate, and consequently, its reliability must be high.

Interoperability: In Smart Grid data flow over generation, transmission, distribution, and consumer networks. Smart grid communication infrastructure must have the capability of providing enough information to the control centers to ensure efficient and reliable operation of the Smart Grid. To achieve this goal, variety of technologies is expected to be used to set up the communication architecture based on adopting multi-tiered topology of communication networks. However, one of the major problems of such topology is interoperability among so many subnetworks.

Quality of service (QoS): Different types of data have different QoS priorities in terms of transmission latency, bandwidth, reliability, and security [9,11]. For example, information related to devices' state, load, and power pricing must flow over the communication network accurately, effectively, and reliably. Also meters' data must have higher priority and guaranteed QoS, while power price data used for summarizing the monthly bill for electric usage have normal priority and QoS.

Security: Security is considered as a challenging issue since the on-going Smart Grid systems facing increasing vulnerabilities due to the ever increase of use of computer networks and also because of the interconnection between the ever-increasing automation, remote monitoring/controlling, and supervision entities [7,9]. Smart Grids are expected to be exposed to outside attacks as well as potential threats from within utilities, such as indiscretions by employees and authorization violation [12]. A detail discussion of cyber security of power systems will be covered under Section 5.5.

5.4.4 Standardization efforts by industry

The industry is putting a lot of efforts to establish standards governing the development of communication networks that suit Smart Grid applications. For example, ZigBee has recently defined an application layer standard for smart energy for HANs aiming at low-cost devices and low energy use [9,13]. Generally, ZigBee is characterized by low rate, low power, and short-range transmissions. It operates by the IEEE 802.15.4 radio specification.

The aim of the smart energy profile is to provide communications primarily related to efficiency, cost, messaging, and usage. The objective of the profile is to support a diversity of devices, including in-home display, programmable communicating thermostat, plug-in vehicles, and load control devices such as pool pumps, water heaters, and appliances. Messaging is considered as a key component of the profile that helps supporting different functionalities, particularly multiple urgency levels, security, registration, device definition, and initialization. The benefits offered by ZigBee smart energy profile include the following:

- It offers utility companies a standards-based technology for implementing secure and cost-efficient HANs.
- It enables customers to choose interoperable devices from different manufacturers. It also enables them to monitor their energy consumption in real time. This in turn provides them with precise information, which helps them in reducing their power consumption.
- It offers regulation organizations global open standard technology leading to easing the specifications of various rules. Additionally, ZigBee smart energy profile helps in implementing advanced SMs and also developing new demand response management to facilitate greener Smart Grids.

5.5 Cyber security of power systems

5.5.1 Basic definitions

To facilitate the discussion of the next section, the following definitions, in the context of Smart Grid, need to be introduced:

5.5.1.1 Cyber infrastructure

Cyber infrastructure is defined [14] as the infrastructure that

includes electronic information and communications systems and services and the information contained in these systems and services. Information and communications systems and services are composed of all hardware and software that process, store, and communicate information, or any combination of all of these elements. Processing includes the creation, access, modification, and destruction of information. Storage includes paper, magnetic, electronic, and all other media types. Communications include sharing and distribution of information.

Examples of cyber infrastructure components include (i) computer systems; control systems (e.g., SCADA); and (ii) networks, such as the Internet, and cyber services (e.g., managed security services).

5.5.1.2 Cyber security

In the context of Smart Grid, cyber security may be defined [14] as security that “encompasses measures to ensure the confidentiality, integrity and availability of the electronic information communication systems and the control systems

necessary for the management, operation, and protection of the Smart Grid's energy, information technology, and telecommunications infrastructures."

Alternatively, cyber security may be defined [15] as

the protection of all things pertaining to the Internet, from networks themselves to the information stored in computer databases and other applications, to devices that control equipment operations via network connections. Vulnerabilities are present in nearly every aspect of the networks used in modern community energy infrastructure.

5.5.2 *Security of power systems and cyber attacks*

The ability of perpetrators to penetrate into electrical power system and install malicious software with the intention to trigger such software at the time of their own choice to cause disruption has led power system companies to believe that their electrical power systems infrastructure is vulnerable [5]. This has raised the concern of electrical utilities and consequently urged them to take appropriate actions to ensure the cyber security of their electrical power systems.

Therefore, ensuring cyber security of electrical power systems is extremely important. Apart from supplying electrical power to industry, commercial buildings, and residential premises, many basic facilities in today's cities such as water, gas, waste water management systems, and traffic signaling systems are all primarily dependent on the wellbeing of electrical power systems, and therefore, any disruption to these systems would directly affect amenities and basic facilities supplied by them. In this discussion, the main concern will be focused on disruptions due to malicious intrusions attacking automatic systems and computer networks that have increasingly been used in recent years to automate and efficiently manage the operation of electrical systems. SCADA systems, which constitute the heart of these automation systems, are usually installed in electrical systems to control, collect, and analyze data from equipment that are extensively deployed in electrical generation plants, transmission and distribution substations, and utilities which deliver electrical power to industry, commercial organizations, and residential premises [16]. SCADA systems are therefore very likely to be the prime target of malicious attacks, that is, cyber-attacks.

According to the National Institute of Standards and Technology (NIST) of North America, more than 66 percent of the total threats due to computer-related commerce in North America are due to SCADA systems that are directly connected to electrical power substations [16]. The risks to which SCADA systems are subjected to are similar to those encountered by personal computers and commercial computer networks.

Additionally, the continuous trend of replacing the execution of manual tasks by automated control devices has led to networking these devices so that they can be controlled by a single SCADA system. However, the establishment of the Internet more than 25 years ago [17] and its universal use in recent years makes it attractive as alternative to private lines that were in use to carry control data in communication networks. However, this makes SCADA systems, which are critical to the control of electrical networks, vulnerable to intrusion [5]. In order to protect

and ensure the integrity of SCADA systems, their security can be built up using well-established security standards for commercial networks. As part of an effort to ensure the security of Smart Grid, NIST has established a Smart Grid Cyber Security Coordination Task Group (CSCTG) whose aim is to address and evaluate processes leading to comprehensive cyber-security policies for Smart Grids [5,14]. This group extended its task of assessing types of risks to cover not only those due to intentional attacks, for example, from discontented employees, terrorists, and industrial espionage, but also risks due to the following [5,14]:

- **Complexity of the grid:** This could lead to weak points, unintentional errors, and increase possibilities to potential attackers.
- **Interconnection of networks:** This may result in introducing common vulnerabilities and cascading errors.
- **Increasing vulnerabilities to communication disruptions and introduction of malicious software:** This could result in denial of service or compromise the integrity of software and systems.
- **Increased number of entry points and paths:** This makes it possible for potential adversaries to exploit and also potential for compromise of data confidentiality, including the breach of customer privacy.

5.5.3 Smart Grid cyber security

The global access to the Internet in recent years has made the world much more connected. Similarly, control and protection systems that electric generation plants and transmission and distribution systems are equipped with are also becoming more connected. Traditionally, these systems have been [18]:

- Few in number.
- Confined to a comparatively few locations such as control rooms, generating plants, and substations.
- Isolated from public networks, which make their security relatively easy to secure.

This makes it easy to provide a high degree of security using simple physical measures such as provision of fences and locks on doors. However, the evolution of Smart Grid technology has changed this scenario due to (i) placing large numbers of intelligent devices into places where in most cases can be physically easily accessed and also (ii) installing many of them onto networks that may be either physically accessible or indirectly logically accessible from public networks. This in turn has led to new Smart Grids cyber-security challenges for several years to come.

Additionally, in recent years, there has been a dramatic shift from using proprietary hardware and software toward using off-the-shelf hardware and software. There has also been an equally dramatic shift from traditional, proprietary communications protocols toward standards-based approaches, particularly Distributed Network Protocol 3 (DNP3) or IEC 61850 for grid control. While the move to standard hardware and software has enabled the interoperability between devices/equipment that are supplied from different vendors, it has on the other side made the attack of Smart Grid much more easier.

It has been advocated [18] that “true security” requires more than simple compliance with applicable standards. It rather requires performing a number of actions to assist users in achieving both “compliance **and** security.”

5.5.3.1 Smart Grid cyber-security challenges

Cyber-security challenges to Smart Grid may be divided into two [18]. These are (a) challenges due to potential infrastructure attacks and (b) challenges faced by grid operators.

(a) Cyber-security challenges due to potential infrastructure attacks

It has been recognized within cyber-security community that despite frequently heard statements such as “a well-funded, highly motivated, intelligent adversary can eventually defeat any cyber security,” successful attacks against critical infrastructure have been rare. However, the view of cyber-security experts is that the “attack surface” of systems is likely to increase dramatically.

It has also been recognized that Smart Grid technologies and devices would bring about tremendous benefits in several areas including reduced cost, increased reliability, and reduced environmental impact. In order to achieve these benefits as quickly as possible, there has been a rush to design, develop, and deploy these technologies and devices. This in turn has led to cyber security not always receive the attention it deserves.

SCADA system and smart metering are considered key components of Smart Grid. In terms of their security they can be expressed simply as concentrated vs. distributed. A SCADA system is normally located in one room (albeit with links to devices in substations, which are themselves mostly located in one room). However, SMs are located everywhere, and consequently, it is not possible to build a fence with a gate and a lock around them “everywhere.”

One of the important challenges that will face electrical utilities in the future is the cost that will be involved in maintaining cyber security for their grids. This may be measured in what is called return on investment (ROI), which constitutes a major factor when considering adding or upgrading facilities or equipment. Currently, ROI related to cyber security is somewhat vague, and how to quantify cyber-security investments will remain a challenge for some time to come.

(b) Cyber-security challenges faced by grid operators

Cyber security represents a complex challenge facing utility operators due to the following factors:

- (i) Modern SCADA/EMS/DMS systems are large, are complex, and incorporate increasingly large numbers of widely distributed components.
- (ii) The distributed nature of SCADA/EMS/DMS systems has led to complex network architectures.
- (iii) SCADA/EMS/DMS systems and networks employ a wide variety of cyber-security equipment and software.
- (iv) Processes required by utilities to manage, monitor, and maintain these assets can be complex and resource intensive.

- (v) Those who target harming energy delivery infrastructures continue to grow in sophistication, number, and level of dedication.

SCADA/EMS/DMS operators, particularly for small- to medium-sized electric utilities, usually do not have full-time on-site IT support. Additionally, it is impractical and potentially dangerous to expect that grid operators possess sufficient expertise in security-related topics to recognize, analyze, and deal with the variety of cyber-security incidents that can occur in today's world.

5.5.3.2 Communication-based attacks

Communication-based attacks are classified based on the type of communication channels and protocols used by SMs to communicate with the HAN, NAN, and the Smart Grid [19]. SMs may be infringed through several entry points that may compromise data integrity and privacy [20]. For instance, data integrity and authentication may be compromised through network attacks such as man-in-the-middle spoofing, impersonation, or denial of service (DoS) attacks. Similarly, data security may be compromised by sabotage/insider attacks such as viruses and Trojan horses. The situation can be very serious, if the attacker manages to get access to the crypto key of all the SMs of a utility by attacking the head-end and modifies the keys. Under this situation, the attacker can interrupt the supply to thousands of consumers that can cause devastating effect on the livelihood, health, and safety of people and businesses.

In order to prevent this from happening, a secured SM should have the ability to (i) successfully prevent cyber/physical attacks and (ii) provide reasonable recovery/survivability mechanism.

Table 5.1 summarizes the different types of wireless communication systems available for Smart Grid applications, their advantages, vulnerabilities, and possible solutions [19].

It will be noted that the term “Long Term Evolution (LTE)” mentioned in the above table refers to a 4G wireless broadband technology developed by the Third Generation Partnership Project (3GPP), an industry trade group [21].

5.5.3.3 Emerging Smart Grid cyber-security technologies

It is obvious that securing large, widely dispersed, and easily accessible networks pose significant challenges. In case of conventional networks, support personnel are usually available and standby to deal with an intrusion. However, under Smart Grid environment conditions, if an intrusion occurs in an inexpensive SM, say 100 miles from the nearest support technician, grid operators will be faced by a completely new scenario in terms of cost vs. benefit considerations that needs to answer the following questions [18]:

- Should a service team be sent immediately or rather better wait?
- How long is too long to wait?
- How long it takes before an intrusion into one meter is used by an attacker to attack neighboring meters or other equipment?

The popular approach that has been in use to secure cyber assets is based on what is called “defense in depth (DID),” whereby a series of obstacles are constructed

*Table 5.1 Vulnerabilities and possible solutions to wireless communication technologies that are used by **Smart Grid** [19]*

Type of technology	Advantage	Vulnerability	Possible solution
Wi-Fi	Open standard, high throughput, strong home market penetration, low cost and relatively secure communication	Traffic analysis, passive and active eavesdropping, man-in-the-middle attack, session hijacking and replay attacks.	Two-way authentication, encryption
ZigBee	High reliability, self-configuration and self-healing, low power consumption and low cost	Jamming, message capturing and tampering, and exhaustion	A utility gateway device between HAN and SM, authentication and encryption
Mobile communications and femto-cells	Consistent coverage in office or home, low power consumption	Network and service availability disruption, fraud and service theft, and privacy and confidentiality disruption	Two-way authentication and encryption
WiMAX	High data rate (1 Gbps for stationary users), low latency, advanced quality of service (QoS), and sophisticated security	Range of attacks (DoS attack, downgrading attack, water torture attack), power-saving attack, man-in-the-middle attack, replay theft of service attack, and traffic analysis techniques	Encryption, intrusion detection schemes, access control to specific applications
Long Term Evolution (LTE)	Low interference and resource efficient	Attacks on the air interface, attacks on the e-NB, and attacks against the core network	Two-way authentication, encryption, introduction of mobile virtual network operator (MVNO)

that an attacker must defeat in order to breach the core of a system. Traditionally, defenses have been in the form of firewalls, intrusion detection systems (IDSs), and malware detection software. The same types of techniques can be used for providing DID for the Smart Grid. However, such techniques must to be characterized as being more compact, much less expensive, more autonomous, more distributed and require less human attention.

Several studies have been reported [22,23] aiming at developing IDSs for advanced metering infrastructure (AMI).

As far as SM is concerned, it has been reported by industry [18] that creative security solutions have begun to emerge in the Smart Grid arena. An example of such solutions is the development of a very cheap hardware-based intrusion detection system that could be incorporated into a single, integrated circuit.

Its estimated cost is less than one dollar, which makes it too cheap to allow installing one into every single SM. Other solutions are expected to emerge in the future with the help and encouragement of industry to creative people.

5.5.3.4 Compliance versus security

It is important for utilities to move from traditional position whereby the primary concern is **compliance** to a position where the primary concern is **security** and thereby Smart Grid security becomes a central part of utilities culture [18]. The difference between compliance and security is sometimes delicate, but it can have a large impact. For example, according to rules adopted by certain organizations, it is mandatory that antimalware software must be installed and maintained on critical cyber assets. If these rules are followed, then this is described as “compliance.” However, it has been recognized that current antimalware solutions are particularly ineffective in dealing with zero-day threats, which lead to the conclusion that in this situation “compliance does not equal security.” It is therefore argued that better solutions would be reached if utilities’ culture directed to meet not only compliance but also security.

5.5.3.5 Smart Grid cyber-security standards

Cyber-security standards are very complex subject. It has been reported [24] that globally the number of standards relating to cyber security in some form or another has exceeded 1,000 publications. Despite the quality and general applicability of most individual standards, there was no comprehensive standard identified that provided a “one size fits all” approach. The discussion of universal cyber-security standards is outside the scope of this book.

As far as Smart Grid applications are concerned, several cyber-security standards have been published in recent years. The most important of these are listed below [18,25]:

- North American Electric Reliability Corporation Critical Infrastructure Protection (NERC CIP) standards in North America
- ISO/International Electrotechnical Commission (IEC) 15408 (Common Criteria)
- ISO/IEC 27002:2005 (formerly ISO/IEC 17799)
- Various National Institute of Standards and Technology (NIST)
- Other security-related standards and recommendations such as the Department of Homeland Security (DHS) “Catalog of Control Systems Security”

However, it has been pointed out by industry [25] that many of these standards do not apply to vendors’ product. They only define security requirements that an organization must meet. For example, in the USA, professionals in electrical power industry are familiar with the NERC CIP standards. These standards define auditable security requirements for utilities. Although they provide valuable security guidance, they are not directly relevant to Smart Grid applications, and primarily target the automation systems used in generation and transmission facilities. Another example is the set of guidelines called “NIST IR 7628 Guidelines for Smart Grid Cyber Security.” These guidelines provide a comprehensive set of high-level security requirements for all aspects of the Smart Grid.

However, apart from the huge size of this document, which probably makes a utility engineer working on a Smart Grid project overwhelmed, more importantly, the document provides high-level guidance, not directly actionable engineering specifications.

However, it has been reported [25] that the Advanced Security Acceleration Project for the Smart Grid (ASAP-SG) [26] would provide the most accessible security guidance for Smart Grid projects. This project was initiated as a utility-driven, public-private collaborative effort aiming at developing recommendations and best practices for architecting, designing, acquiring, integrating, and operating Smart Grid systems. It has developed security profiles for AMI, distribution management (DM), and wide-area monitoring protection and control (WAMPAC). The group is also working on an SA profile. For instance, the ASAP-SG security profile for DM addresses the security requirements of Smart Grid applications such as fault location, isolation, service restoration, voltage optimization and control, VAR management, and integrated volt/VAR control.

The security profiles developed by the ASAP-SG use an engineering approach that starts by analyzing the applications and their use cases, defines the possible failure modes, and then recommends security controls referenced from the DHS “Catalog of Controls System Security” to prevent these failures.

A summary of these security controls and how they can help in building a more secure Smart Grid system is given in the following sections [22].

Policy security controls

Policy security controls are considered as the foundation of every security standard and framework. Security policies are used to define requirements for training and electronic and physical access control. They are also used for regular security assessments, incident handling and disaster recovery procedures, and configuration management. Policy security controls are considered by Smart Grid automation engineer the least exciting and the most difficult to implement, but they are necessary as technical security controls work only if they are enforced.

Network segmentation design

The most basic technical requirement is to design the network architecture so that it isolates field devices and applications from the external world. Although nowadays the Internet is heavily relied on to exchange information, the system should not be built on a public network. Public networks provide no control, ownership, or guarantee of service, even if a virtual private network (VPN) is used. It is therefore important that Smart Grid applications use alternative solutions such as wireless communications or cellular networks in a private mode. The communication network must be divided into independent segments with well-defined communication paths.

Field devices must be ensured to communicate only with the control application, which resides in its own network segment. The control application should also communicate only with field devices and user workstations that are located in a separate segment isolated from the business network. The business network should be the only segment that can have access to the Internet.

Adopting such segmented architecture design helps in reducing the risk of an external threat compromising the application or field devices.

Technical security controls

Typical power systems field devices are not equipped with security controls and features such as centralized authentication, granular access permissions, access logs, and secure communications that are normally available on Windows®- or Linux®-based machines. In fact, most field devices have only password-protected levels and they do not have login accounts.

Although ASAP-SG security profiles do specify some of these security controls, they also need provision of additional controls that are better adapted to Smart Grid applications.

Protection of field devices

To illustrate the ASAP-SG security profile approach, consider a field device such as a recloser or a capacitor bank controller. The device is normally kept in a container, and accessed through wireless or cellular communications. A malicious individual could disrupt the operation of the application, after breaking into a container, by disabling the device, feeding it false information or gaining access to the control system through the communications link.

The security profile uses a systems engineering approach to ensure the protection of a field device. The first step is to lock the container to protect the device. Ideally, the locking mechanism should grant users permission on a per-container basis and perform periodic reauthorization to protect against lost keys and disgruntled employees.

Since it is next to impossible to completely protect the container, the system needs to provide means to monitor that the device is operating correctly, detect any breach or failure, and report it to the control application. The control application should have the ability to isolate a compromised or defective field device.

The security profile defines additional controls to further improve the security, and thereby ensure the reliability of the system. In the event of a power failure, access monitoring must continue to operate. The state of the power source must be monitored and logged as an unexpected power loss could indicate a breach. Additionally, the device must have the ability to monitor and report its health condition, and validate its firmware and settings.

Securing communications

The physical integrity of the device must be ensured first. Then communication systems with the application must be protected. Encryption can be used as part of the solution to ensure data confidentiality and to provide a certain level of authentication. The encryption is considered in most cases as the “cure-all” security solution. However, when it is deployed on a large scale, as it is the case for Smart Grid, its implementation becomes complex. Additionally, encryption algorithms and protocols must comply with approved standards; otherwise, utilities will be tied up to a specific vendor and even risk data exposure.

The IEC 62351 standards are recommended by “NIST Framework and Roadmap for Smart Grid Interoperability Standards” [14] for securing SCADA communication systems. These standards provide guidelines on the use of the Transport Layer Security (TLS) protocol for data encryption. They also define a challenge-response security mechanism to ensure the security of control operations.

This mechanism has been implemented in the Distributed Network Protocol 3 (DNP3) as a secure authentication function.

Both encryption and secure authentication require an automated key management mechanism, which takes us back to the enterprise level.

Managing encryption key of field devices

As previously mentioned, using cryptography or DNP3 secure authentication requires managing encryption keys. Obviously, it is much easier to deploy a system if all devices share the same encryption key. However, the whole system is compromised, if a key is compromised. Therefore, each device should have its own encryption key. Managing tens of thousands or even thousands of encryption keys requires an automated solution at the enterprise level.

Enterprise-level key management solutions are widely used in some industries, and the technology is even built into systems such as Microsoft® Windows Server®. However, key management solutions are generally tied to specific vendor applications. However, standards-based key management exists, but it has not yet applied to field devices. This is expected to change as DNP3 secure authentication becomes more widely used.

Centralized device management is a common requirement in security frameworks, including NERC CIP and the ASAP-SG security profiles. Besides tracking encryption keys, it is important to keep track of all deployed devices and their configuration.

It is normal practice when vendors identify and address vulnerabilities, they issue firmware updates. It is important that utilities should devise some automated enterprise-level configuration management system that tracks all deployed devices with their serial numbers, firmware versions, and current settings. Such a system must have the ability to detect when replacement or modification of a device has occurred, enforce that up-to-date firmware be loaded, and provide the correct configuration settings.

Smart Grid cyber-security standards challenges

What have been covered in the previous sections are barely touching the core of the subject related to the challenges imposed by adopting and introducing Smart Grid cyber-security standards. It has not even addressed critical functions, such as remote access for maintenance. Since all equipment in power systems are now connected and based on programmable devices, it is important that new system failure modes resulting from these capabilities must be taken into account.

Currently there is no device that has the capability of providing all the security controls required to build a secure Smart Grid. It is therefore vitally important for utilities who are engaged in a Smart Grid project to work closely with vendors to ensure that the chosen solution can evolve to meet the requirements outlined above.

It has been suggested [25] that a layered approach need to be used. In order to meet NERC CIP requirements, utilities have been using security appliances and data concentrators to protect substation devices with little or no security. Similar strategies might be adopted in Smart Grid applications where the cost can be justified.

Additionally, it has also been suggested that utilities should plan to adopt enterprise-level IED management approach to provide centralized access control,

monitoring, logging, and configuration management functions, because tracking thousands of device serial numbers, firmware versions, and passwords using a spreadsheet is not practical.

In conclusion, at this time of age it seems there is no magic solution to the Smart Grid security. Building a secure Smart Grid system is considered as a complex engineering problem that requires a collaborative effort from all groups involved, including vendors, enterprise IT groups, and concerned engineering teams.

5.6 Summary

This chapter is devoted to Smart Grid communication system and its cyber security. A classification of power system communication (PSC) systems according to their requirements is given in Section 5.2. They are classified into (i) real-time operational communication systems, (ii) administrative operational communication systems, and (iii) administrative communication systems.

This is followed by discussing the existing electric power system communication infrastructure and highlighting its limitation in Section 5.3. In particular the following have been covered: (i) overview of current PSC systems and their characteristics, (ii) shortcomings of current PSC systems, and (iii) characteristics of future PSC systems that suit Smart Grid requirements.

Smart Grid communication system infrastructure was then discussed under Section 5.4. The topics discussed in this section include (i) fundamental functions of the Smart Grid communication infrastructure, (ii) architecture of Smart Grid communication infrastructure, (iii) Smart Grid communication infrastructure challenges, and (iv) standardization efforts by industry.

Finally, in Section 5.5 cyber security of power systems/Smart Grid was then discussed. It begins with giving definition of cyber infrastructure and cyber security. This is then followed by discussing security of power systems and cyber-attacks. The Smart Grid cyber security was then discussed, which covered (i) Smart Grid cyber-security challenges, (ii) emerging Smart Grid cyber-security technologies, (iii) compliance versus security, and (iv) Smart Grid cyber-security standards.

References

- [1] Simon M. 'The smart grid communication infrastructure for protection: designing to the highest common denominator'. *Protection, Automation and Control World*. 2011; March:18–25.
- [2] Ericsson G.N. 'Classification of power systems communications needs and requirements: experiences from case studies at Swedish national grid'. *IEEE Transactions on Power Delivery*. 2002; **17**(2):345–47.
- [3] Ericsson G.N. 'Cyber security and power system communication – essential parts of a smart grid infrastructure'. *IEEE Transactions on Power Delivery*. 2010; **25**(3):1501–07.
- [4] Hauser C.H., Bakken D.E., and Bose A. 'A failure to communicate – next generation communication requirements, technologies and architecture

- for electric power grid'. *IEEE Power and Energy Magazine*. 2005; **3**(2):47–55.
- [5] Iyer G. and Agrawal P. 'Smart power grids'. *42nd Southeastern Symposium on System Theory (SSST)*; Tyler, TX, 2010, pp. 152–55.
- [6] Kurth R.D., Henderson R.B., (Bob) Burton R.S., Hancock B.S., and Roik J.N. 'Design, implementation and commissioning of a remedial action scheme'. *DistribuTECH Conference and Exhibition San Diego*. California, USA, January 2005, pp. 25–27.
- [7] Yan Y., Qian Y., Sharif H., and Tipper D. 'A survey on smart grid communication infrastructures: motivations, requirements and challenges'. *IEEE Communications Surveys & Tutorials*. 2013; **15**(1):5–20.
- [8] Wang W., Xu Y., and Khanna M. 'A survey on the communication architectures in smart grid'. *Elsevier Journal on Computer Networks*. 2011; **55**(15):3604–29.
- [9] Yu R., Zhang Y., Gjessing S., Yuen C., Xie S., and Guizani M. 'Cognitive radio based hierarchical communications infrastructure for smart grid'. *IEEE Network*. 2011; **25**(5):6–14.
- [10] SBI Energy. *The smart grid utility data market* [Online]. 2010. Available from <https://www.sbiereports.com/Smart-Grid-Utility-2496610/> [Accessed on 24 February 2016].
- [11] Li H. and Zhang W. 'QoS routing in smart grid'. *IEEE Global Telecommunications Conference (GLOBECOM)*; Miami, FL, 2010, pp. 1–6.
- [12] Metke A.R., and Ekl R.L. 'Security technology for smart grid networks.' *IEEE Transaction on Smart Grid*. 2010; **1**(1):99–107.
- [13] <http://www.zigbee.org/>.
- [14] NIST. *NIST framework and roadmap for smart grid interoperability standards – Publication 1108, release 1.0* [Online]. 2010. Available from http://www.nist.gov/public_affairs/releases/upload/smartgrid_interoperability_final.pdf [Accessed on 5 March 2016].
- [15] Public Technology Institute. *Cyber security concerns for local government energy assurance planning* [Online]. USA: Department of Energy; 2011. Available from <http://www.cadmusgroup.com/wp-content/uploads/2013/03/Mark-Lesiw-coc-2011-handout2.pdf> [Accessed on 2 November 2016].
- [16] Oman P., Schweitzer III E.O., and Frincke D. *Concerns about intrusions into remotely accessible substation controllers and SCADA systems* [Online]. USA: SEL; 2000. Available from https://www.researchgate.net/publication/2545933_Concerns_About_Intrusions_Into_Remotely_Accessible_Substation_Controllers_And_Scada_Systems [Accessed on 2 November 2016].
- [17] Edwards C. 'Sharing what we know'. *IET Engineering & Technology Journal*. 2010; **5**(16):16–17.
- [18] Siemens. *Smart grid cybersecurity: white paper* [Online]. USA: Siemens Industry, Inc.; 2012. Available from <http://www.smartsec-europe.com/White%20Paper%20-%20Smart%20Grid%20Cyber%20Security%20-%20Siemens.pdf> [Accessed on 2 November 2016].
- [19] Mahmud R., Vallakati R., Mukherjee A., Ranganathan P., and Nejadpak A. 'A survey on smart grid metering infrastructures – threats and solutions'.

- IEEE International Conference on Electro/Information Technology (EIT)*; Dekalb, IL, 2015, pp. 386–91.
- [20] Kalogridis G., Sooriyabandara M., Fan Z., and Mustafa M.A. ‘Toward unified security and privacy protection for smart meter networks’. *IEEE System Journal*. 2014; **8**(2):641–54.
- [21] TechTarget. *Long term evolution* [Online]. Available from <http://searchmobilecomputing.techtarget.com/definition/Long-Term-Evolution-LTE> [Accessed on 26 February 2016].
- [22] Faisal M.A., Aung Z., Williams J., and Sanchez A. *Data stream-based intrusion detection system for advanced metering infrastructure in smart grid: a feasibility study* [Online]. Abu Dhabi, UAE: Masdar Institute of Science and Technology; April 2012. Available from <http://www.dnagroup.org/techreps/DNA-2012-05.pdf> [Accessed on 3 November 2016].
- [23] Berthier R., Sanders W.H., and Khurana H. ‘Intrusion detection for advanced metering infrastructures: requirements and architectural directions’. *First IEEE International Conference on Smart Grid Communications (SmartGridComm)*; Gaithersburg, MD, 2010, pp. 350–55.
- [24] DBIS (Department for Business Innovation & Skills). *UK cyber security standards – research report* [Online]. UK: Department for Business Innovation & Skills; November 2013. Available from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/261681/bis-13-12-94-uk-cyber-security-standards-research-report.pdf [Accessed on 3 November 2016].
- [25] Benoit, J. *Making sense out of smart grid cyber security standards: White Paper WP083005EN* [Online]. USA: Eaton’s Cooper Power Systems; September 2013. Available from http://www.eaton.com/ecm/groups/public/@pub/@eaton/@corp/documents/content/pct_1353513.pdf [Accessed on 3 November 2016].
- [26] AnerNex. *Advanced security acceleration project for the smart grid (ASAP-SG)* [Online]. USA: Electric Power Research, Engineering, and Consulting. Available from <http://www.enernex.com/projects/advanced-security-acceleration-project-for-the-smart-grid-asap-sg/> [Accessed on 3 November 2016].

This page intentionally left blank

Chapter 6

International standard IEC 61850 and its application to Smart Grid

6.1 Introduction and historical background

The aim of this chapter is to give an overview of the international standards IEC 61850 that deals with the communication networks and systems in substations. It should be pointed out that it is not intended to give a rigor treatment of this subject but to highlight its relevance to the development of the Smart Grid concept and to discuss its application to Smart Grid.

The international IEC 61850 standard is specifically developed for the design of electrical substation automation [1]. It is developed and maintained by the International Electrotechnical Commission (IEC)'s Technical Committee 57 (TC57) [2]. The role of IEC TC57 is to develop and maintain international standards for power systems control equipment and systems including EMS (energy management systems), SCADA (supervisory control and data acquisition), distribution automation, teleprotection, and associated information exchange for real-time and nonreal-time information, used in the planning, operation, and maintenance of power systems.

The first edition of IEC 61850 communication standard for substation automation was introduced in 2004 [3]. It is considered as the basis for the state of the art of substation automation systems. This is then followed by releasing the second edition of IEC 61850 standard in 2011 [3]. IEC 61850 standard provides a new and innovative approach to **substation automation** and **communications**. The aim of such features embodied into IEC 61850 is to reinforce modern computer and network technology to maximize reliability and performance but at the same time minimizes the cost of design, installation, and commissioning.

The international IEC 61850 standard is specifically developed for the design of electrical substation automation [1]. It has been developed to promote rapid configuration and integration into the utility automation system. Recently, IEC 61850 has been considered to be used in a standard-based control for distributed energy resources [4].

Prior to the recent advances in networking technology, substation automation protocols and architecture provided only basic functionality for power systems automation. This is due to the limitations and constrains of the available networking technology at that time, which affected their design and implementation.

The tremendous advances in networking technology in recent years have paved the way to widely open the opportunity for enhancing the automation of power systems' substation. Developments of technologies such as **switched Ethernet** [5], **TCP/IP** [6], **high-speed wide area network (WAN)** [7], and **high-performance low-cost computers** make it possible to introduce new capabilities that could not be imagined previously when the design of substation automation protocols are considered [8].

To take the advantage offered by the new networking technology for the benefit of substation automation, the IEC has developed and released new global standards for substation automation, namely, IEC 61850. In this chapter a basic technical review of these standards will be covered. Among other things that will be covered in this chapter is the **concept of virtual model**, which comprises both physical and logical device models. These models include a set of **standardized communication services**. This chapter will also explain how these standardized models, object-naming convention, and communication services bring significant benefits to substation automation.

Real-time operation of the power system has been always critically dependent on communication system. For example, in the early days of power systems, telephone system was the backbone of power system's communication system that was used to transmit line loadings information back to the control center and to dispatch operators to perform switching operations at substations. However, the introduction of digital communication in 1960s has paved the way for the installation of data acquisition systems (DASs) in power systems to automatically collect measurement data from substations. Bandwidth limitation made optimizing DAS communication protocols necessary to be able to operate over low-bandwidth communication channels. The resulting "cost" of such optimization was the relatively long time it took to **configure, map, and document** the location of various data bits received by the protocols.

As the digital age advances further, the communication bandwidth limitation has disappeared and thousands of analog and digital data points became available in a single intelligent electronic device (IED). It has also become a commonplace for a substation to master **communication data paths** operating at a rate of 64 kbit/s with prospect of migrating to even higher rates. The consequence of achieving the operation at high rates is that the "cost" component of DAS has shifted to the "time" taken to **configuration and documentation**.

However, using devices from different vendors at the same substation has inevitably led to the necessity of using multiple protocols for substation automation, which possibly include many proprietary protocols with custom communication links. Soon it has been realized that interoperability between devices from different vendors is urgently needed for enhancing substation automation. To achieve this, a new generation of communication systems has been contemplated and eventually led to the development of standard IEC 61850 as discussed below.

The following key requirements of the future communication systems have been identified [8]:

- High-speed IED-to-IED communication
- Networking throughout utility infrastructure

- High availability
- Delivery time must be guaranteed
- Standard based
- Multivendor interoperability
- Support for voltage and current samples
- Support for File Transfer
- Autoconfigurable/configuration support
- Support for security

Having identified these requirements, a new generation of communication architecture has been contemplated and the work on the development of the utility communication architecture (UCA) started in 1988. This work resulted in a **profile of “recommended” protocols** for the various layers of the International Standard Organization (ISO) Open System Interconnect (OSI) communication system model. Definition of a “profile” of **protocols, data model, and abstract service definitions** has also been established, which is later on known as **UCA**. The concepts and fundamentals developed in UCA work used later on as a basis for the development of the International Standard IEC 61850: Communication Networks and Systems in Substations that was undertaken by IEC Technical Committee number 57 (TC57), Working Group 10 (WG10).

6.2 Aim and objectives of IEC 61850

The declared aim of IEC 61850 was providing communication within substation. In order to achieve this aim, the following objectives have been identified:

1. Development of a single protocol for the whole substation having in mind the modeling of different data required for the substation.
2. Identification of basic services required to transfer data so that the entire mapping to communication protocol can be ensured.
3. Ensuring high interoperability between systems from different vendors.
4. Development of a common method/format that ensures the storage of complete data.
5. Devising a testing method to ensure that equipment comply with the standard requirements.

6.3 The structure of IEC 61850

The IEC 61850 is structured in ten major documents [8] whereby various aspects of substation communication network are detailed as outlined in Table 6.1.

The documents IEC 61850-3, 4, and 5 are primarily devoted to identify the general and specific requirements of communication in a substation (see the key requirements above). These requirements are then used as a basis to help in identifying the **services and data model needed, application protocol required,**

Table 6.1 *Structural documents of the IEC 61850 standard*

Document No.	Title
IEC 61850-1	Introduction and overview
IEC 61850-2	Glossary of terms
IEC 61850-3	General requirements
IEC 61850-4	System and project management
IEC 61850-5	Communication requirements for functions and device models
IEC 61850-6	Configuration description language for communication in electrical substation related to IEDs
IEC 61850-7	Basic communication structure for substation and feeder equipment
7.1	– Principles and models
7.2	– Abstract Communication Service Interface (ACSI)
7.3	– Common Data Classes (CDCs)
7.4	– Compatible logical node classes and data classes
7.10	– Communication networks and systems in power utility automation: Requirements for web-based and structured access to the IEC 61850 information model
IEC 61850-8	Specific Communication Service Mapping (SCSM)
8.1	– Mapping to MMS (ISO/IEC 9506-1 and ISO/IEC 9506-2) and to ISO/IEC 8802-3
IEC 61850-9	Specific Communication Service Mapping (SCSM)
9.1	– Sampled values over serial unidirectional link multidrop point-to-point link
9.2	– Sampled values over ISO/IEC 8802-3
IEC 61850-10	Conformance testing

the underlying transport, network, data link, and physical layers that will meet the overall requirements.

The principles adopted to construct the architecture of the IEC 61850 are based on the concept of “**abstract**.” According to this concept the definition of the data items and services are abstracted whereby data items/objects and services are created independently from any underlying protocols. The abstract definitions provide flexibility to “**map**” data objects and services to any other chosen protocol that can meet the data and service requirements. The definition of abstract can be found in IEC 61850-7.2 while abstraction of the data projects (known as logical node) can be found in IEC 61850-7.4. Many of data objects are made of pieces such as **status**, **control**, **management**, **substitution**. In order to accommodate these pieces in a larger data object, the concept of “**Common Data Classes (CDCs)**” was specifically developed, which defines the creation of building blocks for larger data objects. Definition of CDC elements can be found in IEC 61850-7.3.

Having obtained data and services abstract definitions, the mapping process of services to an actual protocol is performed. IEC 61850-8.1 explains the mapping of the abstract data objects and services onto **Manufacturing Message Specification (MMS)**. IEC 61850-9.1 and 9.2 explain the mapping of the sample measured values

(unidirectional point-to-point and bidirectional multipoint). The IEC 61850-9.2 document defines what is now known as **process bus** (see Section 6.4).

From a system point of view, a significant configuration effort is needed in order to pull all the pieces together to get them work. This process is facilitated using an XML-based **substation configuration language (SCL)**. The latter is explained in IEC 61850-6. According to this process a formal description of the relationship between substation automation and the substation structure (switchyard) can be established. At the implementation level the switchyard topology itself and the relation of the switchyard structure to the SAS functions can be achieved using logical nodes (LNs) [9], which are configured on IEDs. Each IED must provide an SCL file that describes the configuration of itself.

The final document, IEC 61850-10, of the standard is devoted to testing performance required to determine the conformance with the numerous protocol definitions and constraints set out in the document.

The IEC 61850 standard was originally intended for communication **inside** substation. Recently work has been undertaken to extend the scope of 61850 to make it possible for substation to master communication protocol. Additionally various components of IEC 61850 has also been used for wide area substation-to-substation communication.

6.4 The process bus

Recent advances in low-energy voltage and current sensors make it possible to sample and digitize the base quantities at the source and the resultant sample values can be transmitted back to substation. However, in addition to having sampled values, it became increasingly desirable to have the ability to remotely acquire status information as well as set output controls. This requirement has been addressed by IEC 61850 through the definition of sampled measured values (SMVs) and implementation of the concept of **process bus**. In this context the **process layer** at the substation is defined as that related to collecting information such as voltage, current, and status information from transducers and transformers installed on the primary power system equipment. The collection of this data according to IEC 61850 is defined by two different protocols. The first one is IEC 61850-9.1 (see Table 6.1), which defines unidirectional multidrop point-to-point fixed link carrying a fixed dataset, while the second one is IEC 61850-9.2 (see Table 6.1), which defines a **configurable** dataset that can be transmitted on multicast basis from one publisher to multiple subscribers.

Figure 6.1 illustrates the basic concept of the process bus. Signals from the secondary sides of voltage (VTs) and current transformers (CTs) as well as status information are fed to a **merging unit (MU)** (see Section 6.5). The MUs in a substation sample signals at a prescribed, synchronized frequency rate. This facilitates feeding data to any IED from multiple MUs and to automatically align and process the data. Currently an implementation agreement sets a base rate of 80 samples per mains cycle for protection and monitoring signals and 256 samples per

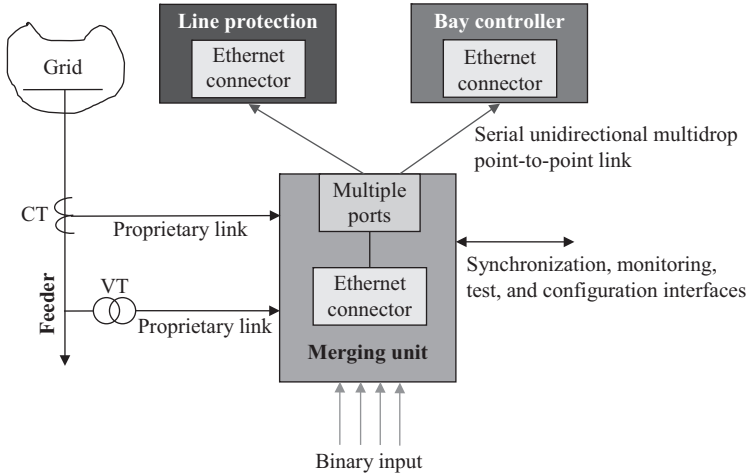


Figure 6.1 The basic concept of the process bus [after 8]

mains cycle for high-frequency applications such as power quality and high-resolution oscillography.

IEC 61850-9.1 specifies a **preconfigured** or **universal** dataset as defined in IEC60044-8. This dataset includes 3-phase voltages, bus voltage, neutral voltage, 3-phase currents for protection, 3-phase currents for measurement, and two 16-bit status words. It will be noted that the analog data values are mapped into 16-bit registers in this mapping.

IEC 61850-9.2 is dedicated to a more generalized implementation of SMV data transfer. In this part, the dataset or “payload” is user defined using the SCL. As a dataset, data values of various sizes and types can be integrated together.

Direct mapping onto an Ethernet transport is stated in both IEC 61850-9.1 and IEC 61850-9.2. It is possible to map anything from 1 to 5 devices onto a single 100 MB Ethernet link, depending on the sample data rate. Multiple 100 MB Ethernet data streams can then be combined into a single Ethernet switch with a 1 GB backbone. In this configuration, 50 or more datasets can be published to multiple subscribers.

6.4.1 Practical implementation of the process bus

As mentioned earlier, the concept of process bus is defined and explained in the IEC 61850-9.2 document. According to this document copper wires of the secondary sides of CTs and VTs are replaced by a standardized **Ethernet switch** known as **process bus**. In this arrangement the interfacing between primary equipment and IEDs is made using **fiber optic cables**, MUs, and Ethernet switch(es). The benefits of such arrangement include: (i) secondary side connections are greatly simplified compared with conventional approach based on utilizing copper wires and (ii) more importantly, this new IEC 61850 standard-based solution ensures the

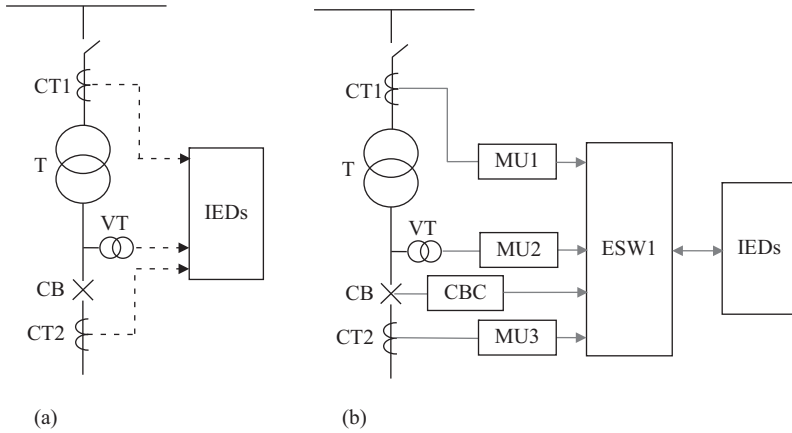


Figure 6.2 A transformer feeder bay using (a) secondary connections based on copper wires and (b) process bus arrangement

interoperability between IEDs from different vendors without the need of using expensive protocol converters.

Figure 6.2 shows the implementation of process bus concept on a transformer feeder [10]. Figure 6.2(a) and (b) shows the connection arrangement before and after the introduction of the process bus, respectively. In Figure 6.2(a) the secondary sides of CT1, CT2, and VT are connected to IEDs using copper wires, while Figure 6.2(b) shows the same feeder but after replacing secondary side connections by process bus arrangement, whereby each of CT1, CT2, and VT is connected to an MU and the circuit breaker CB is connected to a circuit breaker controller (CBC). The MUs and CBC are connected to the Ethernet switch (ESW1). The connections between CT1, CT2, VT, MUs, CBC, and ESW1 are made of **fiber optic cables**. To ensure successful operation of the system, each MU should be capable of receiving the input data from the CT/VT connected to it and send the corresponding sample values to IEDs via the Ethernet switch ESW1. Additionally, the CBC should also be capable of receiving trip signal from appropriate IED.

6.5 Merging unit

Figure 6.3 shows a simplified block diagram of an MU [11]. Its main components include amplifiers, filter, analog-to-digital converter and digital signal processing (DSP) unit. This figure shows the MU is synchronized using 1-pps (pulse per second) signal supplied from GPS receiver. The input to the MU is the analog signal(s) from current and/or voltage transformers and its output(s) is/are the corresponding synchronized and stamped-dated sample signal(s) with 1 pps. It can be seen from the figure that a delay of $D1 + D2$ is introduced by the unit. This delay must be compensated; otherwise, all functions based on the samples derived from the unit will be affected. Sampled data from the unit is fed to IEDs where they are

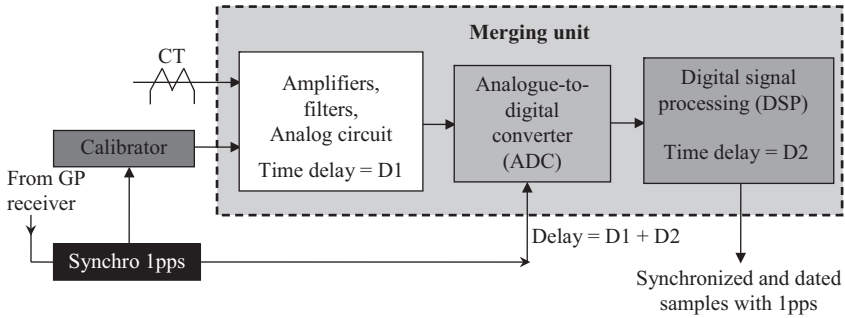


Figure 6.3 A simplified block diagram of the merging unit [after 11]

processed and accordingly a decision is made. The corresponding action depends on the functionality of the device where the data are processed. In case of a protection and/or control devices, the action will be operating their relay output or sending a high-speed peer-to-peer communication signal to other IEDs in order to trip a circuit breaker or initiate some other control action.

6.6 Comprehensive modeling approach of IEC 61850

Protocols that were in use prior to the development of IEC 61850 define how the bytes are transmitted over wires, but they do not specify the way the data should be organized in devices in terms of the application. This meant that power systems engineers are required to manually configure objects and map them to power systems variables and low-level register numbers, index numbers, I/O modules, etc. The novelty of the IEC 61850 is that in addition to the specification of how the bytes are transmitted over wires, it provides a comprehensive model as how power systems devices organize data in a way that is consistent irrespective of types and brands of devices. This obviously eliminates much of the tedious nonpower systems configuration work as the devices can configure themselves. For example, if a CT/VT input is feed to an IEC 61850-complied relay, such relay has the ability to detect the model and automatically assign it to a **measurement unit** without the need of external interaction. The other approach is that some devices require an SCL file to configure objects and the only external intervention needed is to import the SCL file into the device to configure. The IEC 61850 client application is then utilized to extract object definition from the device over the network. This approach leads to very large savings in the cost and effort to configure an IEC 61850 device.

The IEC 61850 device model starts with a physical device as illustrated in Figure 6.4. A **physical device** is a device that is connected to the network and uniquely identified by its network address. Each physical device contains one or more **logical devices**. The IEC 61850 logical device model allows a single physical device to act as a proxy or gateway for multiple devices and, therefore, provides a standard representation of a data.

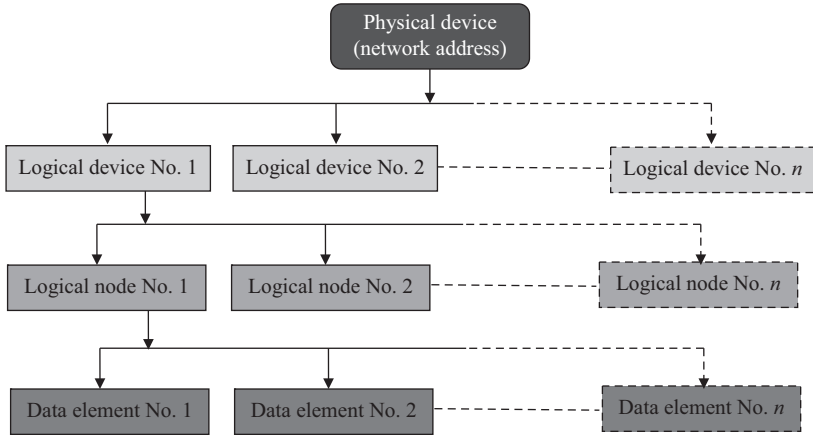


Figure 6.4 The IEC 61850 device model

Each logical device contains one or more **logical nodes (LNs)**. An LN is a name of a group of data and services that is logically associated with a particular power system function as shown in Table 6.2, which illustrates the structure of circuit breaker (XCBR) LN according to IEC 61850-7-4. There are different types of LNs. These include LNs for automatic control whose names begin with letter “A,” metering and measurement whose names start with letter “M,” supervisory control (C), generic function (G), interfacing/archiving (I), system logical nodes (L), protection (P), protection related (R), sensors (S), instrument transformers (T), switchgear (X), power transformer (Y), and other equipment (Z). Each LN has an LN-instance-ID as a suffix to the LN name. For example, if we assume there are two measurement inputs in a device used to measure two 3-phase feeders. The standard name of the LN for a measurement unit for three-phase power is MMXU. To differentiate between the measurements of the two feeders under consideration, the IEC 61850 LN names of MMXU1 and MMXU2 are used. Additionally, to provide further identification for the purpose of the LN, each LN may also use an optional application-specific LN prefix.

An LN may have one or more **data element**, each of which is identified by a unique name. Each **data name** is determined by the standard and functionally related to a power system component. For example a circuit breaker is modeled as an LN with a name XCBR. As an LN it has several data elements, including **Loc** for local or remote operations, **OpCnt** for operations count, **Pos** for position, **BlkOpn** for block breaker open command, **BlkCls** for block breaker close command and **CBOPCap** for the circuit breaker operating capacity.

Each of the data elements within the LN must conform with CDC as specified in IEC 61850-7-3, and each CDC describes the **type** and **structure** of data within the LN. For example, there are CDCs for status information, measured information, controllable status information, controllable analog set point information, status settings, and analog settings. Every CDC has its own specific name and a set of

Table 6.2 The structure of circuit breaker (XCBR) logical node according to IEC 61850-7-4, where *M* and *O* correspond to mandatory and optional, respectively[8]

XCBR class				
Attribute name	Attribute type	Explanation	T	M/O
LNName		Shall be inherited from Logical-Node Class (see IEC 61850)		
Data name	Common data class			
Common logical node				
		LN shall inherit all mandatory data from Common Logical Node Class		M
Loc	SPS	Local operation (local means without substation automation communication, hardware direct control)		M
EEHealth	INS	External equipment health		O
EEName	DPL	External equipment name plate		O
OpCnt	INS	Operation counter		M
Controls				
Pos	DPC	Switch position		M
BlkOpn	SPC	Block opening		M
BlkCls	SPC	Block closing		M
ChaMotEna	SPC	Charger motor enabled		O
Metered values				
SumSwARs	BCR	Sum of switched amperes, resettable		O
Status information				
CBOpCap	INS	Circuit breaker operating capability		M
POWCap	INS	Point-on-wave switching capability		O
MaxOpCap	INS	Circuit breaker operating capability when fully charged		O

CDC attributes, each of which has a defined name, a defined type and a specific purpose. CDC attributes are grouped in categories whereby members of each group consist of individual CDC attributes that belong to a set of functional constraints (FCs). For example, the Single Point Status (SPS) CDC is illustrated in Table 6.3. There are FCs for status (ST) attributes, substituted value (SV) attributes, description (DC) attributes, and extended definition (EX) attributes. In this particular example, the status attributes of SPS class consists of a status value (stVal), a quality flag (q) and a time stamp (t).

According to the IEC 61850, a device model is a virtual model that starts with an abstract view of the device and its objects defined in IEC 61850-7. The abstract is then mapped to a specific protocol stack in IEC 61850-8-1 based on MMS (ISO9506), TCP/IP, and Ethernet. During the process of mapping IEC 61850 objects

Table 6.3 The structure of the single point status (SPS) common data class according to IEC 61850-7-3 [8]

SPS class					
Attribute name	Attribute type	FC	TrgOp	Value/value range	M/O/C
DataSetName	Inherited from Common Data Class (see IEC 61850-7-2)				
DataAttribute					
Status					
stVal	BOOLEAN	ST	dchg	FALSE TRUE	M
Q	Quality	ST			M
T	TimeStamp	ST			M
Substitution					
SubEna	BOOLEAN	SV			PICS_SUBST
SubVal	BOOLEAN	SV		FALSE TRUE	PICS_SUBST
SubQ	Quality	SV			PICS_SUBST
SubID	VISIBLE STRING64	SV			PICS_SUBST
Configuration, description, and extension					
D	VISIBLE STRING255	DC		Text	O
Du	UNICODE STRING255	DC			O
cdcNs	VISIBLE STRING255	EX			AC_DLNDA_M
cdcName	VISIBLE STRING255	EX			AC_DLNDA_M
DataNs	VISIBLE STRING255	EX			AC_DLN_M

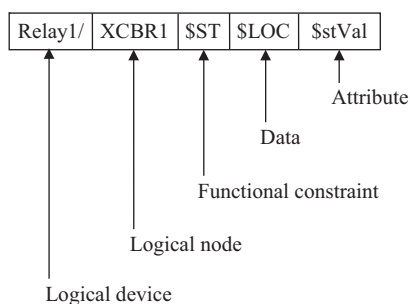


Figure 6.5 The details of an IEC 61850-8-1 object name [after 8]

to MMS, IEC 61850-8-1 specifies a method of transforming the model information into a named MMS object variable that ensures obtaining unique and unambiguous reference of each element of data in the model. For example, assuming we got a logical device called “Relay1” which consists of a single circuit breaker LN called XCBR1. To determine whether the circuit breaker is in remote or local mode of operation, the **IEC 61850-8-1 object** shown in Figure 6.5 needs to be read.

6.7 Mapping process approach of IEC 61850 to protocols

The **abstract data** and the **object model** of IEC 61850 are so designed to provide a standardized method of describing power systems devices that enable all IEDs to present data using identical structures that are directly related to their power system functions. However, the **Abstract Communication Service Interface (ACSI) models** of IEC 61850 are so designed to provide set of services and responses to these services that enable all IEDs to identically behave from the network behavior perspective. The abstract model is critical to achieve this level of interoperability. However, these models need to be operated over a set of real protocols that are practical to implement and can be operated under the computing environment commonly found within power systems industry. To achieve this, IEC 61850-8.1 is initially mapped to the Manufacturing Message Specification (MMS) protocols of ISO 9506. This is because MMS is the only public, that is, ISO standard, protocol that has proven implementation track record and, therefore, can easily support the **complex naming and services models** of IEC 61850. Also while it is possible theoretically to map IEC 61850 to any protocol, the process can get very complex and cumbersome when IEC 61850 objects and services are mapped to a protocol that only provides read/write/report commands for simple variables that are accessed by **register numbers** or **index numbers**. This is why MMS was chosen for UCA in 1991 and also chosen for IEC 61850. MMS is considered a very good choice because it can support **complex named objects** and **rich set of flexible services** that support the mapping to IEC 61850 in a straightforward manner.

The mapping of IEC 61850 objects and service models to MMS is based on a service mapping where a specific MMS service/services are chosen as a means to implement various services of ACSI. For example, the control model of ACSI is mapped to MMS using read and write commands. This is followed by mapping various object models of IEC 61850 to specific MMS objects. For example, the IEC 61850 logical device object is mapped to an MMS domain.

Figure 6.6 displays an overview of IEC 61850 functionality and associated communication profiles [8]. In addition to mapping to the application layer, IEC 61850-8.1 defines profiles for other layers of communication stack that are dependent on the service provided. This is illustrated in Figure 6.6, which shows that the **sampled value** and **Generic Object Oriented Substation Event (GOOSE) applications** map directly into **Ethernet data frame** and consequently eliminate the need of processing any middle layers; the **MMS** connection layer operates on TCP/IP or ISO; and the **Generic Substation Status Event (GSSE)**, which is identical to UCA GOOSE, operates over connectionless ISO. The same figure shows that **all data** maps onto an **Ethernet data frame** using either the data type **Ethertype** in case of **sampled value**, **GOOSE**, **TimeSync**, and **TCP/IP** or the data type **802.3** for **ISO** and **GSSE** messages.

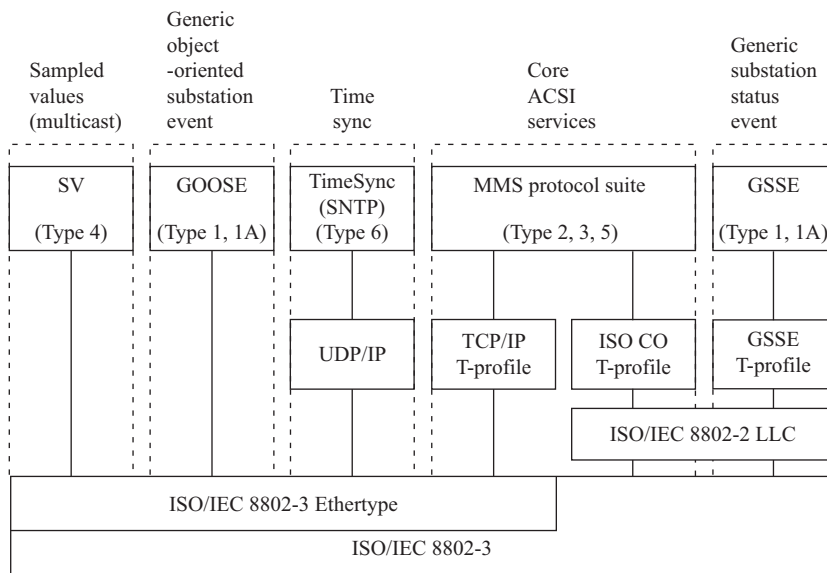


Figure 6.6 An overview of IEC 61850 functionality and associated communication profiles [8]

6.8 IEC 61850 substation configuration language

The substation configuration language is defined in IEC 61850-6.1. It is based on eXtensible Markup Language (XML), which enables describing the configuration of IEC 61850-based systems. The hierarchy of configuration files is specified by SCL. This enables the description of multilevel system in unambiguous and standardized XML files. SCL files including system specification description (SSD), IED capability description (ICD), substation configuration description (SCD), and configured IED description (CID) files are all constructed using the same method and format. However, the scope of each of them is different depending on the need.

In addition to the ability of an IEC 61850 client to extract an IED's configuration from an IED when it is connected to that IED over a network, there are several scenarios whereby the availability of a formal off-line description language can bring enormous benefits to users outside the process of configuring IEC 61850 client applications. Such benefits include:

1. SCL can be used to enable **off-line system development tools** to automatically generate the **files required for IED configuration** from power system design. This obviously eliminates most, if not all, manual configuration tasks and consequently greatly reduces the cost and effort of IED configuration.

2. SCL makes it possible to **share IED configuration** among users and suppliers, which helps in reducing or eliminating the **inconsistencies** and **mis-understandings** in system configuration and requirements. To ensure that IEDs are properly configured, users can provide their own SCL files.
3. SCL makes it possible for IEC 61850 applications to be configured off-line without the need to connect IEDs to a network for client applications.

Substation configuration language may be used to fit the requirements of individual users. For example, a user may decide to use CID files in order to provide help in IED configuration using its existing system design processes. Alternatively, SCL may be used to restructure the entire power system design process aiming at eliminating manual configuration, eliminating manual data entry errors, reducing misunderstanding between system capabilities and requirements, enhancing the interoperability of the end system, and greatly increasing the productivity and effectiveness of power system engineers.

6.9 IEC 61850 substation architecture

Figure 6.7 shows the IEC 61850 substation architecture [8,12]. Basically it consists of several MUs, process bus, several relays scribed to dataset, station bus, and two clocks Clk1 and Clk2.

Merging units are used to collect and digitize data from electronic/optical voltage and current transformers/sensors as well as status information. This layer is known as **process layer**. It is worth mentioning that MUs can be physically located either at the switchyard or inside the control room. Data from MUs are collected by redundant 100 MB fiber optic Ethernet connections. The connection points are Ethernet switches [13], 1 GB internal buses, and 1 GB uplinks that support Ethernet

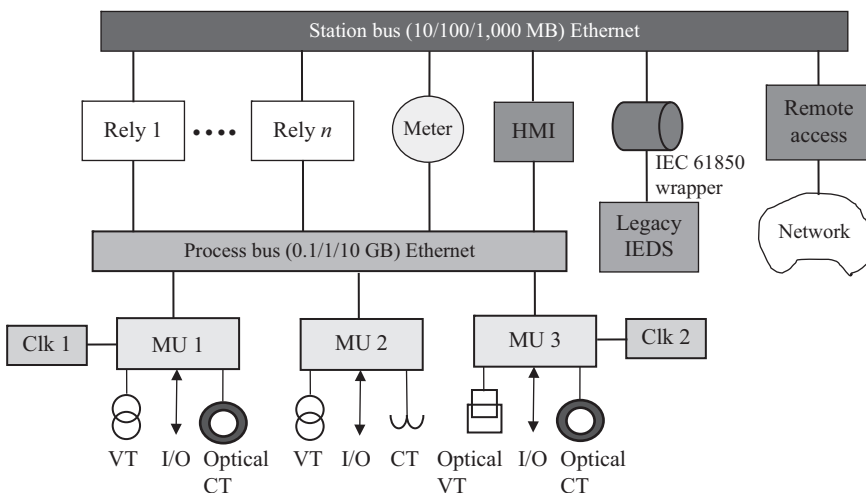


Figure 6.7 IEC 61850 substation architecture

priority and Ethernet virtual local area network (VLAN). The VLAN Ethernet switch ensures delivering datasets only to those switch ports/IEDs that have subscribed to the data.

The reason of having two clocks in the architecture illustrated in Figure 6.7 is that in case Clk1 fails, Clk2 is automatically activated and connected online, which ensures the continuation of providing sampling synchronization.

The substation level consists of **station bus**, which is based on 10 MB Ethernet or above depending on how recent the technology is used. The purpose of this bus is to provide the **primary communication** between the various LNs, which in turn provide various functions performed at the substation including protection, control, monitoring and data logging. Communication system may be operated either on a connection-oriented basis, that is, request of information and configuration, or on a connection-less basis, that is, IEC GOOSE. Redundant communication architecture is preferred due to the strain placed by IED-to-IED data transmission on the communication system, which may lead to its failure.

Figure 6.7 also shows the illustrated architecture that supports **remote network access** for all types of data reads and writes. Since all communication systems are networked, several **remote clients** can get access to the vast variety of available information. Examples of such clients include Human Machine Interface (HMI), operators, maintenance staff, and various engineering and planning departments. The best location for performing security functions such as encryption and authentication is at the remote access point. This ensures relieving the burden on individual IEDs from performing encryption on internal data but at the same time provides security for all external data transfer.

6.10 Smart Grids and IEC 61850

As discussed in Chapter 1, the Smart Grids can be thought of as applications that require **distributed automation** and **a significant information exchange**. In other words, an existing electrical power network can be transformed to a Smart Grid by equipping it with **automation** and **communication infrastructure** [14]. It is important that such infrastructure be flexible so that it can deal with various physical communication channels as well as huge volumes of information and communication requirements. This is exactly what the IEC 61850 concept can handle. It provides a large set of **abstract communication services** [15], which support the many different requirements that can be mapped on the communication technologies. The IEC 61850 also defines a concept for highly standardized, **semantic object models** [16] that can be easily extended to any kind of application.

Smart Grids place a **major focus on smart distribution**, which includes **distributed automation**, **smart aggregation of distributed energy resources into virtual power plant**, and **smart metering and interface**. Several activities both in standardization and in demonstration projects have been conducted to apply IEC 61850 to the first two elements. For example, IEC 61850-7-420 is dedicated to define **object models for distributed generation**. The models developed in the first edition of IEC 61850-7-420 have focused on **combined heat and power (CHP) plants**, **photovoltaic**, **fuel cells**, and **reciprocating engines**.

At the time of writing this book, it was decided to launch several technical reports that describe cases and further models, which include:

- IEC 61850-90-7 for inverter-based applications including scheduling.
- IEC 61850-90-8 for electrical vehicles.
- IEC 61850-90-9 for battery storage devices.

It is also planned to issue IEC 61850-90-6, which deals with distributed automation sometime in the future.

6.10.1 *Example of Smart Grid demonstration projects using IEC 61850*

There are several Smart Grid demonstrating projects worldwide that use IEC 61850-based communication. **Web2Energy** [17] is an example of such a project, which is run by a consortium consisting of 11 European companies funded by EU community. Under this project it is planned to set up a field demonstration that encompasses a complete range of **smart distribution**. A practical feeder is to be transformed in a self-healing grid. Several distributed generation plants of different types including biomass, hydro, photovoltaic, wind as well as battery storage and controllable loads are to be integrated in a virtual power plant. Additionally, about 200 households are to be equipped with smart meters. IEC 61850 will be used by the self-healing grid and distributed generation plants to communicate with the control center over various communication channels. One of the objectives of this project is to establish the three pillars of smart distribution, namely, **network automation**, **smart aggregation**, and **smart metering** (see Figure 6.8).

The aim of network automation is to reduce recovery supply time following interruption from 1 to 2 h range to few seconds. Smart aggregation concerns with

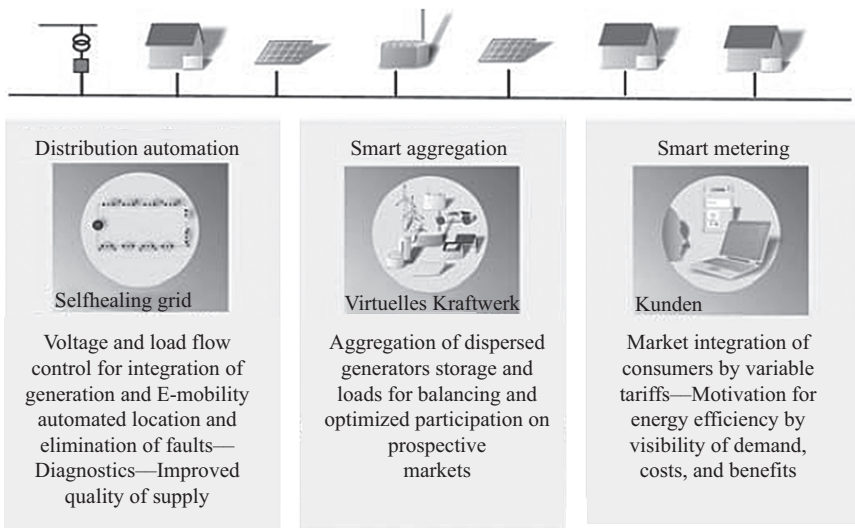


Figure 6.8 *The three pillars of smart distribution [17]*

various decentralized plants that form the **virtual power plant**. The aim of this part is to develop a coordinated strategy between participating plants to maximize their effectiveness. This is achieved by equipping individual plants with RTU and smart meters to be monitored by the virtual power plant and also partially controlled. Finally, the aim of smart metering is to help consumers to manage their use of energy in the best possible way by identifying times at which energy is cheap and, therefore, can consume cost-effective energy and times at which energy is expensive and, therefore, avoid refraining from nonessential energy consumption.

6.11 Summary

This chapter is devoted to the application the international standards IEC 61850 to Smart Grid. An overview of the standards IEC 61850 is given highlighting its relevance to the development of the Smart Grid concept. The discussion started by giving an introduction and background of IEC 61850, its aim and objectives and its structure. The concept of “process bus” is then introduced and its practical implementation discussed. This is followed by discussing the comprehensive modeling approach of IEC 61850 and mapping process approach of IEC 61850 to protocols. Substation configuration language (SCL) as specified in IEC 61850 is then discussed, followed by developing an IEC 61850 substation architecture model. Finally, an explanation as how IEC 61850 can be used to transform conventional electrical power network into Smart Grid is given. This is followed by covering an EU-funded project known as “Web2Energy” that uses IEC 61850-based communication system. In this project the use of IEC 61850 by self-healing grid and distributed generation plants to communicate with the control center over various communication channels was highlighted.

References

- [1] Prat R., Rodriguez G., and Magnago F. ‘Monitoring and controlling services for electrical distribution systems based on the IEC 61850 standard’. *Scientific Research: Energy and Power Engineering*. 2011; **3**(3):299–309. Also Available from http://file.scirp.org/pdf/EPE20110300009_51982430.pdf [Accessed 10 November 2016]
- [2] IEC. *TC 57 POWER SYSTEMS management and associated information exchange* [Online]. Available from <http://tc57.iec.ch/index-tc57.html> [Accessed 17 January 2015]
- [3] Dawidczak H., Dufaure T., and Englert H. *Compatibility of the IEC61850 edition 1 and edition 2 implementations* [Online]. Frankfurt, Germany: CIRED – 21st International Conference on Electricity Distribution; June 2011. Available from http://www.cired.net/publications/cired2011/part1/papers/CIRED2011_0794_final.pdf [Accessed 27 October 2016]
- [4] Andren F., Brundlinger R., and Strasser T. ‘IEC 61850/61499 control of distributed energy resources: concept, guidelines, and implementation’. *IEEE Transactions on Energy Conversion*. 2014; **29**(4):1008–17

- [5] PC Magazine Encyclopedia. *Definition of switched Ethernet* [Online]. Available from http://www.pcmag.com/encyclopedia_term/0,2542,t=switched+Ethernet&i=52318,00.asp [Accessed 26 October 2016]
- [6] Internetguide. *What is TCP/IP (Internet Protocol Suite)* [Online]. Available from <http://www.internet-guide.co.uk/tcp-ip.html> [Accessed 26 October 2016]
- [7] PC Magazine Encyclopedia. *Definition of WAN* [Online]. Available from http://www.pcmag.com/encyclopedia_term/0,2542,t=WAN&i=54193,00.asp#fbid=kEE1yZhyE4- [Accessed 31 October 2016]
- [8] Baigent D., Adamiak M., and Mackiewicz R. *IEC 61850 communication networks and systems in substations: an overview for users* [Online]. Available from <http://store.gedigitalenergy.com/faq/Documents/General/IEC61850.pdf> [Accessed 29 October 2016]
- [9] Schwarz K. *What is a logical node?* [Online]. Germany: SCC; 2014. Available from http://www.nettedautomation.com/download/What-is-a-Logical-Node_2004-08-12.pdf [Accessed 29 October 2016]
- [10] Anombem U.B., Li H.Y., Crossley P., Zhang R., and McTaggart C. 'Process bus architecture for substation automation with life cycle cost consideration'. *The 10th International Conference on Developments in Power System Protection (DPSP 2010)*; Manchester, UK, March 2010, pp. 1–5
- [11] Tholomier D. and Chatrefou D. 'IEC 61850 process bus – it is real'. *Protection, Automation and Control World (PAC World)*. Winter 2008; **3**:48–53
- [12] Liang Y. and Campbell R.H. *Understanding and simulating the IEC 61850 standard* [Online]. Available from <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.176.5160&rep=rep1&type=pdf> [Accessed 12 February 2016]
- [13] PC Magazine Encyclopedia. *Definition of Ethernet switch* [Online]. Available from <http://www.pcmag.com/encyclopedia/term/42788/ethernet-switch> [Accessed 29 October 2016]
- [14] Brunner C. 'IEC 61850 and smart grids'. *Protection, Automation and Control Magazine (PAC World)*. 2011; **16**:27–27
- [15] EPRI. *IEC61850 Part 7-2 – Abstract common services interface* [Online]. Available from [http://xanthus-consulting.com/IntelliGrid_Architecture/New_Technologies/Tech_IEC61850_Part_7-2_-_Abstract_Common_Services_Interface_\(ACSI.htm](http://xanthus-consulting.com/IntelliGrid_Architecture/New_Technologies/Tech_IEC61850_Part_7-2_-_Abstract_Common_Services_Interface_(ACSI.htm) [Accessed 27 October 2016]
- [16] Kreonke D.M. *Chapter 4: the semantic object models* [Online]. Available from https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=3&cad=rja&uact=8&ved=0ahUKEwiY5tqq_rPAhXLCcAKHUBeBQUQFggsMAI&url=http%3A%2F%2Fssyu.im.ncnu.edu.tw%2Fcourse%2FCSDb%2FUnit04.ppt&usq=AFQjCNEciycnCcTa268TzzSe1srTLFZFSG [Accessed 27 October 2016]
- [17] Buchholz B.M. and Styczynski Z.A. *The three pillars of Smart Distribution realized by IEC 61850 communications* [Online]. 2011. Available from https://www.web2energy.com/news-downloads/publications/?tx_drblob...735 [Accessed 27 October 2016]

Chapter 7

Power system protection under Smart Grid environment

7.1 Introduction

Development of the Smart Grid concept that eventually leads to transforming conventional power system to a Smart Grid could profoundly affect the way relaying and protection of power systems are implemented. This is due to the fact that Smart Grid, as discussed earlier, is equipped with several new and advanced technologies including information and bi-directional communication systems, distributed control system, sensors installed at different locations on the Smart Grid, and so on. To take the full advantage of the benefits offered by the Smart Grid concept, there is an urgent need for replacing electromechanical relays, which are still in service in many utilities worldwide, by their microprocessor counterpart [1]. Modern microprocessor relays, which are also known as intelligent electronic devices (IEDs), have several capabilities that suit Smart Grid environment. This includes their capability to record and store current and voltage waveforms before, during, and after fault condition, the time at which the fault occurs, changing the setting, and they have the ability to communicate with other devices. In order to fully take the advantage of these capabilities, these devices must be interconnected, which in turn makes it possible to introduce further capabilities such as Generic Object Oriented Substation Event (GOOSE) [2,3].

This chapter begins with reviewing protection of power system prior to the Smart Grid era and then proceeds to discuss power system protection under Smart Grid environment highlighting the expected benefits. The operating concepts of Smart Grid protection relays will then be explained followed by discussing intelligent fault circuit indicators (FCIs) for Smart Grid applications. Communication infrastructure that suits protection requirements will then be discussed. The architecture of Smart Grid protection system (SGPS) will be discussed highlighting the application of multiagent technology and the relationship between multiagent systems and IEC 61850. This will be further explained by using examples on development of smart adaptive protection systems for microgrids and smart distribution networks (DNs). Finally, the chapter will be concluded by presenting protection system architecture based on IEC 61850.

7.2 Protection prior to the Smart Grid era

Prior to the Smart Grid era, the adopted protection philosophy is based on providing protection to individual equipment at the substation level. This was initially achieved using electromagnetic relays, but more recently these relays have been replaced, in many utilities worldwide, by IEDs. The latter can continuously monitor network operational parameters and therefore determine, via built-in dedicated algorithms, the healthy status or otherwise of the equipment they protect. IEDs have also the capability of recording the data they gather, which are indispensable for postincidents analysis.

At the grid level synchronous phasor measurement units (PMUs), which are capable of gathering information several times during a single power cycle, have been introduced to help in developing a detailed picture of power network's dynamics for planning, control, and postfault analysis [4,5]. However, due to network's limited and out-of-date communication infrastructure, it was not possible using these data beyond the substation in which they are generated.

One of the early use of these rich data is PMU-based wide-area measurement system (WAMS), whereby a large number of PMUs were installed in the Western Grid, USA in the context of Eastern Interconnect Phasor Project. A dedicated communication infrastructure has specifically been installed to support and get the system working [4].

Protection systems are applied locally to safeguard specific components and by central control through the SCADA system. The central control system is too slow, and the protection systems are limited to protection of specific components only [5].

7.3 Protection systems under Smart Grid environment

Performance of protection relays/systems can be enhanced when they operate under Smart Grid umbrella [1]. This is due to two factors. First, information related to changes in power system operation configuration, which is made available as it happened by the Smart Grid structure, is extremely useful that enable transforming the settings of protection relays from being static to dynamic. This means the settings of relays can be programmed to change automatically so that they suite the most recent power system operation configuration immediately after it happened. Second, communication system that constitutes an important and integral part of Smart Grid infrastructure makes it possible for relays to share information with sensors installed on lines, such as FCIs, which in turn improves fault-locating algorithms.

7.3.1 Operating concepts of Smart Grid protection relays

IEDs currently used in protection systems have both data processing and telecommunication capabilities [6]. However, the information and communication technology (ICT), which constitutes an integral part of the Smart Grid, makes it possible to collect real-time wide-area information about power system [7]. This in

turn has enabled IEDs to communicate with each other and to share information about the updated status of configuration of power system. Accordingly, the following concepts for Smart Grid protection relay systems have been proposed.

7.3.1.1 Adaptable to power system configuration changes

The setting of protection relays in conventional power systems are normally fixed. Their values are calculated based on advanced knowledge of power system conditions and also on the assumption of unidirectional power flow, particularly, for the case of DNs. However, relay settings of protection system operating under Smart Grid environment are determined based on supervising the operating and nonoperating margins of each relay characteristic quantitatively to precisely detect changes in power system configuration as it happened utilizing analog input data under normal and faulted conditions. The benefits gained from adopting this approach include modifications of relay settings to suit actual power system configuration and check the coordination of each protection relay element based on wide-area data, and detection of the critical point of system operations [7].

7.3.1.2 Intelligently collecting protection relay data

The operating concept of Smart Grid protection relays can be realized by applying agent systems. Agents may be defined as active, social, and adaptable software system entities situated in some environment and capable of autonomous execution of actions in order to achieve their set objectives [8]. An agent system has the ability to intelligently collect protection relay data and also evaluate data from wide-area protection relays without having any effect on protection functions. By applying this approach it is possible to update the applications executed inside protection relays without the need to take equipment out of service [7].

7.3.2 Fault circuit indicator

A fault circuit indicator (FCI) is a device that is designed to provide visual or remote indication of a fault on power system. It is normally used in DNs to automatically detect and identify faults and consequently help in reducing the outage time. FCIs are installed on overhead lines as well as underground cables. Overhead FCIs are used to visualize the occurrence of an electrical fault on an overhead line, while underground FCIs are used to locate faults on underground cables.

(i) Operating principles of FCIs

When a fault occurs on a conductor of a grounded system, the FCI senses the magnetic field produced by the fault current flowing through a conductor [9]. Consequently, the FCI “trips.” The trip status can be shown by the FCI either by changing the state of a mechanical flag, an LED (light emitting diode) display flashing, or by a remote indication device.

The operating principle of FCIs used for ungrounded systems is based on sensing the sum of the currents flowing through the three phases. It operates if the sum is higher than a threshold value that is normally caused by an imbalance condition due to a fault on one or more of the three phases.

(ii) **Intelligent fault circuit indicator for Smart Grid applications**

A key requirement to achieve the full benefit and functionality of conventional FCIs is the availability of maintenance staff along distribution feeders to check the mechanical flag change or LED flashing display to find out the fault location. The procedure can be laborious, particularly, for situations whereby FCIs are smudged because they are not periodically cleaned. Therefore, to maximize the benefits of FCIs and to reduce fault-location time by reporting fault status back to control center, which in turn would lead to significant and immediate improvement in reliability and hence improve the electricity service supplied to customers, a ZigBee-/communication interface-based intelligent FCI that suits Smart Grid applications has been proposed [10-12].

ZigBee is one of many types of wireless networks. It is a low-speed low-rate wireless area personal network (LR-WPAN), which is based on the IEEE 802.15.4 standard. ZigBee was chosen because the protocol it uses is a general-purpose protocol with low-cost and low-power-consumption wireless communication.

Figure 7.1 shows a schematic diagram of the ZigBee-based intelligent FCI [10,11]. It basically consists of three main components: fault current detecting module, ZigBee module, and microcontroller unit (MCU) module. The RF transceiver used in the ZigBee module is microchip MRF24J40MB, which is compatible with the IEEE 802.15.4 standard and has the transmitting range up to 4,000 ft (1,219.2 m). In the MCU module, the microchip PIC18LF4620 is used, which features 10 MIPS (million instructions per second) performance, C compiler optimized RISC (reduced instruction set computer) architecture, 8×8 single cycle hardware multiply, lower idle power consumption, 13 ADC channels with 10-bit resolution and 100k samples per second, Serial *Peripheral* Interface (SPI), and inter-integrated circuit (I2C) peripheral.

The fault current detecting module is made of two magnetic reed switches and an LED-based alarm. If the two magnetic reed switches are called SW1 and SW2 with high and low rated interrupting currents, respectively, then SW1 is used to detect abnormal currents flowing through a distribution feeder, while SW2 is used to detect normal currents of the feeder. Generally, the value of the high rated interrupting current

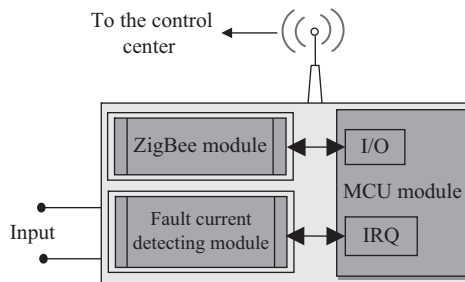


Figure 7.1 Hardware architecture of the ZigBee-based fault circuit indicator [after 11]

is set approximately to the value of the rated short-circuit current of a distribution feeder, typically 600 A or 1,000 A, while the value of the low rated interrupting current is set to the minimum recovery current. This is typically equal to 12 A. Three modes of operations, normal, fault, and restoration modes, can be identified depending on the position status of SW1 and SW2 as explained below:

Normal mode: If the magnitude of feeder current on which the intelligent FCI is installed is smaller than that of the rated interrupting current of SW1, then SW1 remains in its OFF position, that is, open circuit. This corresponds to the normal mode of operation of the intelligent FCI. It will be noted that the status of SW2 in this mode of operation is not important and, therefore, may be ignored.

Fault mode: When the magnitude of the current of the feeder on which the intelligent FCI is installed becomes greater than that of the rated interrupting current of SW1, the latter assumes ON position, which indicates the occurrence of a fault on the feeder. Consequently, the fault condition is detected by the external interrupt of the MCU module related to SW1. The information related to the fault is then transmitted, by the wireless network represented by the ZigBee modules, to the rear-end processing system. This includes parameters such as feeder number and location. The MCU also enables the LED-based alarm built into the fault current detecting module and the external interrupt for SW2. The intelligent FCI then assumes the restoration mode.

Restoration Mode: As mentioned earlier, after the occurrence of a fault the intelligent FCI assumes the restoration mode. When the power of the feeder section under consideration is restored following the clearance of the fault, the magnitude of the feeder current will obviously be less than that of the rated interrupting current of SW1 but higher than the magnitude of the rated interrupting current of SW2. Consequently, the latter assumes ON position. This condition is detected by the external interrupts of the MCU module for SW2, which is transmitted to the rear-end processing system. The LED-based alarm is then turned off, which leads the intelligent FCI to return back to the normal mode.

7.4 Smart Grid communication infrastructure that suits protection requirements

A Smart Grid communication infrastructure that satisfies protection requirements should have the following characteristics: **security**, **dependability**, **time**, and **reliability**. The definitions of these characteristics are given below [1].

- **Security:** It is the ability of the communication system to refrain from an incorrect operation or misinterpretation of data. This should not be mixed up with cyber security. Because cyber-security breach can lead to data corruption. However, the system itself should have the ability to deal with corrupted data and act on it correctly.

- **Dependability:** It is the ability of the communication system to operate or deliver data whenever requested.
- **Time:** It is the time period a signal/message takes to travel starting from its initiation at its origin until its actual delivery to its final destination. Requirements are normally based on the total time, which may be made up from several sub-time parts. When the architecture varies or problems exist, sub-time parts become important.
- **Reliability:** It is the capability of communication system to consistently deliver the requirements of the above three characteristics.

7.5 Smart Grid requires smarter protection

Under Smart Grids environment, abundant and precise information is made available with the help of introduction of nonconventional instrument transformers (NCIT) [13], IEC 61850, advanced metering infrastructure (AMI), WAMS, etc. The information and communication technologies that are specifically developed to support Smart Grid make it possible for protection devices to use and process such abundant information, which in turn enables protection devices to make correct decisions more easily [14].

However, Smart Grid environment poses new challenges to protection devices due to excessive employment of controllable devices, such as FACTS and HVDC, as well as use of centralized and distributed renewable energy sources (RES), and energy storage systems. This necessitates protection devices to be smarter. Their performance must be high in terms of their **speed** of operation, **security**, and **sensitivity**. They might be described by being **3s** protection devices.

Recently a special attention has been given for investigating and developing smarter protection capable of meeting the new challenges imposed by Smart Grid environment by innovatively taking advantage of abundant information. This goal can be achieved by adopting the following three approaches [14]:

- (i) Efficient use of information at the local bay level
- (ii) Integration of substation information
- (iii) Use of integrated wide-area information

(i) *Efficient use of information at the local bay level*

Currently the operation of most existing protection devices is based on the information obtained at local bay. For example, a distance relay operates using current and voltage signals that are measured locally, and a line-differential relay operates using current signals that are obtained from the terminals of the line. Using information at the local bay independently from other bays and/or other stations provides several benefits including **fast response** and **high security**. The introduction of microprocessor relays has enhanced the performance of protection devices using local bay information. Microprocessor relays make it possible to use the wide-frequency spectrum of local signals.

This in turn has led to improve the performance of protection relays in terms of their **speed**, **reliability**, and **sensitivity**. An example of such relays is the traveling wave-based relays [15], which are characterized by being of ultra-high-speed operation and immune from swings, CT saturation, and fault resistance, and it becomes possible to develop and apply new mathematical tools, protection principles, and algorithms that proved to be useful in extracting more useful information from the measured signals. An example is the protection principles based on superimposed components [15] and secondary disturbance components [16,17].

Under Smart Grid environment, performance of protection devices can be further enhanced by smarter utilization of local bay information by developing novel protection principles and algorithms. An example of such principles is the development of fast power swing unblocking element for distance protection [14]. Application of NCIT can also maximize extracting the information embodied in local bay signals. NCIT has no magnetic core and, therefore, has much better linear characteristics compared to conventional CT. This enables NCIT to truly scale down primary current and voltage signals without losing any of their properties. This in turn makes them capable of handling very large frequency bandwidth signals, and therefore, they are very suited to traveling-wave-based protection relay applications.

(ii) ***Integration of substation information***

Information integration as applied to power system is considered as one of the main features of Smart Grid that has led to many advantages. This is particularly true at the substation level. The extensive use of the standard IEC 61850 inside the substation makes information sharing within the whole substation much more reliable, fast, and economically feasible. Part 9-2 of the standard, that is, IEC 61850-9-2, specifies the mapping of analog sampling over bidirectional bus type serial link, which allows the multiuse of data, changing the parameters of electronic current and voltage transformers/transducers, and transmission of supervision data, commands, and trip signals. The defined GOOSE communication can be used to coordinate several IDEs to realize special applications such as interlocking and trip commands.

(iii) ***Use of integrated wide-area information***

The continued integration of distributed energy resources (DERs), distributed generation (DG), storage systems, and electric vehicles into electrical networks, in recent years, has increasingly led to operating power systems in flexible as well as complex manner. This in turn raised the need of having highly flexible and adaptive protection systems. Successful operation of such protection systems is highly dependent on the information fed to them. Recent advancements in **information and communication technology** as well as **advance standard and communication** such as **wide-area measurement and control systems** (WAMACS) have enabled the creation

of **wide-area information integration** (WAI) for protection systems. Such information integration has opened huge opportunity for protection improvement as WAI makes it possible for protection to recognize changes in operation as well as fault conditions as soon as it happened. This has led to introducing new concepts such as “**network protection**” and “**wide-area protection**.” Protection systems designed based on these new concepts make it possible not only protecting individual power system components but also the network.

Similar to information integration inside a substation, the information collected within WAI about the network is an invaluable tool that enables protection systems to recognize the precise picture of all changes to which the network is subjected to and consequently adapt themselves in terms of maintaining their maximum sensitivity and selectivity that suit the most up-to-date operating condition of the network.

7.6 Architecture of Smart Grid protection system

Architecture of SGPS must be based on the efficient use of the computing power of the IEDs located at different locations and connected to each other using a high-speed communication network [6]. It is important to ensure maximizing the performance and flexibility of SGPS. This can be achieved by distributing various tasks and functions to various IEDs, in other words, applying “distributed intelligence.” This approach can be implemented using the IEC 61850 standard [18,19] as a framework, which provides a consistent way to handle the protection and automation system information. By applying the well-defined object-oriented data model of the IEC standard, it is possible to enable interoperability between devices from different vendors.

It will be noted that the IEC 61850 standard was initially developed aiming at substation automation. However, new data models have been developed to extend the application possibilities of the standard. One such model is the part IEC 61850-7-420, which defines the object models related to DERs [20].

The functional elements are considered as the lowest level of functions in the standard. They are represented as logical nodes (LNs). LNs are located in certain physical devices (PDs). The latter are commonly constituted from IEDs. An IED normally contains several LNs. The actual protection or control function can be formed from a number of LNs. The LNs used to form a single function can be distributed among several PDs. This is achieved by defining logical connections (LCs) between the LNs so that they can communicate with each other and act as a single unit. LC between different PDs uses either one or multiple physical connections (PCs).

In this hierarchical object model, the distributed intelligence can be applied so that the physical location of each LN in a function is carefully selected among the involved IEDs. However, in some cases it may be more convenient to take part of the measurement from a distant IED, while in other cases it is necessary to operate

a circuit breaker LN (XCBR) by an IED from other location. More advanced functionalities would be achieved by processing the measurements at various locations and transmitting only the processed data from various locations to the protection function making the final decision. These examples should serve giving some idea of the practical meaning of distributed intelligence.

SGPS need to be adaptive. In order to meet the adaptability requirements, some control functions must be provided to initiate the necessary actions in response to changes of the grid state. The aim of these “master” functions is to continuously monitor the grid status and accordingly adjust the action of other functions following predefined rules. The basic role of these master functions is to:

- Activate and deactivate protection functions and
- Adjust the settings of protection functions.

Additional task may be allocated to master functions that may involve adjusting the available functions in case there is indication of any malfunction in the Smart Grid system. For example, a failure of communication system as SGPS heavily depends on the communication.

It will be noted that the IEC 61850 standards focus on definition of the communication and data encapsulation and do not provide any basis for specifying functions. Therefore, it is not possible to rely only on these standards to develop applications where the active functions, such as the master functions mentioned above, have a central role. This can be resolved with the help of the IEC 61449 standard, which is specifically developed for function block definitions [21]. Using the IEC 61449 standard together with IEC 61850, it is possible to create flexible and adaptable protection and control systems.

(i) ***Application of multiagent technology***

Distributed intelligence-based applications can be realized by employing automated agent technology, which is commonly known as multiagent system [6]. A multiagent system is a combination of several agents that communicate with each other to achieve a common goal. In this context, an agent is basically an autonomous software entity that operates without human intervention, and it is also able to react to changes that occur in their environment. Multiagent systems are characterized for being proactive, which means that they may take initiatives in order to achieve the goal. Recently multiagent systems are replacing SCADA system to control and monitor the operation of electric power systems. Their capabilities have led to successfully apply them for Smart Grid control [22].

(ii) ***Multiagent systems and IEC 61850***

The LNs defined in the IEC 61850 standard can also be considered as intelligent agents [23]. Using this approach, an application is presented as an agent system that approximately resembles an IEC 61850 object model. The aim is to give generic description of protection system functionalities without having possible limitations of IEC 61850. The basic unit (BU) of the protection system, in this

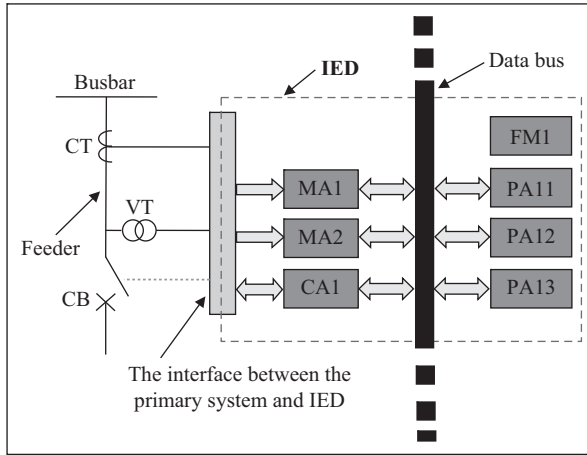


Figure 7.2 Basic unit of the proposed protection system [after 6]

approach, is defined as consisting of a circuit breaker (CB) together with the associated measurement devices and an IED. This is illustrated in Figure 7.2, which consists of a primary system represented by a feeder section, an IED, and measuring devices represented by current and voltage transformers. The IED has several agents. For the case under consideration, this includes measurement agents MA1 and MA2, a control agent CA11, a function management (FM) agent FM1, and protection agents PA11, PA12, and PA13. In the same figure, the thick vertical line represents the data bus that is extended beyond the IED boundaries by the telecommunication links. The figure also shows the interface between the primary system and the IED.

The function of measurement agents is to process the raw measurement data received from the measuring device and send it to the other agents requiring the data, while the function of control agents is to control the actions performed by the primary system, for example, opening and/or closing the breaker. Referring to Figure 7.2, it can be seen that within an IED there are several protection agents whose role is to perform the actual protection functions. Finally, FM agents are used to achieve the required adaptability. This is done by:

- Monitoring the system state and accordingly.
- Adjusting the protection functions in response to the changes taking place in the system.

The adjustment of the protection functions involves activation and deactivation of specific protection functions and specifying suitable protection settings as well as adjusting the associated communication between involved agents. Obviously, the number and roles of the needed FM agents depend on the system design. A general principle could be that a single FM agent is allocated to take care of a basic protection function, for example, an overcurrent, in a single protection zone.

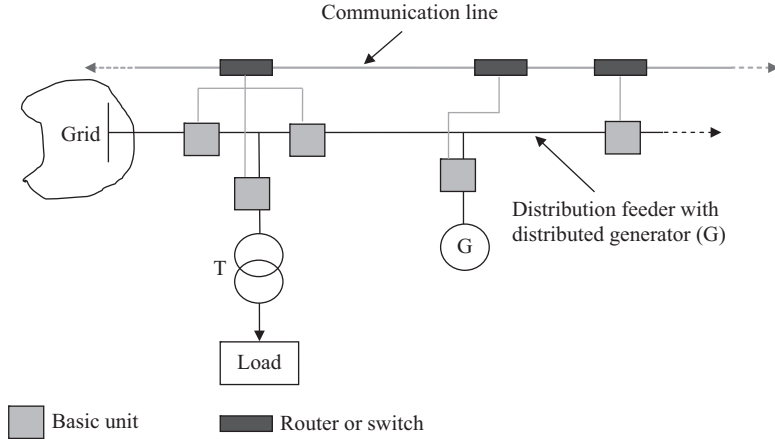


Figure 7.3 A distribution feeder with basic units [after 6]

It is important to note that the structure and components of the BU depends on its location in the power system. However, it usually consists of at least a CB and an IED capable of controlling it. This is to ensure the necessary functionality of the primary system represented by disconnecting the faulted section and switching the backup connections. In addition to these two basic components, the BU includes both current and voltage measuring devices as shown in Figure 7.2. Under certain circumstances, such as the need to synchronize islanded part of the network back to the main grid, two voltage devices are installed one at each side of the CB.

Figure 7.3 shows a section of an electric DN that contains several BUs. Three different types of nodes are used in this network. These are as follows:

- Switch station feeding a satellite distribution substation
- Distributed generator
- Line breaker

Figure 7.3 also shows the communication system alongside electric DN. The key nodes used for the communication system are either routers or Ethernet switches. In situations where several BUs are located in one place, such as the switching station shown in this case, the arrangement shown in this figure is considered the most suitable one. In cases where there is only one BU located at one location, it might be possible integrating the communication interface and the BU together.

7.7 Examples on development of smart adaptive protection systems

In this section two examples related to development of adaptive protection systems will be discussed. The first example is specifically developed for microgrids applications while the other one suits medium-voltage smart DN applications.

7.7.1 *Smart adaptive protection for microgrids*

Perhaps a good example that shows the development of smart protection using wide-area information integration is the development of **adaptive protection system** dedicated to microgrids application [24]. A microgrid is a low-voltage DN into which small-scale (micro-sources) DERs, such as solar, wind, hydro and storage systems, are integrated [24,25]. A microgrid may be defined according to the U.S. DOE [22] as an integrated energy system consisting of interconnected loads and DERs which as integrated system can operate in parallel with the grid or in an intentional island mode.

Therefore, microgrids can be operated either connected to medium-voltage DNs, that is, grid-connected or in islanded mode. The large number of scenarios a microgrid can be operated due to the connection and disconnection of micro-sources and its operation in grid-connected and/or isolated modes poses huge challenges to protection systems, in terms of their selectivity and sensitivity. This is due to the following reasons:

- Isolation of the microgrid from the main grid due to a fault condition on the main grid could lead to substantial drop in the value of the short-circuit level available to protection devices installed within the microgrid. When this happens, it would greatly undermine the sensitivity of these protection devices.
- Changes in connection status of micro-sources would, obviously, affect currents' magnitude and direction throughout the network. This in turn would affect both sensitivity and selectivity of protection devices within the microgrid.
- In certain circumstances sub-islands might be created due to abnormal events within the microgrid, which in turn could cause mal-operation of protection devices.

It is obvious that the dynamic operation of microgrids described above requires a dynamic and smart approach to the settings of protection devices capable of making their settings adaptable to the operating changes of the microgrid. This example will be used to explain how this can be achieved.

7.7.1.1 **Definition of the problem**

Consider Figure 7.4, which shows a typical microgrid network consisting of two radial feeders connected to a medium-voltage DN [24]. As the figure shows, several DERs are integrated into the network. The DERs may include wind, photovoltaic (PV) panels, fuel cells, and batteries. The microgrid network is formed when the circuit breaker CB1 is opened. Operating this network in this way presents huge challenges to protection devices due to the following factors:

- Magnitude of short-circuit current in islanded microgrid mode of operation can be very much less than its value in grid-connected operation, which adversely affects the sensitivity and selectivity of protection relays.
- Short-circuit current required for the operation of overcurrent (OC) relays highly depends on the connection point and feed-in of micro-sources. Consequently, short-circuit currents can vary both in the magnitude and the direction.

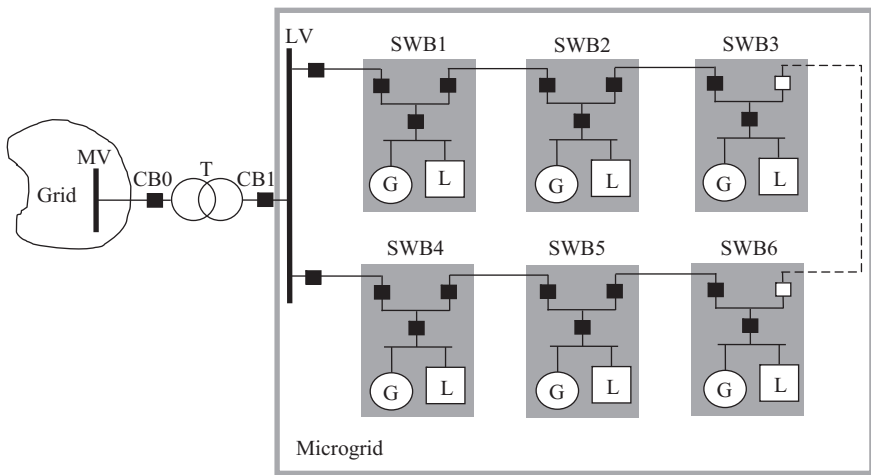


Figure 7.4 Typical microgrid network consisting of two radial feeders connected to a medium-voltage distribution network [after 24]

- Due to the intermittent nature of micro-sources using wind and solar and periodic variation of load, the operating condition of microgrid is constantly changing.
- Certain types of renewable energy-based generators, for example, photovoltaic, are interfaced to the grid via power electronic (PE) devices. These devices can limit the magnitude of short-circuit current during fault conditions, which could pose challenges to protection devices, particularly, in islanded-microgrid operation mode.
- In order to meet losses minimization and other economic targets, the topology of the network needs to be changed regularly.
- Island networks of different size and content might be formed as a result of faults on the main grid or within the microgrid.

Any of the above factors or combination of them makes generic OC protection with single setting unable to function properly and also could lead to loss of relay coordination. In order to accommodate the consequences due to the factors listed above, in terms of **available short-circuit current, generation level, network topology, formation of islands, and load variation**, a new protection philosophy based on dynamically adaptive settings need to be contemplated as a viable solution to protection of microgrids.

7.7.1.2 Solution

In order to equip the microgrid shown in Figure 7.4 with a protection system that features dynamically adaptive settings capable of automatically changing its relay settings in response to any changes in the status/operating condition of the networks or any of its components, the network needs to be equipped with a centralized adaptive

protection system (CAPS) having the following main components: (i) a microgrid central controller (MGCC), (ii) a communication system, and (iii) sensors installed on all CBs with all associated relays must be of numerical type equipped with communication capabilities. Figure 7.5 shows the microgrid shown in Figure 7.4 equipped with a centralized adaptive protection system and communication system. The CAPS works as follows: Data are polled from individual protection devices that enable MGCC reading electrical parameters and the status of individual CBs. The obtained information is used by a dedicated unit in the MGCC to decide whether changing the settings, that is, the tripping characteristics, of a particular relay is needed or not. The tripping command is decided by each relay locally independent of MGCC.

When a CB is tripped in response to an abnormal condition, the MGCC updates the topology of the network and consequently activates its dedicated unit responsible for periodical checking, which eventually leads to modification of relay settings if it is needed. The relay settings that suit the most up-to-date topology of the network are obtained either from off-line fault analysis or from on-line fault analysis.

Off-line fault analysis: An **event table** is generated by conducting off-line fault analysis that covers a wide range of scenarios that considers all possible configurations including both network topology and feeding-in states of DERs. This is followed by calculating relay settings for every considered scenario that ensure proper operation of protection devices for the scenario under consideration. The resultant relay settings are then tabulated in an **action table** that has the same dimension as that related to the event table.

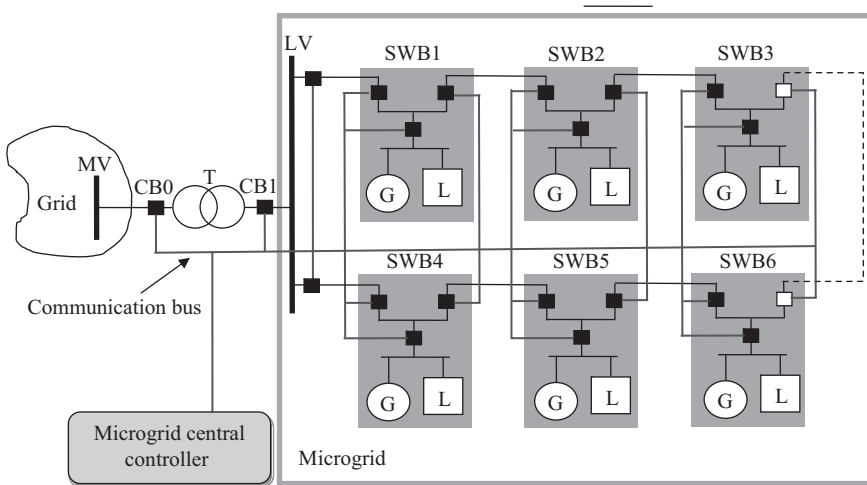


Figure 7.5 The microgrid shown in Figure 7.4 equipped with a centralized adaptive protection system and communication system [after 24]

If the MGCC during its periodical checking detects a change in the configuration of the network, the information related to the new configuration is used to construct a **status record** that has the same dimension as that of the event table. The corresponding relay settings are then retrieved from the action table and uploaded them into the effected protection relays.

On-line fault analysis: As the name implies, the process of updating relay settings in response to changes in network configuration is carried out in real time. If the real-time measurements obtained from the MGCC periodical checking reveal the need to update the relay settings as a consequence of network configuration changes, an online fault analysis is carried out and the results obtained are used to determine the corresponding new relay settings.

7.7.2 Adaptive protection for smart distribution networks

In this context it is important to remember the differences between conventional DN and its smart DN counterpart. Compared to conventional DN, smart DN is particularly characterized by being [6] (i) able to accommodate different types of DG with various output powers. (As stated previously, this resulted in bidirectional flow of power. This in turn remarkably affects the operation of protection system.), (ii) able to perform self-healing (This implies that the system has the capability of continuing the power supply following any kind of disturbances. In the case under consideration, one possibility to achieve the self-healing functionality is to switch over to island operation when a fault occurs somewhere in the network. As far as protection is concerned, when this happens, protection devices must have the ability to adapt protection configuration that suits the new system state.), and (iii) able to automatically perform backup connections, which also helps in achieving self-healing feature. This is done by intelligently rerouting the supply in the event of certain fault cases. For the case related to the commonly radial operated distribution feeders, they usually have open points (switches or line CBs) designated as backup connections as shown in Figure 7.6. Under fault conditions these

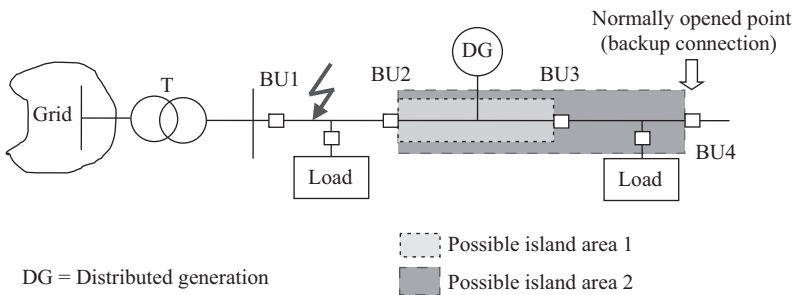


Figure 7.6 Typical distribution feeder equipped with BUs and a backup connection point, where DG is distributed generation [after 6]

switches/CBs need to be automatically closed, but at the same time, the faulted section must be isolated from both sides.

7.7.2.1 Definition of the problem

Consider the distribution feeder shown in Figure 7.6, which is supplied from a grid. It contains a DG that may consist of several generating units and a single backup connection point. The feeder is assumed to be divided into several segments using CBs connected along the line. The figure also shows some loads that are in real life represented by distribution substations supplying several customers. Figure 7.6 also shows that this network is equipped with the necessary BUs, which are connected to a fast communication network that allows communication between all the devices in the electric network. Each BU may contain several different protection agents that are all controlled by FM agents. The FM agents continuously monitor and assess the state of the network and consequently change the settings of different agents and their operating status according to predefined set of rules.

The rules are usually created beforehand to match all possible network changes and faults to achieve the best condition that suit the connection status of the network. When an FM agent detects a change in the system that matches one or more of these rules, it triggers the corresponding settings for the protection agents.

The FM agents control the agents that are active and consequently control the protection settings that are in use. In this example, some of the basic functionalities of the protection system will be demonstrated.

It is assumed that the feeder is subjected to a fault on the section between BU1 and BU2 as shown on Figure 7.6. The task of the protection agents is to clear the fault and disconnect the smallest possible part of the network. After the isolation of the faulted BU1–BU2 section, the remaining healthy part of the network may operate using one of the following scenarios:

- Scenario No. 1: Maintain the operation of BU2–BU3 section, which contains both load and generation in synchronism with the main grid by closing the normally open point (backup connection) at BU4.
- Scenario No. 2: Operate the healthy network as an islanded network or a microgrid, which is supplied from DG.

In both scenarios, associated protection systems need to be adaptive as discussed below.

Scenario No. 1

When a fault is detected, the protection agents compare fault directional information to decide the faulty section. The sequence of detecting the faulty section in this example may be summarized as follows:

- BU1 (refer to Figure 7.6) detects the fault in the forward direction of its location and consequently sends this information down the feeder to all other BUs over the line.

- Additionally, the fault information is sent to the DG together with interlocking command for a short duration necessary to clear the fault.
- BU2 detects the fault in the backward direction of its location and by comparing the directional information received from BU1 and, accordingly, determines that the fault must be between BU1 and BU2. Consequently, BU1 and BU2 disconnect the faulty BU1–BU2 section from the network.
- Additionally, a command is sent to BU4 to close the backup connection point to maintain the healthy part of the network connected to the main grid.
- The interlocking of generating units is cancelled following the clearing of the fault.
- The information related to the events described above is sent to FM agents, which make them aware of network topology changes.
- Accordingly, FM agents respond by requesting the associated protection agents to change their settings taking into account the new network topology reality.

Scenario No. 2

Operate the healthy network as an islanded network or a microgrid, which is supplied from DG installed at BU2–BU3 section.

As mentioned previously, a possible way to achieve self-healing in Smart Grids is operating in a controlled island mode of operation. Therefore, in the example under consideration, an islanded network or a microgrid may be formed from the healthy part of the network that contains DG. The size of such an island is determined by the amount of generation available and the load connected. In other words, the balance between the generation and load consumption must be ensured when creating an island. The information required to create an island consists of the power flow at the CBs, which define the boundary of such an island and are also used to disconnect the island from mains. Therefore, the task of agents is to determine the power flow at various BU locations and, accordingly, dynamically change the possible island size, using collected data, until the generation-load consumption balance criterion is maintained. In the example under consideration, there are two possible island areas. The first area is spanning from BU2 to BU3 while island area 2 can be formed between BU2 and BU4 as shown in Figure 7.6.

7.8 Protection system architecture based on IEC 61850

The ability of IED devices to handle multiple protection and control functions on one hand and the recent development of IEC 61850 standard, which makes it possible for IEDs, supplied by different vendors to communicate with each other and therefore exchange high-level data between them, has opened the way to innovatively redesign substation protection systems compared to existing practices. This has led to a new protection system architecture based on IEC 61850 [26]. One of important features of the new protection system architecture is to optimizing the

cost/performance ratio without sacrificing redundancy and reliability requirements, which can be achieved by reducing the number of protection IEDs required to perform protection and control functions as specified by existing practices. The benefit gained from such an exercise is major cost saving. The way to realize this is by **selectively activating** required protection functions within each bay IED. The latter is achieved by combining substation protection and bay level protection in a decentralized system.

7.8.1 Traditional practices

Traditionally, the standard practice adopted by utilities is to keep bay control functions separated from protection systems. Consequently, the multifunctional capability of the numerical protection relays was not fully exploited in the protection and control scheme applications. This in turn has led to allocating separate IEDs for main 1 and 2 functions [26]. However, the improvement in reliability has led to combining protection and control functions as an integrated function in the bay control IED. Examples of control functions include CB fail, OC, synchronizing, and delayed auto reclosing (DAR). Generally, busbar protection is kept as a standalone system using either high- or low-impedance principles.

7.8.2 New opportunities offered by the introduction of IEC 61850 standard

International standard IEC 61850 describes the concepts for substation communications covering protection, control, and metering functions [27]. It facilitates the interoperable exchange of communication between IEDs from different vendors. Its introduction, therefore, has opened the opportunity for utilities to make use of modern technology to redesign their secondary protection system while maintaining reliability and redundancy. Such a move requires the revision of the currently adopted specifications to take advantage of new developments and therefore to reduce the cost, maintenance routines, and spares [26]. It has also provided guidelines for future developments as how to move from traditional systems to the next generations of “computer” relays. This in turn makes it possible to embed a large number of protection functions in a single IED device. Consequently, as soon as analog inputs and plant status information are made available to an IED, customized solution for a particular application can be worked out, which can be communicated with IEDs from other manufacturers [26].

The experience gained from various IEC 61850 projects worldwide has shown the benefits utilities can have in terms of simplicity, flexibility, and standardized engineering. Such benefits include shorter commissioning times, higher availability, efficient diagnosis and service, and easy expandability, which are considered as important factors that can lead to reduction in overall costs of an installation over its lifetime.

To demonstrate the benefits gained from using multifunction capability of IEDs and interoperability based on communication protocol IEC 61850, four types

of protection and control system architecture have been considered [26]. They are labeled as simplified protection and control system architecture type 1, type 2, type 3, and type 4. Station protection and bay level protection in a decentralized arrangement were utilized. To compare the saving of hardware between the proposed new protection and control system architecture and conventional system, a study was conducted using a typical substation that consists of four overhead line feeders, three transformers, two bus couplers, and one bus section. The comparison is made between conventional approach and the proposed architecture type 4. The outcome of the study shows the following solution:

1. Solution based on conventional approach

The hardware are as follows:

- 4 × Line Protection Type 1
- 4 × Line Protection Type 2
- 3 × Transformer Protection Type 1
- 3 × Transformer Protection Type 2
- 10 × Bay Control Units
- 1 × Centralized BBP
- Disturbance Recorder

2. Solution based on the proposed approach

The identified hardware are as follows:

- 10 × Bay Unit Supplier 1
- 10 × Bay Unit Supplier 2
- 1 × Central Unit Supplier 1
- 1 × Central Unit Supplier 2
- Integrated Disturbance Recorder

Additionally, the advantages that can be gained from adopting the proposed protection system architecture include the following:

1. Decentralized system of individual bay unit ensures fast clearance of faults and reliable fault isolation within the bay.
2. The total number of IEDs can be reduced by half. This in turn means overall reduction in cost, spare parts, hardware, engineering, commissioning, maintenance, space, copper cable, etc.
3. The number of CT core requirements is reduced.
4. Reliability and availability are enhanced due to continuous self-supervision of individual bay unit and central unit.
5. Securing integrated disturbance recording for optimal fault evaluation.
6. Securing integrated event recording for optimal fault evaluation.
7. Spares stocking levels are reduced due to adaptation of modular design.
8. Software is the main factor that defines functionality.
9. The total project cost and execution time is reduced.
10. The availability of the complete system can be improved due to maintaining the redundancy of source, application, and communication.

7.9 Summary

Development of the Smart Grid concept could profoundly affect the way the relaying and protection of power systems are implemented. This chapter is therefore devoted to discuss power system protection under Smart Grid environment. Initially, an overview of the protection prior to the Smart Grid era is given. This is followed by discussing relaying protection under Smart Grid environment highlighting the expected benefits. The operating concepts of Smart Grid protection relays and intelligent fault circuit indicator for Smart Grid applications are then covered. This is followed by discussing the communication infrastructure that suits protection requirements. How Smart Grid requires smarter protection is then explained. This is followed by discussing the architecture of Smart Grid protection system highlighting the application of multiagent technology and the relationship between multiagent systems and IEC 61850. Examples on development of smart adaptive protection systems are then given. These include smart adaptive protection for microgrids and adaptive protection for smart DN's. The chapter is concluded by presenting protection system architecture based on IEC 61850 under which two topics were covered: smart adaptive protection for microgrids and new opportunities offered by the introduction of IEC 61850.

References

- [1] Simon M. 'The smart grid communication infrastructure for protection: designing to the highest common denominator'. *Protection, Automation and Control Magazine*. March 2011; **15**:18–25
- [2] NETEON. *What is GOOSE (Generic Object Oriented Substation Event)* [Online]. Available from http://www.neteon.net/PDFFiles/Goose_Generic-Object-Oriented-Substation-Event.pdf [Accessed 7 May 2011]
- [3] ABB. *High-speed busbar protection with GOOSE* [Online]. Available from https://library.e.abb.com/public/de69878cebade451c125754a00238b42/REF615GOOSE_HighSpeed_article_756767_EN.pdf [Accessed 30 April 2016]
- [4] Hauser C.H., Bakken D.E., and Bose A. 'A failure to communicate'. *IEEE Power and Energy Magazine*. 2005; **3**(2):47–55
- [5] Iyer G. and Agrawal P. 'Smart power grids'. *42nd Southeastern Symposium on System Theory (SSST)*; Tyler, TX, 2010, pp. 152–55
- [6] Kauhaniemi K. and Voima S. *Adaptive relay protection concept for smart grids* [Online]. Vaasa, Finland; 2012. Available from http://www.vei.fi/files/pdf/701/SMART_AND_MICRO_GRID5_Full_paper.pdf [Accessed 19 March 2016]
- [7] Kawano F., Baber G.P., Beaumont P.G., *et al.* 'Intelligent protection relay system for smart grid'. *Tenth IET International Conference on Developments in Power System Protection (DPSP 2010). Managing the Change*; Manchester, 2010, pp. 1–5

- [8] Lapouchnian A. *Modeling mental states in requirements engineering – an agent-oriented framework based on i* and CASL*, MSc thesis [Online]. Toronto, Canada: York University; 2004. Available from <http://www.cs.toronto.edu/~alexei/pub/MScThesis.pdf> [Accessed 20 April 2016]
- [9] Schweitzer Engineering Laboratories (SEL), Inc. *Fault indicators and sensors* [Online]. 2014. Available from https://cdn.selinc.com/assets/Literature/Publications/Product%20Catalogs/FIS_Catalog_2014.pdf [Accessed 9 March 2016]
- [10] Luan S., Teng J., Chen C., and Liu Y. *Development of an intelligent fault indicator for smart grids* [Online]. Singapore: IACSIT Press; 2011. Available from <http://www.ipcsit.com/vol6/5-E011.pdf> [Accessed 7 March 2016]
- [11] Luan S., Teng J., and Chen C. 'Development of a novel fault indicator for distribution automation'. *International Journal of Information and Electronics Engineering*. 2011; **1**(2):105–109
- [12] Teng J., Huang W., and Luan S. 'Automatic and fast faulted line-section location method for distribution systems based on fault indicators'. *IEEE Transaction on Power Systems*. 2014; **29**(4):1653–62
- [13] Liu K., Shenxing S., Dong X., and Bo Z. 'Study of non-conventional instrument transformer and IEC61850 impact on current differential protection'. *IEEE Conference on Transmission and Distribution and Exposition (IEEE/PES 2008)*; Bogota, Latin America, 2008, pp. 1–6
- [14] Su B. and Li Y. *Trends of smarter protection for smart grid* [Online]. Available from http://www.aesieap0910.org/upload/File/PDF/4-Technical%20Sessions/TS48/TS4804/TS4804_FP.pdf [Accessed 4 April 2011]
- [15] Johns A.T. and Salman S.K. *Digital protection for power systems*. Peter Peregrinus Ltd, IEE Power Series 15; 1995
- [16] Bo Z.Q., Welled G., Dai F.T., and Yang Q.X. 'Transient based protection for transmission lines'. *Proceeding of the International Conference on Power System Technology, POWERCON'98*; Beijing, 1998, pp. 1067–71
- [17] Xia M.C. and Huang, Y.Z. 'Wavelet analysis in transient-based protection for power system high voltage transmission line'. *Proceeding of the International Conference on Wavelet Analysis and Pattern Recognition (ICWAPR)*; Qingdao, 2010, pp. 427–30
- [18] Adamiak M., Baigent D., and Mackiewicz R. *IEC 61850 communication networks and systems in substations: an overview for users* [Online]. Available from http://www.gedigitalenergy.com/multilin/journals/issues/Spring09/IEC_61850.pdf [Accessed 13 April 2016]
- [19] Baigent D., Adamiak M., and Mackiewicz R. *IEC 61850 communication networks and systems in substations: an overview for users* [Online]. Available from <http://store.gedigitalenergy.com/faq/documents/general/iec61850.pdf> [Accessed 13 April 2016]
- [20] IEC. *IEC 61850 Part 7-420 DER logical nodes (FDIS) – communication networks and systems for power utility automation for distributed energy*

resources (DER) [Online]. IEC. Available from <http://osgug.ucaiug.org/srgsystems/OpenAMIEnt/Shared%20Documents/AMI-ENT1.0/USB%20Docs/DER%20Logical%20Nodes%20FDIS%2057-61850-7-420.pdf> [Accessed 5 April 2016]

- [21] Higgins N., Vyatkin V., Nair N.K.C., and Schwarz K. 'Distributed power system automation with IEC 61850, IEC 61499, and intelligent control'. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*. 2011; **41**(1):81–92
- [22] Pipattanasomporn M., Feroze H., and Rahman S. 'Multi-agent systems in a distributed smart grid: design and implementation'. *IEEE/PES Power Systems Conference and Exposition, PSCE'09*; Seattle, WA, 2009, pp. 1–8
- [23] Apostolov A., 'Multi-agent systems and IEC 61850'. *IEEE Power Engineering Society General Meeting*; Montreal, Quebec, 2006, pp. 1–6
- [24] Oudalov A. and Fidigatti A. *Adaptive network protection in microgrids* [Online]. Available from <http://www.microgrids.eu/documents/519.pdf> [Accessed 4 May 2016]
- [25] Lasseter R.H. 'Microgrids'. *Proceeding of IEEE Power Engineering Society Winter Meeting*; New York, NY, 2002, pp. 305–08
- [26] Muthu K. and Chidambaram R. 'Simplified protection system architecture based on IEC61850 for the next generation IEDs'. *Tenth IET Conference on Developments in Power System Protection (DPSP 2010). Managing the Change*; Manchester, 2010, pp. 1–5
- [27] Redfern M.A., Sun X., An W., Crossley P.A., Yang L., and Grasset H. 'IEC61850 and designs for future relays'. *Tenth IET International Conference on Developments in Power System Protection (DPSP 2010). Managing the Change*; Manchester, 2010. pp. 1–6

Chapter 8

Application of Smart Grid concept to distribution networks

8.1 Introduction

As stated in Chapter 2, conventional electrical power system normally comprises generation, transmission, distribution, and consumers' load subsystems (networks). The conventional role of distribution network is to transfer electrical power supply from generation and transmission subsystems to consumers' loads. It is this direct connection between a distribution network and consumers that makes distribution network directly responsible to guarantee the quality and reliability of the electrical supply [1]. It is, therefore, expected that by transforming conventional distribution network to a Smart Grid, the quality, reliability, and security of electrical power supplied to customers would be directly affected.

This chapter presents a comparison between conventional and smart distribution networks, discusses the reasons behind the need for smart distribution networks, and covers the basic components (building blocks) of a smart distribution network, the path that has been followed to transfer conventional distribution networks into smart distribution networks.

8.2 Smart distribution networks versus conventional distribution networks

A conventional distribution network (DN) is characterized as being [2]: (i) passive, (ii) the power flow through it is unidirectional, whereby the power flows from transmission network to consumers' loads, (iii) the focus is placed on feeder automation, i.e., improving energy availability or continuity, which means ensuring—(a) medium voltage (MV) fault location when a feeder is subjected to a fault condition, (b) reconfiguration of distribution network as required by network's condition, (c) ensuring MV distribution loop management, and (iv) no interaction between the network and consumers connected to it.

In contrast, a smart distribution network (SDN) is characterized as being: (i) active [2], (ii) has the ability to give access to distributed energy resources (DERs) including renewable energy sources (RESs), (iii) the power flow through it is bidirectional due to the integration of DERs [2], (iv) automation of its feeders

getting smarter, compared with those of conventional DNs, in terms of the ability to [2]—(a) locate MV faults under multidirectional power flow as well as the ability to monitor the power flow and (b) perform energy demand management in terms of LV load management and monitoring transformer temperature overload—and (v) capable of providing the environment for consumers to interact with it and with the market [1].

8.3 Why distribution networks need to be smart?

In recent years, several developments have been made that affected directly the way distribution networks should operate. This in turn makes the application of Smart Grid concept to these networks necessary. Such developments include:

- (i) Liberalization of the electricity market [3],
- (ii) Continued trend of integrating distributed energy resources, including renewable energy sources, into distribution networks which has led to transforming these networks from being passive into active. This in turn has led to fundamental shift in distribution network management from passive to active management [3], and
- (iii) Development of intelligent domestic appliances.

These developments have fundamentally changed the functionality of distribution networks. It has been identified that the functionality of future distribution network needs to be smart at four levels as follows [4]:

- (i) **Distribution network level:** This level involves equipping the network with (i) more automated MV distribution networks with self-healing capabilities, (ii) monitoring and controlling LV networks, and (iii) supporting the network with information and communication technology (ICT) infrastructure.
- (ii) **Integration level:** This level concerns with efficiently integrating distributed energy resources, including renewable energy sources, electric vehicles, and electricity storage and aggregation into distribution networks.
- (iii) **Energy management level:** This level concerns with the management of end-use energy efficiency, aggregation, and retail.
- (iv) **Customers level:** Distribution network should have the capability of handling smart customers which would be aware and actively participating in the operation of distribution network.

8.4 Basic building blocks of a smart distribution network

In addition to conventional distribution network and the associated information and communication system (ICS), several components or devices need to be incorporated to them to be able to obtain a working smart distribution network. In this section, we shall give a brief description of such components or devices that form

the building blocks of a smart distribution network. This will also facilitate the discussion of the remaining of this chapter. The building blocks include:

8.4.1 Agents

In the context of smart distribution networks, an agent is a device that can be either a physical entity or a virtual entity, that is, with no physical existence [5]. The physical entity agent acts in the environment whereby it is designed to directly control a distributed energy resource. The virtual entity agent is essentially a piece of software that makes bids to the energy market or stores data in a database.

8.4.2 Characteristics of agents

The main characteristics of agents are as follows:

- **Autonomy:** Agents have a certain degree of autonomy. This means that they can take decisions without the interference of a central controller or commander. This is achieved by driving them by a set of tendencies. For example, a tendency for a battery system could be “to charge the batteries when the price for the kWh is low and the state of charge is low too.” Thus, the multiagent system decides when to start charging the battery based on its own rules and goals and not by an external command. In addition, the autonomy of every agent is related to the resources that it possesses and uses. For example, these resources could be the available fuel for a diesel generator, the wind for a wind-turbine generator, or the sunlight for a photovoltaic generator.
- **Capable of acting in their environment:** This means that agents have the ability of perceiving the changes in the environment in which they are found within and consequently they respond to such changes with their own actions whenever necessary. For instance, by altering the power production of a generator, the set points of the other local units are consequently changed.
- **Have proactive ability:** This means that agents have their own goals and do not just act in response to changes that have occurred in their environments. They also initiate actions to try to achieve their goals. In multiagent systems, an agent has certain behaviors and tends to satisfy certain objectives using its **resources**, **skills**, and **services**. An example of these skills could be the ability to produce or store power, and an example for the services could be the ability to sell power in a market. The way that the agent uses the resources, skills, and services characterizes its behavior. Consequently, the behavior of every agent is decided by its goals. An agent that controls a battery system whose goal is to supply uninterruptible power to a load will have different behaviors than a similar agent, whose primary goal is to maximize profits by bidding in the energy market.
- **Have social ability:** This means that agents can communicate with each another via agent communication language (ACL). This may be considered as part of their capability for acting in the environment. As an example, let us consider a system that includes a wind-driven generator and a battery system: the battery system uses power from the wind generator to be charged when

wind blows, while it is discharged when wind stops blowing. In order to optimally achieve this operation, two agents are needed to exchange many messages. This is considered as a social type of action because, with the two agents communicating with one another, the environment is essentially altered in a different way than if the two agents were acting without any kind of coordination.

- Have partial or no representation of the environment: For example, the agent of a generator, in a power system, knows only the voltage level of its own bus and, possibly, it can estimate what is happening in certain specific buses. However, the agent does not know what is happening in the whole system. This is the core of the multiagent system technology, since the goal is to control a very complicated system with minimum data exchange and minimum computational demands.

8.4.3 *PowerMatch*

As the name implies the PowerMatch is a concept whose implementation leads to a close match between the electrical supply and demand. It is also considered as a market-based control concept for supply and demand matching (SDM) in electricity networks with a high penetration of distributed generation [6]. The main objective of SDM is to optimize the difference between electrical supply and demand, which is achieved by using the expected electricity generation and devices' consumption, to alter their operation in order to increase the overall match between electricity production and consumption. PowerMatcher is implemented such that each device is represented by a control agent, which tries to operate the process associated with the device in an economical optimal way. The electricity consumed or produced by the device is, respectively, bought, sold by the device agent on an electronic exchange market.

8.4.4 *E-terra trade*

The E-terra trade is a family of energy software [7,8] developed by industry that is geared to both market players and market managers, such as independent system operators (ISOs), distributed system operators (DSOs), and transmission system operators (TSOs)/regional transmission organizations (RTOs) [7]. This software, which is designed to help suppliers formulate and submit bids, is normally integrated into standard energy management systems. Tools suitable for ISOs, DSOs, and TSOs/RTOs include secure HTML-based visualization systems, enabling markets to be evaluated from different points of view, plus a trademarked market clearing system.

8.4.5 *E-terra control*

E-terra control is a software platform developed by industry. It may be defined as a network-based distributed system that implements simple, reliable, high-performance SCADA across a wide area network (WAN) [9]. It has an infrastructure built using the latest web-based technology. Its purpose is to support standard SCADA system and to integrate multiple enterprise functions and view real-time data across the entire business.

E-terra control is focusing on flexibility to adapt [10]. It is anticipated that application of Smart Grid concept would lead to getting involved with an

unprecedented number of acquisition devices, including remote terminal units (RTU), intelligent equipment devices (IED), and ever growing number of smart meters. The key to the solution would be a scalable SCADA, with capabilities to manage a wide diversity of equipment which e-terra control would provide.

A SCADA system that would suit a Smart Grid environment needs to be more than reliable and scalable, and changes to the system must be integrated quickly without affecting the performance or availability of the system. E-terra control is designed such that it allows for changes to occur online to both the database and displays, while the system is running and performing critical SCADA functions.

In addition to the fundamental SCADA functions, e-terra control offers a wide range of advanced functions, while keeping fast learning curve. This includes the following [9]:

- Real-time data viewing and processing
- Alarm processing and filtering
- Alarm acknowledgment and deletion
- Equipment and device tagging
- Flexible calculation package
- Windows-based powerful user interface
- Network topology processor
- Abnormal state and tagging summaries
- Event and alarm logging
- Audible alarm annunciation
- Real-time trending

8.5 Evolvment of distribution networks into Smart Grids

Both USA and Europe have led the way to transform existing distribution networks to be smart through initiating appropriate projects led by electricity industry with participation from stake holders including academia, manufacturers, and regulatory bodies. Two such projects which are initiated by EU, namely FENIX [11] and ADDRESS [12] will be briefly discussed in the following sections.

8.5.1 *Flexible Electricity Networks to Integrate the eXpected Energy Evolution (FENIX)*

It has been recognized that one way to achieve the reduction in greenhouse gas emissions and the dependency of many industrialized countries on fossil energy imports is by using distributed energy resources (DER) units including local renewable energy sources (RES). Until recently, the adopted policy used for connecting DER/RES units is generally based on a so-called fit-and-forget approach. The continued deployment of these units in large scale has made such an approach not sustainable because it:

- Adversely affects the deployment rates of DER/RES units,
- Increases the costs of investment and operation of the electric power system, and
- Affects the integrity and security of the system.

It has been suggested that the way forward to address these problems is by ensuring that DER/RES units take their share in providing the flexibility and controllability necessary to support secure system operation together with large conventional power plants. Historically, transmission system operators (TSOs) have been responsible for the security of the electric power system. With integration of DER/RES units, which usually occurs at distribution networks, it becomes vitally important that distribution system operators (DSOs) must operate their network actively using local resources. This represents an important shift from traditional central control philosophy, which until recently, used to control typically hundreds of generators to a new distributed control concept applicable for the operation of possibly millions of generators and controllable loads. DER/RES units are too small and numerous to be visible or manageable on an individual basis.

The solution of this problem is suggested by introducing the concept of a virtual power plant (VPP) by clustering DER/RES units into a portfolio that has similar characteristics to transmission-connected generation.

8.5.1.1 The concept of VPP

The concept of VPP was introduced as a mechanism that enables the integration of DERs/RESs units into electrical distribution networks [14]. Using this concept, individual DERs/RESs units can gain access and visibility across energy markets, and benefit from VPP market intelligence to optimize their position and maximize revenue opportunities. Additionally, the operation of distribution networks can benefit from optimal use of all available generation capacity connected to them, as well as ensuring an increased efficiency of operation. The VPP also makes DERs/RESs units visible to the system operator and presents a resource that can be used for active control of electricity networks.

The concept of virtual power plant is defined as [11,13,14]:

A Virtual Power Plant (VPP) aggregates the capacity of many diverse DERs, it creates a single operating profile from a composite of the parameters characterizing each DERs and can incorporate the impact of the network on aggregate DERs output. A VPP is a flexible representation of a portfolio of DERs that can be used to make contracts in the wholesale market and to offer services to the system operator. There are two types of VPP, the Commercial VPP (CVPP) and the Technical VPP (TVPP). DERs can simultaneously be part of both a CVPP and a TVPP.

Figure 8.1 illustrates the concept of VPP whereby a 132 kV/33 kV/11 kV distribution network together with its integrated distributed energy resources and the loads connected to it, shown within the loop of Figure 8.1(a), are aggregated together and represented as an equivalent single generator/load system connected at 400 kV transmission voltage point as shown in Figure 8.1(b). It is important to keep in mind that the characteristics of the equivalent single generator/load system should be the same as the overall original 132 kV/33 kV/11 kV distribution network together with its integrated distributed energy resources and the loads

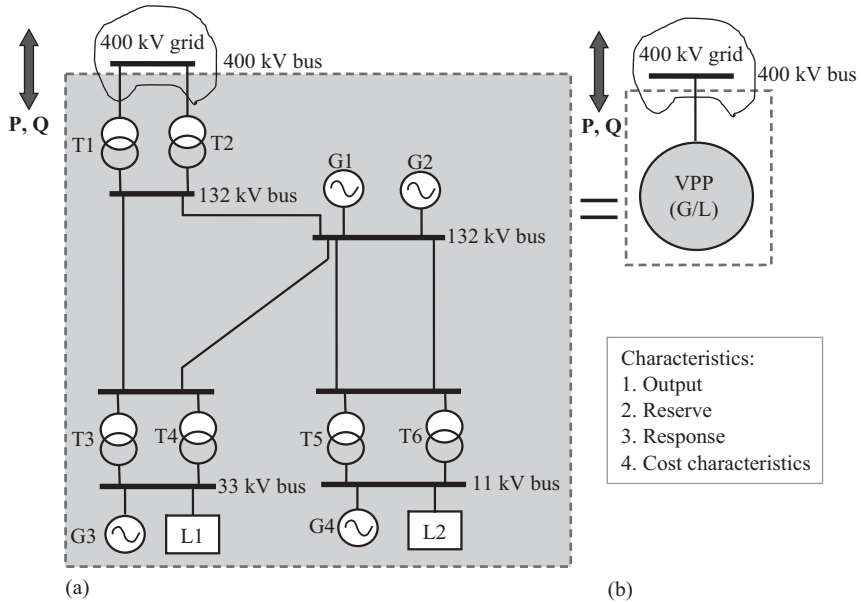


Figure 8.1 The concept of virtual power plant [after 11]

connected to it. Such characteristics include (i) output, (ii) reserve, (iii) response, and (iv) cost characteristics.

Distributed generators and responsive loads cannot be fully integrated into system operation and market-related activities due to their size and huge number. This problem can be overcome by introducing the VPP concept, whereby individual characteristics from a portfolio of DERs are aggregated, so that it can be used in a manner similar to transmission-connected generation.

Similar to any large-scale generator, the VPP can be used to facilitate DER trading in various energy markets and can also provide services to support transmission and distribution system management. Market participation and system management and support activities are described, respectively, as “commercial” and “technical” activities, corresponding to the concepts of commercial VPP (CVPP) and technical VPP (TVPP) [11].

8.5.1.2 Commercial virtual power plant and the commercial benefits of VPP aggregation

The commercial virtual power plant (CVPP) is a representation of a portfolio of distributed energy resources that can be used to participate in energy markets in the same manner as transmission-connected generating plant. CVPP is characterized by an aggregated profile and output which represents the cost and operating characteristics of the DER portfolio. It is important to note that the impact of the distribution network is not considered in the aggregated CVPP profile. However, having DER in the portfolio reduces imbalance risk associated with individual

market participation and provides the benefits of diversity of resource and increased capacity achieved through aggregation. By adopting CVPP, distributed energy resources can benefit from economies of scale and market intelligence to maximize their revenue opportunities.

Functionality of CVPP includes: (i) trading in the wholesale energy market, (ii) balancing of trading portfolios, and (iii) provision of services that are not location-specific to the system operator. The operator of a CVPP can be any third party or balancing responsible party with market access, such as an energy supplier.

In systems allowing unrestricted access to the wholesale markets, CVPPs can represent DERs from any geographical location in the system. However, in markets where energy resource location is critical, the aggregated portfolio is restricted to include only DER from the same location (i.e., distribution network area or transmission network node). Under such circumstances, a CVPP can still represent DER from various locations, but aggregation of resources must occur by location, resulting in a set of DER portfolios defined by geographical location. Figure 8.2 summarizes the inputs to and output from CVPP activity [11].

8.5.1.3 Technical virtual power plant and system management perspective of VPP

Technical virtual power plant (TVPP) tackles aggregation of distributed energy resources units with respect to services that they can offer to the grid [14]. It consists of distributed energy units located at the same geographic area. It is represented by an aggregated profile which includes the influence of the local network on the portfolio output and also represents the DER cost and operating characteristics. The functionality of TVPP includes: (i) local system management for DSO and (ii) providing system balancing and ancillary services to TSO. The operator of a TVPP requires detailed information about the local network, which makes DSO the best candidate to take this role. The TVPP makes energy resources connected to the distribution network visible to the system operator and therefore makes it possible for distributed generation and demand to contribute to transmission system management. The TVPP can also facilitate the use of distributed energy resource capacity in the distribution networks if active network management is required.

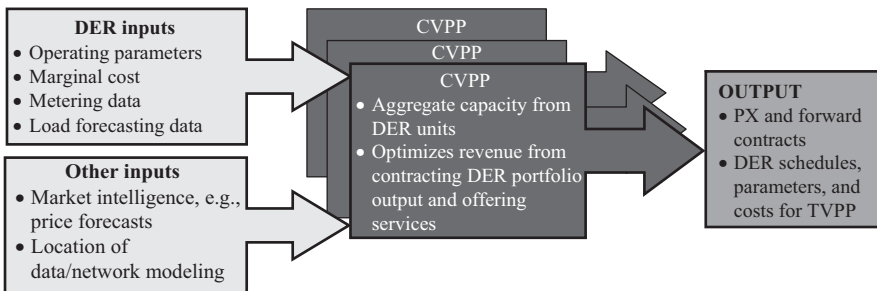


Figure 8.2 Inputs to and output from CVPP activity [after 11]

TVPP aggregates and models the response characteristics of a system containing distributed generation, controllable loads, and networks within a single geographical grid area. In essence TVPP provides a description of subsystem operation. A hierarchy of TVPP aggregation may be created to characterize systematically the operation of DER at low, medium, and high voltage regions of a local network. However, at the distribution–transmission network interfaces the TVPP presents a single profile representing the whole local network (see Figure 8.1). This technical characterization is equivalent to the characterization that the transmission system operator has of transmission-connected generation.

8.5.1.4 Large-scale VPP

Large-scale VPP (LSVPP) can be defined [11] as an aggregation of a large number of DER units that may include different DER technologies, responsive loads, and storage devices which, when integrated, would lead to a system that has a flexibility and controllability similar to large conventional power plants. In this context, DER technologies include wind turbine generator (WTG) systems, photovoltaic (PV) systems, hydroelectric power (Hydro) stations, and combined cooling, heating, and power (CCHP) systems.

The concept of LSVPP can be used to fully integrate DER and demand-side participation. In order to achieve this, distributed control approach needs to be implemented. This in turn requires the design of appropriate distributed control system architectures as well as developing communication and information infrastructures.

Additionally, an appropriate market and commercial structure need to be put in place to support the exchange of services among all actors including TSOs, DSOs, and VPPs. For this reason, the EU in its project FENIX has initiated three interdependent subjects of research to establish the basis for the operation of future highly decentralized electricity supply systems. These include the development of:

- The distributed system control architecture,
- The information and communication architecture, and
- The supporting market and commercial structure.

8.5.1.5 Practical implementation of CVPP

According to the study outcome conducted under the EU project FENIX [11], a practical CVPP consists of the following components (see Figure 8.3):

- An e-terra trade software tool such as Areva e-terra trade together with an intraday process optimization (IPO) that can manage the CVPP as an entity in the market. This tool can be responsible for maintaining bilateral trade positions, generation capacity and schedules, and market bids and offers.
- An e-terra control software platform that provides a flexible and scalable SCADA (a real-time data acquisition software platform) server such as Areva e-terra control that can manage the SCADA system of the DERs that are integrated into distribution network.

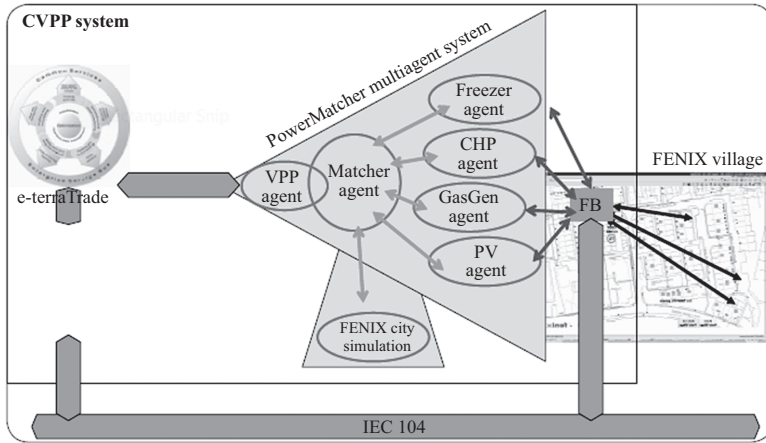


Figure 8.3 Illustration of the components used in Northern Scenario FINEX CVPP system [11]

- A PowerMatcher for aggregating the DERs to a composite unit for e-terra trade and disaggregates instructions back to the DERs. Such tools consist of a market specific VPP Agent interface, core Matcher Agent for aggregation/disaggregating, and individual agents for different types of DER.
- Smart meters at DERs
- DER interface boxes referred to in Figure 8.3 as FENIX box (FB) that are installed at each DER whose function is to facilitate remote access for monitoring and control.

8.5.2 Active Distribution network with full integration of Demand and distributed energy RESourceS (ADDRESS)

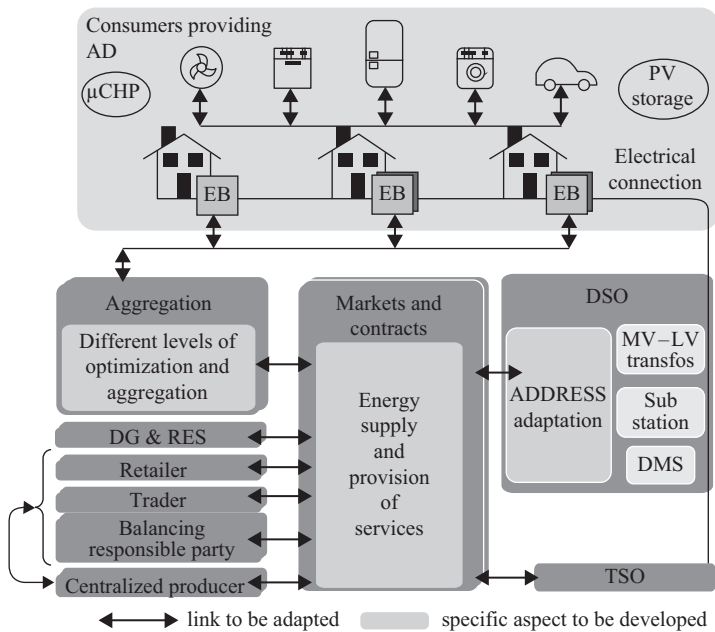
In the Smart Grids context a large-scale R&D Project coded as ADDRESS was initiated and cofounded by the European Commission in 2008 under the Seventh Framework Programme [15,16] aiming at the “Development of Interactive Distribution Energy Networks.”

ADDRESS for **Active Distribution network with full integration of Demand and distributed energy RESourceS**. The aim of the project is to develop a comprehensive commercial and technical framework for the development of “Active Demand” and the market-based exploitation of its benefits. In this context, “Active Demand” (AD) means the active participation of domestic and small commercial consumers and prosumers, that is, both consumers and producers of electricity, in the electricity markets and in the provision of services to the other electricity system participants. AD involves all types of equipment that may be installed at the consumers’ premises. This includes electrical appliances (“pure” loads), distributed generation, such as PV or microturbines, and thermal or electrical energy storage systems.

In order to enable interoperability among participants in data exchanges, various methods, tools, and international standards were used in the ADDRESS project. ADDRESS is considered the first European project that used IEC-CIM information model to define semantic exchanges between ADDRESS actors [16].

8.5.2.1 ADDRESS architecture

Figure 8.4 shows a simplified representation of the ADDRESS architecture [12,16]. The top box contains the consumers and prosumers that provide AD. Examples of these include domestic loads (refrigerators, washing machines, electric cookers, etc.), electric vehicles, microcombined heat and power generators, microwind turbine generators, PV generation units, and electrical energy storage systems. The AD providers are interfaced with the aggregator, represented by the left-hand side box underneath the AD box, by energy management boxes (EB). However, as the figure shows, the aggregator is also interfaced to the “Market and Contractor,” represented by the middle box placed under the AD box. In addition to the aggregator, the “Market and Contractor” is also interfaced to other electricity market



where

AD = Active demand	PV = Photovoltaic generation unit
DG = Distributed generation	RES = Renewable energy source
DMS = Distribution management system	Transfos = Transformers
EB = Energy management box	TSO = Transmission system operator
MV = Medium voltage	μCHP = Microcombined heat and power generation unit
LV = Medium voltage	

Figure 8.4 Simplified representation of ADDRESS architecture [12]

players, including DG and RES, retailers, traders, balancing responsible party, central electricity's producers, DSOs, and TSOs.

In the ADDRESS architecture, the aggregator is considered a central player. It is defined [12] as a deregulated participant whose main function is to mediate between consumers/prosumers, who offer their "demand flexibilities" for sell, and the markets where the aggregators offer (sell) these flexibilities for the use of the other electricity system players. In other words, it may be said that the aggregator purchases consumers'/prosumers' flexibility, packages it into tradable AD products, and then sells these products on the markets to electricity system participants. In this context, "demand flexibility" is equal to modifications in consumers' consumption and/or prosumers' electricity production. Consequently, this implies that an aggregator [12]:

- Acts as the gateway to consumers and prosumers for managing their flexibility,
- Must have a very good knowledge of consumers and prosumers at all levels, and
- Must have the ability to manage the risks associated with AD. More precisely these risks are related to price and quantity.

8.5.2.2 ADDRESS concepts

Apart from the aggregator being a central player, the ADDRESS is based on the following main concepts [12]:

(i) Interaction between the power system participants:

Such an interaction is based on the exchange of **real-time price signals and volume signals** (mainly power-based signals). In this context, "real time" means a time scale of 20–30 minutes ahead or longer, which could be an hour ahead, a day ahead, etc. These signals may additionally be modulated by geographical/topological information or other type of information whenever is needed. It is important to note that as far as this concept is concerned, direct load control by DSO is not considered but load limit must be observed to insure the security of the grid operation.

(ii) Demand approach (in contrast to "generation" approach):

It is important to develop an appropriate approach that deals with domestic and small commercial consumers. Such approach would involve:

- Development of appropriate technologies at consumers' premises.
- The services are "requested" through appropriate price and/or volume signal mechanisms and provided on a voluntary and contractual basis.
- Dealing with societal and behavioral aspects is based on the results obtained from studying the accompanying measures.

(iii) Provision of distributed intelligence and local optimization

Such a provision is needed to:

- Deal with topologically dependent services.
- Allow the participants to optimize their real-time response according to the real-time signals.

It is important to highlight that the challenge related to this concept is to put the "right amount" of intelligence at the "right place."

8.5.2.3 ADDRESS participants and the AD services provided to them

With reference to Figure 8.4, it can be seen that in addition to aggregators and consumers, the following two types of participants can be identified [12]:

- Regulated participants: These include DSOs and TSOs.
- Deregulated participants: These are the competing participants and may be divided into the following three main categories:
 - **Electricity producers:** Include central electricity producers, decentralized electricity producers, and producers with regulated tariff and obligations (reserve, volume, curtailment, etc.)
 - **Intermediaries:** These include retailers, production aggregators, electricity traders, electricity brokers, and balancing responsible parties (BRPs).
 - **Consumers:** These include large consumers.

In order to identify and describe the possible services that AD can provide to the participants, the needs and expectations of all the participants with respect to “active demand” must be analyzed on the basis of their functions and stakes. Based on this process, 24 different AD services for the nine deregulated players and seven different AD services for DSOs and TSOs have been identified.

In order to formulate these identified services, standardized AD products and AD services must be first defined.

AD products

AD products are what an aggregator provides, i.e., sells, to the players and which the players use to create the services [12]. It is a specific “power against time” demand response shape to be provided by an aggregator during a specific period of time. In the context of AD and ADDRESS, the aim is to change the consumption pattern of groups of consumers. In other words, “re-profiling” the demand via the circulation of appropriate price and volume signals is broadcasted by aggregators.

AD services

AD services are AD products that are acquired and used by a player [12]. It is a specific example of the use of basic **active demand products**. The terminology here means that the services actually refer to the fulfillment of specific needs of the players.

A thorough consideration of those *services* has led to the identification of **three basic AD-based products** as summarized in Table 8.1 [12].

Table 8.1 shows the identified AD products, namely scheduled reprofiling (SRP), conditional reprofiling (CRP), and bidirectional conditional reprofiling (CRP-2). The table also shows that SRP and CRP products imply single specific unidirectional volume, which could possibly be a volume range. However, the CRP-2 can be considered as the combination of two separate CRP with the appropriate associated demand reduction and increment.

Reference use cases

Once the main relationships between the different ADDRESS players have been clarified, the use cases for the different AD services identified can be defined.

Table 8.1 *AD products and their main characteristics*

AD product	Conditionality	Typical example
Scheduled reprofiling (SRP)	Unconditional (obligation)	The aggregator has the obligation to provide a <i>specified</i> demand modification (reduction or increase) at a given time to the product buyer.
Conditional reprofiling (CRP)	Conditional (real option)	The aggregator must have the capacity to provide a <i>specified</i> demand modification during a given period. The delivery is called upon by the buyer of the AD product (similar to a reserve service).
Bidirectional conditional reprofiling (CRP-2)	Conditional (real option)	The aggregator must have the capacity to provide a <i>specified</i> demand modification during a given period in a bidirectional range $[-y, -x]$ MW, including both demand increase and decrease. The delivery is called upon by the buyer of the AD product (similar to a reserve service).

The use case for a service may be defined as all the interactions represented on a timeline that take place between the players involved in the provision of the service (including those involved in the technical verification), along with their internal processes. Therefore, the use cases for the AD services are considered very important for the development of the technical and commercial architectures in the ADDRESS project.

By taking the services provided to the retailer and the DSO as a basis, four **reference use cases** have been defined, two for SRP products and two for CRP products. It has been found that by introducing only minor changes, the use cases for the retailer could be adapted for all deregulated players. It was also noted that the use cases for the DSO are very similar to those for the TSO. In fact, the procedure that accompanies the usage of an AD service generally involves the following processes:

- (i) **Internal optimization:** Potential AD buyer must first determine the best option available that meet their needs. This step involves comparing the available options. For example, AD product such as SRP and CRP and energy-based products such as forward energy contracts that are available to the AD buyers. The AD buyer then decides how much and which AD products are needed and the maximum price it is willing to pay. The AD buyer may buy from standardized marketplaces such as a power exchange and over-the-counter markets or negotiate a bilateral contract which allows the AD buyer to include specific conditions that meet additional requirements.
- (ii) **External optimization:** This subprocedure is performed by counterparties, that is, aggregators and authorities, that is, market operators, which facilitate commercial transactions and supervise the safe operation of the power systems. It is important that system operators such as DSOs and TSOs must be consulted for technical feasibility of commercial transactions. Final results of

the transactions are announced only after the verification of technical feasibility. Under certain technical constraints, an AD buyer may not be able to obtain the whole amount of AD service it intends to consume originally.

- (iii) **Execution:** The transaction is executed when the aggregator(s) communicates with its consumers, which are considered the ultimate active demand providers, through their energy box. In response to the signals they receive, the consumers submit their demand response.
- (iv) **Settlement:** As the name implies, this process involves settling any amount due among the parties involved in the transactions. To promote good performance, rewards may be given to consumers/aggregators for over-performance while penalties are imposed otherwise.

8.5.2.4 ADDRESS interoperability of data exchanges

The methods and tools adopted in the ADDRESS project to insure interoperability in data exchanges include the following [16]:

- Definition of a service-oriented architecture (SOA) for ADDRESS,
- Description of some ADDRESS use cases in UML (activity diagrams, sequence diagrams),
- Description of the ADDRESS information model in UML as an extension of the IEC TC57 CIM model. The information model allows users to have a common semantic among ADDRESS partners and to define message payload types,
- Description of some ADDRESS message payload types in XML XSD (XML Schema), and
- Simulation of ADDRESS message payload types using web services (WS) or an enterprise service bus (ESB).

A methodology was proposed to be implemented for ADDRESS' SOA to specify data interchanges between ADDRESS actors from UML use case modeling down to message exchange interface deployment.

Specifying use cases for the different business domains covered within ADDRESS project, that is, transmission, distribution, market, customer, and aggregator, is also considered important. Use cases are specified for:

- **Internal processes:** This covers specific business functions related to the internal behaviors of ADDRESS actors.
- **External processes:** These processes focus on interactions between actors to ensure the exchange of external data required to process internal business functions of actors.

The use cases that describe **external** processes and the supporting data exchanges are important because they are essential requirements for interoperability among different organizations, that is, ADDRESS actors or data exchange participants, through the proposed SOA approach.

Immediately after the external use cases are finalized, they are received as an input in order to specify data interchange format corresponding to the external

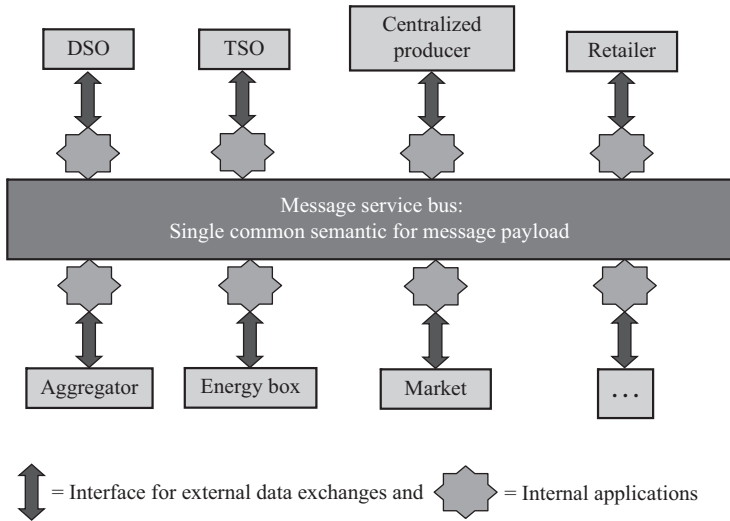


Figure 8.5 *Single semantic for data interchanges among ADDRESS actors*
[after 16]

interactions between ADDRESS actors. The content of those data is called **message payload**. The specification of the format of those data exchanged among actors leads to the specification of application interfaces which have to be implemented by each actor participating in the ADDRESS business processes.

Communication interoperability between ADDRESS actors is implemented using a single common semantic for external data interchanges, which is based on international standards from IEC TC57, such as the CIM, as well as SOA standards for the implementation of those interfaces. The objective is illustrated in Figure 8.5.

In order to fully benefit from the use of SOA interfaces between actors, XML Schema Definition (XSD) has been used for the specification of the message payload and Web Service Description Language (WSDL) for the specification of the interface implementation. This is illustrated in Figure 8.6.

Each defined message payload is expressed using XSD as syntax. The resulting XSDs are then embedded into a service interface based on WSDL standard. From those web services definitions, application programming interface (API) code for each interface can be generated in a **contract first** way. This means that the basic code API structure is generated automatically from the WSDL definition which is acting as an interface contract between applications.

The generated API code is then integrated and plugged into an ESB to facilitate communication and routing of data.

Interested readers are advised to refer to [16] for more information as how to build XSD syntactic representation of ADDRESS message payloads from the use cases defined by business experts and the steps to be followed to go from use case modeling down to message payload syntactic generation for the implementation of the web service interfaces.

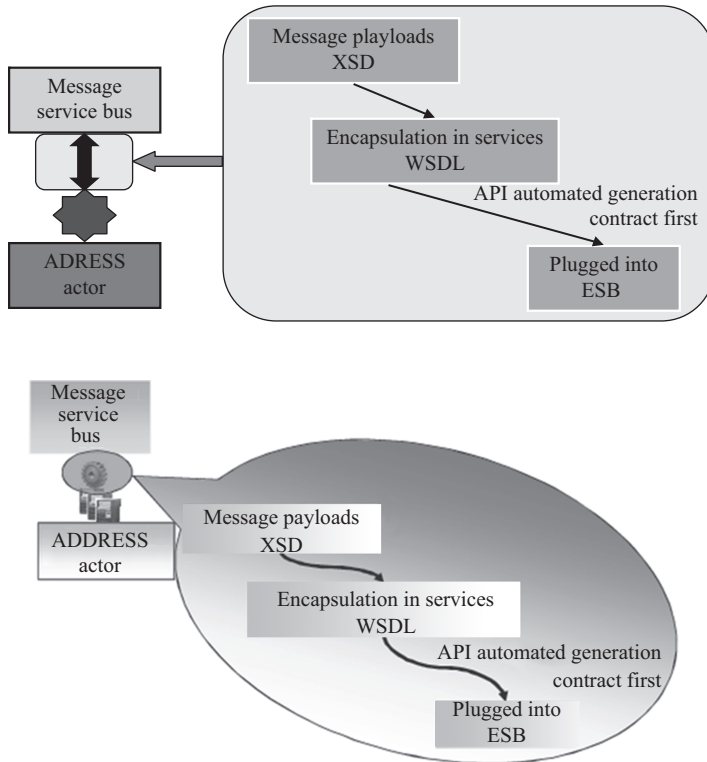


Figure 8.6 Building application interface API based on SOA for message payload exchanges [after 16]

8.6 Summary

An overview of the application of Smart Grid concept to distribution networks is covered in this chapter. It begins by outlining the main differences between conventional distribution networks and their counterpart smart distribution networks in Section 8.2. This is followed by explaining as why distribution networks are needed to be smart in Section 8.3. The basic building blocks from which a smart distribution network consists of are then covered under Section 8.4. Finally, the evolvement of conventional distribution networks into smart distribution networks is discussed in Section 8.5. In this context and in order to achieve this objective two EU projects namely, FENIX and ADDRESS have been initiated which are briefly covered respectively in Sections 8.5.1 and 8.5.2.

In FENIX project the concept of a VPP has been introduced as way forward to ensure the flexibility of distribution networks with regard to the integration of DER/RES units. The aim of ADDRESS project is to develop a comprehensive commercial and technical framework suitable for the development of “Active Demand” and to exploit its market-based benefits.

References

- [1] Li J., Meng X., and Song X. 'Research on technical framework of smart distribution network'. *IEEE International Conference on Advanced Power System Automation and Protection (APSAP)*; Beijing, 2011, pp. 286–90
- [2] Pipet P. *Power distribution automation solution-smart grid data aggregation* [Online]. 2011. IEA/ADEME Workshop XVII; May 2011. Available from <http://www.leadsm.org/wp/files/Tasks/Task%2017%20-%20Integration%20of%20Demand%20Side%20Management,%20Energy%20Efficiency,%20Distributed%20Generation%20and%20Renewable%20Energy%20Sources/Sophia%20Antipolis%20public%20workshop/Pipet-Smart%20Grid%20Data%20Aggregation.pdf> [Accessed 18 October 2016]
- [3] Djapic P., Ramsay C., Pudjianto D., *et al.* 'Taking an active approach'. *IEEE Power and Energy Magazine*. 2007;5(4):68–77
- [4] Entsoe. *European Electricity Grid Initiative (EEGI) Roadmap and Implementation plan, Version V2* [Online]. May 2010. Available from http://www.smartgrids.eu/documents/EEGI/EEGI_Implementation_plan_May%202010.pdf [Accessed 18 October 2016]
- [5] Jiang Z. 'Agent-based control framework for distributed energy resources microgrids'. *Proceeding of IEEE/WIC/ACM International Conference on Intelligent Agent Technology (IAT'06)*; 2006. pp. 1–7
- [6] Kok J.K., Warmer C.J., and Kamphuis I.G. *PowerMatcher: multiagent control in the electricity infrastructure* [Online]. Utrecht, Netherlands: AAMAS'05; 2005. Available from http://www.cs.huji.ac.il/course/2005/aisemin/articles/2006/docs/itIT25_75.pdf [Accessed 18 October 2016]
- [7] 'Tech Watch: E-Terra Trade'. *IEEE Spectrum*. 2003;40(1):58
- [8] Alstom. *e-terraplatform: the power to adapt* [Online]. 2010. Available from <https://www.gegridsolutions.com/alstomenergy/grid/Global/Grid/Resources/Documents/Automation/NMS/e-terraplatform.fr-FR.pdf> [Accessed 19 October 2016]
- [9] Areva. *Integration of MORE CARE DG management software with AREVA's eterra SCADA* [Online]. 2004. Available from http://renknownet2.iwes.fraunhofer.de/pages/wind_energy/data/RenKnowNet_Dispower_Highlight_No11.pdf [Accessed 19 October 2016]
- [10] Alstom. *e-terracontrol: flexible and scalable SCADA for the power industry* [Online]. 2010. Available from <https://www.gegridsolutions.com/alstomenergy/grid/Global/Grid/Resources/Documents/Automation/NMS/e-terracontrol.fr-FR.pdf> [Accessed 19 October 2016]
- [11] EU. *Flexible electricity networks to integrate the expected energy evolution* [Online]. 2009. Available from http://fenix.iwes.fraunhofer.de/docs/att2x/2009_Fenix_Book_FINAL_for_selfprinting.pdf [Accessed 19 October 2016]
- [12] Belhomme R., Sebastian M., Diop A., *et al.* *ADDRESS technical and commercial architecture* [Online]. European Community's Seventh Framework Programme (PF7); October 2009. Available from <http://www.addressfp7>.

- org/config/files/ADD-WP1_Technical_and-Commercial_Architectures.pdf
[Accessed 20 October 2016]
- [13] Pudjianto D., Ramsay C., and Strbac G. 'Virtual power plant and system integration of distributed energy resources'. *IET Renewable Energy Generation*. 2007;1(1):10–16
 - [14] Kieny C., Berseneff B., Hadjsaid N., Besanger Y., and Maire J. 'On the concept and the interest of Virtual Power plant: some results from the European project FENIX'. *IEEE Power & Energy Society General Meeting (PES'09)*; 2009. pp. 1–6
 - [15] EU. *Active Distribution Network with Full Integration of Demand and Distributed Energy RESourceS (ADDRESS)* [Online]. Available from <http://www.addressfp7.org/> [Accessed 20 October 2016]
 - [16] Kostic T., Effantin C., and Lambert E. 'How to increase interoperability in European SmartGrid projects? The ADDRESS experience regarding model driven integration based on international standards'. *IEEE International Energy Conference and Exhibition (ENERGYCON)*; Florence, 2012, pp. 652–57

This page intentionally left blank

Chapter 9

Smart Grid enables the integration of electric vehicles

9.1 Introduction

It has been reported that transportation in 2013 accounted for more than 30% of the world's energy consumption and approximately 72% of global oil demand [1].

Factors, such as volatility in oil prices, political instability in oil-producing countries, and environmental damage due to carbon emission caused by internal combustion engines, have led to contemplating electric transport by introducing electric vehicles (EVs) to ensure economic growth, energy independence, and greenhouse gas reduction.

Consequently, the interest and investment in EVs by many car manufacturers worldwide started in late 2010s and continued to grow since then. The level of such interest is reflected, for example, in the pilot EV programs launched in the USA and the commitment of over \$30 billion of both public and private investments to EV-related products and projects.

Several business, technical, and regulatory challenges need to be addressed to ensure the success of the electrification of transportation. An example of such challenges is charging systems and related infrastructure that need to be put in place. In order to achieve this goal, several bodies including utilities, regulators, providers of EV charging stations, which are also known as EV supply equipment (EVSE), and other parties must join their efforts to simplify permitting processes, establish business and billing models, and tackle regulatory issues.

An important issue that must be resolved is the impact of EVs on the grid. Charging a single EV using a fast charger can double a home's peak load. It is therefore vitally important for utilities that they should manage EV charging efficiently. The solution can be achieved by devising "smart" EV charging. The key to this is the Smart Grid, whereby the vision and control required to protect components of the distribution network can be easily provided. This ensures that components such as transformers are not overloaded by EVs as well as that electricity-generating capacity is used efficiently. Using Smart Grid can help utilities to efficiently manage EV charging by enabling them to decide when and how EV charging occurs while sticking to customer preferences, collect EV-specific meter data, apply specific rates for EV charging, engage consumers with information on EV charging, and collect data for greenhouse gas reduction credits.

9.2 Types of electric drive vehicle

Electric drive vehicles may be divided into three types as follows [2]:

(i) **Hybrid electric vehicles**

Hybrid electric vehicles (HEVs) are powered by an internal combustion engine or other propulsion source that runs on conventional or alternative fuel and an electric motor. The latter uses energy stored in a battery. The idea of using an electric motor is that the extra power provided by it results in a smaller engine. This in turn results in better fuel economy while maintaining the performance. HEVs combine the benefits of high fuel economy and low emissions with the power and range of conventional vehicles.

Note that HEVs do not require a plug to charge the battery. Instead, they charge using regenerative braking power and the internal combustion engine. They capture the energy normally lost during braking by using the electric motor as a generator, storing the captured energy in the battery. The energy from the battery provides extra power during acceleration and auxiliary power when at standstill.

(ii) **Plug-in hybrid electric vehicles**

Plug-in hybrid electric vehicles (PHEVs) are equipped with an electric motor operated by energy stored in a battery, in addition to an internal combustion engine or other propulsion source, which uses conventional fuels. The benefits offered by PHEVs include using electricity from the grid to charge the battery that costs less if charging is done during certain time and reduces petroleum consumption compared with conventional vehicles. PHEVs can also reduce emissions, depending on the electricity source.

PHEVs are equipped with larger battery packs compared with HEVs. This makes it possible for current PHEV models to travel about 10–40 miles using only electric power. This is commonly referred to as the all-electric range of the vehicle.

PHEV batteries can be charged either by (i) an external electric power source or (ii) the internal combustion engine, or (iii) regenerative braking power. If a PHEV is driven using only its internal combustion engine, its fuel economy will be comparable to that of an HEV of a similar size. However, if a PHEV is fully charged, the obtained stored electric energy can be used to drive it for only a shorter distance compared to its all-electric range (see (iii) below).

(iii) **All-electric vehicles**

Electric vehicles are equipped with only an electric motor. These types of vehicles use a battery to store the electrical energy that drives the motor. EV batteries are charged by plugging the vehicle into an electric power source. Some agencies, such as the U.S. Environmental Protection Agency (EPA), consider EVs as zero-emission vehicles even though generation of the electricity they use may contribute to air pollution. This is because EV motors produce no exhaust and therefore no emissions. Also EVs are considered to help reducing petrol consumption because they use no other fuel.

9.3 Benefits of transportation electrifications

Several benefits can be gained from the electrification of transportation. The most important of these is the expected significant reduction of greenhouse gas (GHG) emission as a result of replacing internal combustion-based vehicles by electric vehicles. In this context, it has been reported that, for example, the total USA carbon emissions can be potentially reduced by as much as 27% through vehicle electrification, utilizing off-peak power generation and energy delivery capacity to charge plug-in electric vehicles [3]. Other benefits include (i) peak load shaving by feeding back the energy stored in EVs to the grid when peak load occurs. This process is referred to as “vehicle to grid” (V2G), (ii) support the frequency of the grid as advocated by some researchers, and (iii) take the full advantage of off-peak load renewable energy-based generation (REBG), such as wind and solar, whereby the batteries of EVs are charged using this type of generation instead of traditional fossil fuels. This in turn would lead to maximizing the potential GHG reduction benefit of vehicle electrification by effectively eliminating carbon emissions which does not exist in case of EV transportation [3]. However, it is important to note that such benefits can only be realized in conjunction with Smart Grid.

9.4 The driving factors toward transportation electrification

It has been reported [1] that three factors, in particular, are driving transportation electrification worldwide. These are as follows:

(i) **Volatility and high prices of oil**

Over the past decade (2000–2010), the price of oil has been highly volatile. It raised from roughly \$25 a barrel in 2000 to \$75 in 2006 and soared to its highest value of \$147 a barrel in 2008 before it settled down to around \$80 in early 2010 [1]. Consequently, petrol prices have fluctuated widely as well. Additionally, it has been observed that every recession happened during the past 35 years (1975–2010) has been preceded by or concurrently occurred with a high increase in the price of oil. In contrast, electricity prices have been relatively stable. For example in the USA, the price of electricity remained in the range of \$50–75 per MWH, while retail rates raised by an average of less than 2% per year.

(ii) **Energy independence and security**

The emergence of new economies in countries such as Brazil, India, and China has led to the growth of competition for oil worldwide. This in turn has created economic risks for the USA and Europe. However, relying on importing oil from volatile oil-producing countries in Middle East, Africa, and South America has created concerns over security and oil availability. In order to reduce the total dependence on oil imported from such countries, several initiatives were taken by western countries. The most important of these involves the exploitation of renewable energy sources which fits well in the transportation electrification program as it will become apparent later on.

(iii) Environmental benefits

As stated earlier, transportation is considered as a major contributor to the emission of carbon dioxide. It has been reported that inherently clean electric vehicles are more than three times as efficient as their counterpart petrol-based vehicles. Therefore, it is very likely that transport electrification will cut greenhouse gases significantly. It has been reported [4] that even if EVs were initially powered by electricity generated solely from conventional power plants, carbon emission would still be reduced compared to petrol-based vehicles. Additionally, powering EVs solely from existing off-peak generating capacity means that utilities could initially support EV charging without the need to add generating capacity. The environmental benefits of EVs are further enhanced because most utilities nowadays use a mix of renewable and non-renewable energy sources to generate electricity. Excess and expensive to store renewable wind power over night is a growing natural source that can be utilized for charging EVs during night to be used for the following day.

9.5 Challenges to EV adoption

There are several challenges that prevent or delay EV adaptation [1]. Such challenges need to be first overcome by ensuring the success of EV-related industries which include car manufacturers, electric utilities, and governmental agencies. Beside the major challenge of integrating charging stations into the electric grid, these challenges may be classified into (i) challenges faced by customers and (ii) challenges faced by utilities as discussed in next sections.

9.5.1 Challenges faced by customers

The challenges facing consumers that must be addressed include:

(i) High cost

EVs can be more expensive compared with traditional petro-powered vehicles. This depends on the size of the battery used. Hybrid EVs, including PHEV, are likely to be more expensive than petro-powered vehicles because they have both an electric motor and an internal combustion engine as mentioned previously. For example, it has been estimated [5] that in 2015 the cost of a PHEV with a range of 40 miles is \$11,800 more than a standard car with a petro-fueled internal combustion engine, while the cost of an EV with a range of 100 miles is \$24,100 more.

The measures taken by car manufacturers regarding pricing initial models of EVs and governmental subsidies could help bridging the initial gap by making EVs cost competitive. For example, Nissan decided that its all-electric LEAF with a base price of \$32,780 in the USA translates into \$25,280 to buyers after tax credits. Similarly, Mitsubishi announced its i-MiEV all-electric vehicle is priced at less than \$30,000 in the USA. Regarding the governmental subsidies it has been reported [5] that, for example, buyers in the USA are eligible for up to \$7,500 in federal tax

credits, which are scheduled to start phasing out as each manufacturer sells 200,000 EVs. According to the same reference China has planned to cover \$8,800 of the cost of each EV purchased for more than a dozen of its large city government and taxi fleets. However, it has been argued that while these pricing measures and governmental subsidies would definitely help jump-start the market for EVs, they are not sustainable in the long term.

(ii) **Potentially long charging times**

The charging time of EVs may take long time. It may take from half an hour to a day or even more depending on battery capacity, state of its charge, and the type of charging infrastructure or EVSE used. There are three levels of charging technologies with different capabilities of supplying power. These are AC Level 1 (L1) charging, Level 2 (L2) EVSEs, and DC Fast Charging. L1 and L2 are designed to suit individual residences, multidwelling units, and similar structures, while DC Fast Charging is designed for the use of commercial installations, such as commercial charging stations.

L1 charging is designed such that the consumer plugs into a traditional 110 V plug at 12 A, charging at 1.3 kW. This level of charging is relatively slow. However, Level 2 EVSEs need to be permanently mounted and wired to an electrical panel at 220 V. L2 is specified at between 208 and 240 V with charging current between 12 A and 80 A. However, most vehicles are designed to suit L2 charge at no more than 30 A, which corresponds to 6.6 kW.

(iii) **Anxiety due to unavailability of public rapid charging infrastructure**

Lack of public rapid charging infrastructure causes anxiety for being abandoned, which in turn causes a concern to potential EV buyers. However, studies [5] have shown that drivers who already have EVs mostly commute within the range of their planned EV or are otherwise able to avoid public charging. This problem is gradually being resolved with participation from car manufactures. For example, Nissan makes charging points available across the UK to charge its LEAF car. Their locations can be found by visiting [6].

(iv) **Inconvenience due to long waiting time to get L2 chargers installed**

In case of traditional cars, consumers normally buy a car and drive it home. For EVs, consumers are expected to take the advantage of the convenience of the faster L2 chargers. However, this requires permits and must be installed by a licensed electrician. For L2 EVSEs, consumers may need to wait 1 or 2 months before their charger is installed at their home. Obtaining a permit may involve one or more utilities, which must be contacted and informed about the required additional power. Obviously, this causes inconvenience to potential EV buyers.

9.5.2 *Challenges faced by utilities*

Utilities will face many challenges as a result of accommodating EVs. Examples of the key challenges include (i) the high costs of upgrading the infrastructure of utilities' systems, (ii) impact of peak load due to uncontrolled charging, (iii) impact on local distribution system due to clustering of EVs, (iv) impacts due to additional administrative burden, and (v) billing issues related to charging electric vehicles.

9.5.2.1 High costs of upgrading the infrastructure of utilities' systems

Consumers are expected to bear the cost of installing their residential EVSEs. However, utilities will be responsible for the other related EV infrastructure costs. Such costs include upgrading distribution networks, as equipment such as transformers, substations, and extra line capacity are needed to support the expected increased load from EVSEs. Some chargers may draw electrical load equivalent to a house. For example a typical L2 charger load is 6.6 kW compared to a typical residence of approximately 7 kW. Consequently, utilities are required to invest in updating their distribution networks and possibly they may also be required to add generation and transmission capacity.

9.5.2.2 Impact of peak load due to uncontrolled charging

Perhaps the most serious challenge faced by utilities is their ability to deal with peak load impacts of uncontrolled charging. This requires putting in place a load management mechanism that enables utilities when EVSE load is applied to their grid. Absence of such mechanism is likely to cause a de-stabilizing effect on the grid. This situation may result as a consequence of a high percentage of consumers charge their EVs simultaneously when they get home back from work.

9.5.2.3 Impact on local distribution system due to clustering of EVs

Investigations dealing with analyzing current demographics of hybrid vehicle owners expect that EV early adopters are likely to emerge in neighborhood clusters. Consequently, utilities need to be prepared to deal with multiple customers connected to the same transformer who charge their EVs overnight. Just one or two active L2 chargers could overload a transformer, creating reliability problems. Based on data from EPRI of the USA, it has been shown that if two customers connected to the same transformer decided to switch on their L2 chargers, 6.6 kW each, during the peak load time, their load could exceed the emergency rating of roughly 40% of today's distribution transformers [1].

9.5.2.4 Impacts due to additional administrative burden

No matter who installs, operates, or owns charging infrastructures, utilities represent the authority that deal with facilitating the permitting process and therefore they are the ones who plan and allocate the fund for the necessary network upgrades. If it is decided that upgrades are required, for example, for L2 EVSE installation, the consumer will not be able to install the EVSE until the utility has ensured the grid is capable of supporting the additional demand. This process will obviously place an additional administrative burden on utilities and create significant pressure on them to avoid being a bottleneck to EVs accommodation.

9.5.2.5 Billing issues related to charging EVs

Utilities are urgently required to embark on developing business models for providing charging services. This raises many questions for which answers need to be

found out. For example, how utilities are compensated for the power used by charging stations that are owned and operated by third parties? What happens if a driver charges at a public station? What method a utility should use to keep track of which resident in an apartment complex plugged into a charging station and bill them accordingly? Is there any requirement by utilities to develop transfer pricing agreements similar to what is currently used by mobile phone operators, to accommodate “roaming” concept and/or develop parking meter-like pay stations to accommodate “unit price” transactions per battery charge?

However, integration of EVSE is complicated further by the rules that define who is or is not a utility and who owns what part of the electrical network infrastructure as they vary between regulated and deregulated markets. Additionally, the emergence of charging providers who own EVSEs and resell electricity for charging raises the issue of whether these companies need to be regulated.

9.6 Types of EV charging systems

Development of an EV market requires reliable interface infrastructure. This means that enough pairing residential plugs and public charging stations must be developed in large scale to meet the fast growing demand resulting from the continued increase in EVs penetration [7].

In general EV charging systems/stations, or EV supply equipment (EVSE), may be classified into three types. They are described by their charge “level” as Level 1 (L1), Level 2 (L2), or Level 3 (L3) as outlined in next sections [1,8].

9.6.1 L1 AC charging systems

L1 charging systems use a standard 110/120 V outlet and takes 11–20 h to charge a fully discharged EV. L1 charging systems are designed to be portable and are suitable for on-road emergency situations, whereby an EV’ battery charge runs low and it is needed to plug its charger into a readily available outlet. L1 charging systems are relatively slow.

9.6.2 L2 AC charging systems

The operating voltage of L2 stations is specified at between 208 and 240 V and will charge between 12 A and 80 A. This is usually takes place at home when the driver is having rest or sleeping [8].

Some Charging Stations, such as AV’s EVSE-RS+, include robust communication capability and can be “plug in” to the Smart Grid.

9.6.3 L3 DC Charging stations

L3 charging stations are DC fast charging systems, specifically designed for commercial installations such as auto plants, airports, and retail distribution centers. Charging time of these stations is in minutes instead of hours. They are ideal for public charging infrastructure that can be used for charging large vehicles with

large size batteries such as those used for buses and commercial or service fleets with very little recharging downtime.

9.7 Smart Grid enables smart charging

As it has been mentioned earlier, even low levels of EV integration can have a significant impact on the grid (see, e.g., Section 9.5.2). Such impact can be managed effectively by enabling smarter charging using Smart-Grid technologies. A Smart Grid, which is normally equipped with intelligent monitoring, distributed control and communications capabilities, enables utilities to carefully manage the charging process of EVs, by effectively transforming it into “smart charging.” Smart charging enables utilities to perform several smart actions. This includes (i) decide when and how EV charging occurs, (ii) collect EV-specific meter data, (iii) apply specific rates for EV charging, (iv) implement demand response (DR) programs, (v) engage consumers with information on EV charging status and bill impacts, and (vi) collect data for greenhouse gas credits.

However, Smart Grid has the potential to enable EVs to be used in the future as distributed storage devices, feeding electricity stored in their batteries back into the system when needed, a process referred to as “vehicle-to-grid, or V2G, supply” [9]. This obviously would help reducing electricity system costs by providing a cost-effective means of providing regulation services, spinning reserves, and peak-shaving capacity.

In order to effectively support EVs smart charging, the following capabilities must be provided by the associated Smart Grid:

9.7.1 Robust, reliable, and secure connectivity

Provision of a robust connectivity to residential EVSE chargers is vital for remote support as it helps eliminating unnecessary onsite service calls. For example, in case a customer encounters a problem with an EVSE device, a good communications infrastructure would help in remotely troubleshoot the faulty device and accordingly advise the customer to take appropriate actions without having to make an onsite visit.

Communicating with the EVSE may be made either over the neighborhood area network (NAN) or home area network (HAN). However, communicating over NAN provides the same security as other utility meters, better range and propagation characteristics eliminating the need for HAN repeaters, peer-to-peer communications between an EVSE and other Smart-Grid devices, which ensure multiple communications paths for higher reliability, robust device monitoring, and remote upgrade capabilities.

9.7.2 Integration of EV charging infrastructure into demand side management (DSM) system

It is important that a utility back office must have the ability to support, integrate, and optimize EV charge management as part of an integrated DSM operation. This

approach helps not only in managing EV charging but also in optimizing it against other DR programs and tying to utility energy procurement and dispatch. Tying to the electric grid topology can also help in enhancing the reliability of the grid by conducting localized management of charging for individual residents, such as coordinating the load on particular electric circuits.

9.7.3 Provision of distributed intelligence

As it has been discussed in the previous chapters, the virtue of Smart-Grid concept is that intelligence and communications are embedded into all devices of generation and distribution systems. This should ensure a comprehensive management of EV charging. For example, equipping transformers with monitors, software, and communications could empower these devices to communicate directly with EVSEs. Consequently, a transformer can be made to control the time at which connected EVs charge and therefore avoid being overloaded which may lead to its failing.

Smart Grid enables tying EV smart charging to nearly all its elements. This in turn makes it possible for utilities to efficiently manage EVs over a common Smart-Grid platform.

9.7.4 Provision of a separate meter at the EVSE integrated into AMI

Providing a separate or a secondary meter in an EVSE infrastructure that is integrated into a back-end advanced metering infrastructure (AMI) system capable of supporting EVSE meters enables utilities to separate EV charging from the primary meter. This in turn makes it easy for utilities to bill EV charging at a separate rate.

This kind of arrangement would also make it easy for utilities to track and report EV charging usage for greenhouse gas credits. Additionally, AMI data can be used by utilities to predict local reliability issues. For example, it is possible for a utility to compare the peak load on a single transformer before and after the installation of an EVSE and consequently determine whether the transformer needs to be replaced or upgraded. Having separate EVSE metering makes it easier to differentiate EV charging loads from normal loads, which helps in managing EV loads and in forecasting future demand.

9.7.5 Integration of EV charging infrastructure into DR system

Under Smart-Grid environment, DR programs enable utilities to shape the electricity load by switching of certain loads such as thermostats or air conditioners as required. The same can be applied to control switching on/off EV charging equipment. A Smart Grid that integrates EV load management with other DR load controls makes it easy for utilities to fully optimize the demand side of the electricity equation which enables them to efficiently manage electricity supply requirements.

9.7.6 *Integration of EV charging infrastructure into distributed automation (DA) system*

Utilities can achieve greater flexibility in managing reliable delivery of electric power if EVSE is integrated into distributed automation. This includes the planning or extension of circuits required to accommodate EV demand. EVSE-DA integration also helps utilities in maintaining power quality as such integration enables them to increase renewable energy-based generation.

9.7.7 *Coordination with renewable energy-based generation*

By properly managing EV charging, utilities can reduce peak demand impacts, optimize generation from intermittent renewable energy sources such as wind, and coordinate such generation with EV charging.

Therefore, it can be concluded that utilities that plan in advance supporting smart charging will avoid disruption of their network and have greater visibility and control over any required infrastructure upgrades. A robust Smart-Grid infrastructure also enables utilities taking an active role in managing EV charging and also benefiting from electrification of the transport.

9.8 Load management of EVs using Smart-Grid technologies

9.8.1 *The difference EVs make to electricity load*

The continued growth of the deployed number of EVs will have a significant impact on the need for investment in the associated grid capacity and Smart-Grid technologies. EVs could account for a substantial percentage of total electricity consumption particularly peak load. This depends on their rate of penetration. The higher the percentage of EVs electricity consumption, the larger the potential benefits from Smart-Grid technologies that improve the ability of utilities to manage load whereby charging is scheduled as much as possible outside peak load hours. This in turn would reduce the need to build additional generating stations and also reinforce the capacity of the transmission and distribution system to meet the resulting high peak load.

However, it has been reported [10] that there are several barriers which limit the widespread commercialization of EVs. The most important of them is the high overall cost of EVs and limited distance between charges. This has led to the conclusion that the deployment of EVs and, therefore, their associated load demand is likely to remain relatively modest in most countries for at least the next two decades.

9.8.2 *Optimizing scheduling of EV charging using Smart-Grid technologies*

Smart-Grid technologies can be used to optimize scheduling of EV charging, whereby EV charging is performed during off-peak load periods, thereby flattening the daily load curve. This would significantly reduce the need for reinforcement of

both generation and network systems. This would also help in minimizing CO₂ emissions caused by electricity generation from fossil fuels.

A key to this is the use of AMI, which enables a two-way flow of information, provides customers and utilities with real-time data, and enables customers to schedule charging in a manner that ensures minimizing costs to customers as well as the utility to which they are connected. AMI has the ability to collect, store, and report customer consumption data for any required time intervals, including in real time. Such information can be used to send price signals to the consumer, providing an incentive to avoid charging during peak load periods when electricity prices are at their highest values. It will be noted that sophisticated algorithms and communication protocols are needed to handle the telemetry necessary to deal with such information flows.

By using AMI, it is also possible to perform remote connect or disconnect operations. Such capability enables grid operators, for example, to partially disconnect by remote control a certain number of EVs while they are recharged if the grid capacity is saturated. Such arrangement is known as “direct load control.” Alternatively, automated charging equipment may be installed to allow customers to schedule charging at off-peak load periods.

Similar Smart-Grid technologies can be used for public battery-charging locations in urban areas, such as those being installed in several European and American cities. Such charging facilities can be used by commuters to recharge their EVs while at work and leave them to charge throughout the day, extending the commuting range which should give them a peace of mind.

9.8.3 EVs can help in meeting peak load

Vehicles are usually parked for long time, up to an average of 95% of the time. This has led to the possibility of using EVs, in the future, as distributed storage devices with the help of Smart-Grid technology. The stored energy in EVs batteries can be either fed back to the grid, that is, vehicle-to-grid (V2G) when it is needed or may be used within the home or office, that is, vehicle-to-home (V2H). Using V2G feedback can help in reducing electrical system costs as such arrangement leads to a cost-effective means of providing regulation services, spinning reserves, and peak-shaving capacity. The stored energy in EVs batteries would be particularly useful in handling sudden, very short surges in load, such as those happening during television breaks or just after major sporting events. For such arrangement to work, there must be incentives to EV owners, for example, the price of the power they sale to grid is attractive. Obviously to go along this route, a separate meter needs to be installed for this purpose.

9.8.4 Management of intermittent renewable energy-based generation using EVs

As previously explained, using Smart-Grid technologies may help EVs' batteries to have dual functionality, (i) as a type of storage capacity and (ii) as a source of variable load. This in turn could support more widespread deployment of intermittent

renewable energy-based generation such as wind and solar. Theoretically, the energy stored in EVs' batteries could be used as back-up energy to compensate for unpredictable and sudden fluctuations in wind and/or solar-based power generation. This is made possible by initially storing excess energy generated during windy and/or sunny periods, whereby the energy fed from the grid-to-vehicle (G2V) and later on, during peak-load periods or when wind and/or solar-based generation is low for weather-related reasons, the stored energy in aggregate fed back into the grid (V2G). In this way, the variability of wind and/or solar generation can be compensated for. This obviously could lead in savings on investments necessary to provide the required generation capacity using fossil fuel-based power plants.

Additionally, by improving the management of EV-charging load, Smart-Grid technologies can help in ensuring a better temporal match between EV-charging load and available renewable energy-based generation. This is particularly important where the market penetration of renewable energy-based generation is very high.

9.8.5 Effect of regulation, electricity pricing business models for EVs charging stations on load management of EVs

- **Effect of regulation**

It is extremely important that the adapted regulatory frameworks should include, among other things, incentives for EV owners to schedule charging their EVs intelligently and to participate in V2G supply if economically viable. It is possible to make V2G supply economically viable by providing flexibility in pricing and other contractual terms.

In order to achieve economically efficient solutions, regulation must also evolve in response to varying market conditions, technology, and consumer behavior.

- **Effect of electricity pricing/tariffs**

The timing of EVs charging/discharging will be strongly influenced by the applied tariff structure. It is therefore important that pricing arrangements, supported by Smart-Grid technologies, must be designed to discourage G2V at during peak load periods while encouraging V2G to support the grid during the same periods and also during other times when ancillary services are required.

It has been argued that the most appropriate pricing structure depends on how consumer behavior evolves as well as the type of Smart-Grid technologies used. One way is to apply what is called "time-of-use (TOU)" tariffs. Such tariffs can vary by intra-day periods, day of the week, and season depending on the average cost of generating and delivering power during the period under consideration. TOU rates are typically notified well in advance and are based on static peak and off-peak rates that reflect the average cost of generating and delivering power during those periods.

The second approach is referred to as "dynamic tariffs" that takes into account real-time changes in actual operating conditions. Dynamic tariffs vary on a day-ahead or real-time basis. With dynamic tariffs, customers are encouraged to adjust

their consumption patterns according to the cost of electricity provided at a particular time, which is directly related to load levels, reliability concerns, and critical events. The way dynamic tariffs work is as follows [11]:

- (i) *Real-time prices (RTP)*: Such prices fluctuate hourly to reflect the wholesale price of electricity and are typically notified on a day-ahead or hour-ahead basis.
- (ii) *Critical peak prices (CPP)*: They mix TOU and RTP features. TOU is maintained under normal operating conditions while a higher price is applied under predefined conditions such as when system reliability is compromised or fuel prices jump.
- (iii) *Peak time rebates*: This approach rewards customers for reducing their demand instead of penalizing them for their consumption during specific periods.

Dynamic tariffs can be employed where direct load control is used to automatically reduce EV load. This is usually done using remote control and communications technologies, whereby pre-programmed customers preferences are taken into account. Passive programs may also be used but in this case they rely on the end-user to manually reduce consumption based on individual preferences and dynamic rates.

- **Business models for EVs charging stations**

Charging of EVs can be made either from home or using public charging stations. Home charging of EVs can be made using customer's existing electricity supplier, which may be either the local distribution company or independent retailer. However, public charging stations, which are important for reassuring EV users especially in the early stages of market development, may be developed using several models [9]. Such stations may be operated by the local electricity distribution company or by a separate entity which can be either private or public, that may be responsible for running the station or for selling the electricity as well [12]. There is a possibility that existing service stations selling conventional oil-based transport fuels introduce electricity charging facilities alongside their fuel pumps.

In this context, a work conducted on business models for solar-powered charging stations to develop infrastructure for EVs [13] proposes models that include models for nonprofit organizations such as universities, industries like single businesses and shopping centers, utilities, public parking, and parking for government offices. Workplace charging has been given particular attention due to length of time and frequency of charging.

9.9 Flexibility of electric vehicles and their integration into Smart Grid

In addition to the availability of a power source such as the grid, electric cars must be equipped with a charging interface for their internal battery. The existing grid

may be used as a source of power for electric cars and also as a platform for using renewable energy sources for charging. Using existing grid for this purpose is not a straightforward because the capacity of the grid was originally neither designed for the additional load by EVs nor for the simultaneous integration of renewable energy-based generation.

However, it is well known that an average vehicle is most of the time parking and therefore can potentially be connected to the grid [14]. This makes an electric vehicle flexible regarding the charging time schedule. Such flexibility can be best accommodated in the Smart-Grid context.

The challenge to the distribution network due to the increase in power demand caused by the continuing growth of number of EVs was identified in 1998 [15]. This in turn has led to the early development of a load leveling strategy in the presence of EVs to avoid the inevitable creation of higher peak load levels in the power demand curve [16].

The problem is even more aggravated by the large share of renewable energy-based generation (REBG) due to their intermittent nature and the consequent fluctuating of their supply. This makes electrical supply from this type of generation less predictable and less flexible than conventional methods. Ultimately the growing share of REBG manifested itself in decreasing the reliability of the generation and consequently has raised the need for making the grid more flexible and to the necessity of managing demand side more efficiently. This and other considerations such as the desire to keep investments into grid reinforcements as low as possible have led to the concept of Smart Grid, as discussed in details in preceding chapters.

The way forward that has been considered to manage the energy flow between the grid and the batteries of EVs is development of “energy storage systems (ESS).”

9.9.1 *Definition of flexibility in relation to EV*

In the context of a system, “flexibility” may be defined as a variable which measures the degree of freedom of the system [15]. This means that successful operation of system’s primary task is not affected by the value chosen for the variable.

However, utilization of flexibility depends on the variable value. Applying this to a passenger car, the flexibility results from the fact that the vehicle is used less frequently than it could be used.

A good example related to “the flexibility of the charging process” is an overnight charging process, when the time needed for charging is usually shorter than the parking time. Charging is basically equal to the energy E supplied to the battery during the charging period t_1 to t_2 . This in turn equals to the integration of power over the charging period as described in (9.1):

$$E = \int_{t_2}^{t_1} p(t)dt \quad (9.1)$$

This implies that the distribution of the power over time does not affect the final result. Consequently if the end of the charging time period, that is, t_2 is known, the

energy acquired by EV battery, E , as a result of the charging process can be defined within the boundaries determined by the rated power of the supply and the batteries charging capability. Therefore, the flexibility of an EV may be defined as the scheduling of charging its battery to take place within its boundaries. In order to utilize the flexibility based on this definition, car drivers need to be encouraged using incentives [17] to charge their EVs whenever they are parked.

9.9.2 Components related to EV-Smart-Grid integration

Figure 9.1 shows the components that are related to EV-Smart-Grid integration [15]. These components include (i) EV battery system and its management, (ii) charging systems which include on-board and off-board charging systems, (iii) power quality at the grid connection point, (iv) communications system, which consists of (a) communication between vehicle and charging station, (b) communication between charging station, and (c) the central system and communication grid connection point, and (v) renewable energy-based generation including photovoltaic and wind. A brief discussion of these components is given below:

- **EV battery management system**

Currently, the most widely used type of energy storage system (ESS) in EVs are batteries. Such system must have the ability to simultaneously coup with

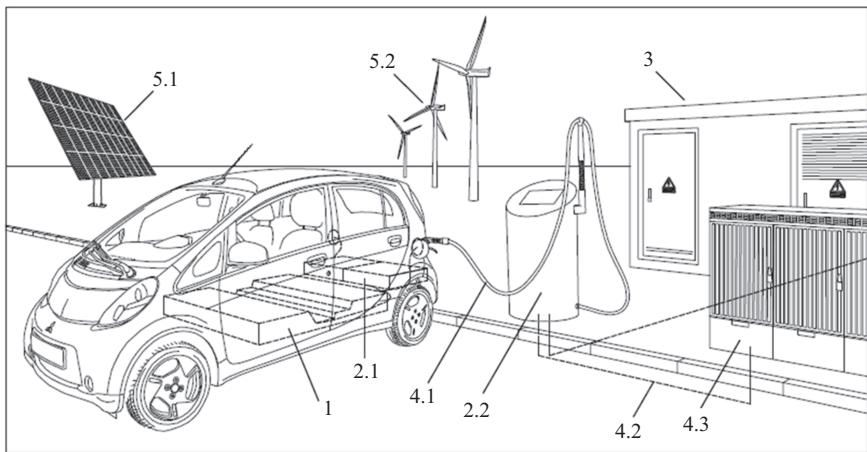


Figure 9.1 EV components related to EV-Smart-Grid integration. Legend: 1, battery management system; 2.1, on-board charger; 2.2, off-board charger; 3, power quality controller at the grid connection point; 4.1, communication between vehicle and charging station; 4.2, communication between charging station and the central system; 4.3, communication grid connection point; 5.1, photovoltaic power generation (Smart Grid challenge); 5.2, wind power generation (Smart Grid challenge) [15]. Reproduced by permission of IEEE

several requirements including (i) high energy density, (ii) high power density, (iii) operating at wide range of temperature, (iv) low self-discharge, (v) high number of charging cycles, and (vi) low acquisition costs [15].

The objective of battery management system (BMS) is to make the battery safe, reliable, and cost efficient. This in turn ensures keeping the battery system operating within its intended range. The specific characteristics and needs of the Smart Grid and EVs, such as deep charge/discharge protection and accurate state-of-charge (SOC) and state-of-health (SOH) estimation, make it necessary to have an efficient BMS. It is also important that the BMS should have accurate algorithms to measure and estimate the functional status of the battery and, at the same time, be equipped with state-of-the-art mechanisms to ensure the protection of the battery from hazardous and inefficient operating conditions [18]. To achieve this, a BMS is required to perform safety measures such as the prevention of power flow in a damaging direction. An effective tool for realizing BMS is the application of indirect measurement to the state of charge (SOC), which is considered of high importance. This is usually determined based on a battery model which is fed by measurable values. This task, together with the safety management, constitutes the main task of the BMS. Currently, this is subjected to ongoing investigation because chemical processes are difficult to observe and every new battery technology requires a new model as well as new indirect measurable quantities. A good overview of the ongoing research on BMS can be found in [18].

- **Charging systems**

Charging systems that an EV can be equipped with are of three types. These are (i) off-board charger, (ii) on-board charger, and (iii) integrated on-board charger.

- (i) *Off-board charger*

Figure 9.2(a) shows the topology of an off-board charger. It is an external unit, rather than a component of the EV. Additionally, voltage output of an off-board charger is a high DC voltage. Consequently, the BMS must have the ability to charge the battery using this voltage. Being an external unit and not integrated into the EV represents a major drawback of this topology. This makes it impossible for the battery of an EV to be charged unless an appropriate charger that provides the needed high DC voltage is made available onsite.

- (ii) *On-board charger*

The on-board charger is equipped with a combination of AC/DC rectifier and DC/AC inverter which makes it bidirectional and therefore enables vehicle-to-grid (V2G) charging capability [19]. Figure 9.2(b) shows the topology of an on-board charger. The charger in this case constitutes a component of the EV. This makes it possible for EV to be charged almost everywhere using a single-phase and three-phase supply.

- (iii) *Integrated on-board charger*

Figure 9.2(c) shows the topology of an integrated on-board charger. The main feature of this type of charger is that it is integrated into the existing AC

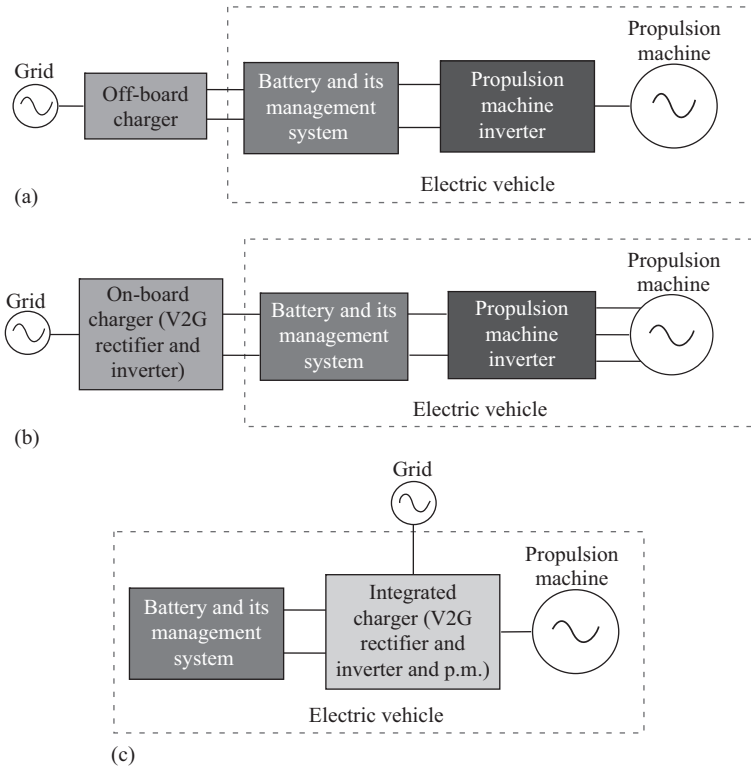


Figure 9.2 Schematic diagrams of (a) an off-board charger topology, (b) an onboard charger topology, and (c) an integrated on-board charger topology [after 19]

propulsion machine (p.m.) inverter. Consequently, all power electronics devices are accommodated in one unit. Such design makes it the most efficient approach of implementing a charger in an EV. This topology satisfies its main objectives related to minimizations of manufacturing costs, maintenance costs, and weight of the EV.

- **Power quality controller at the grid connection point**

When an EV is interfaced with an electrical grid, an AC to DC or DC to AC conversion systems are, respectively, required to perform G2V or V2G actions. These conversion systems are either integrated in the car or in the charging station. Since these systems are power electronic-based devices, they introduce harmonics which affect the power quality of the grid supply. As the number of EVs continues to grow, power quality is expected to be problematic [20–25], and therefore special measures need to be taken to resolve it. Details of a proposed solution to mitigate the power quality degradation can be found in [20,26].

- **EV communication system**

As explained previously, communication system constitutes an integral and important part of Smart-Grid infrastructure. As far as EV applications in the context of Smart Grid are concerned, different types of information need to be exchanged. For example, this includes energy prices, switching commands, billing data, and/or authentication data for invoicing SOC [27].

Communication link related to EVs application may be divided into two sections; the first one is between the vehicle and charging station and the second section is between the charging station and the central system. However, data transmission channel may be divided into a physical component and a logical encoding component. The physical component consists of wired and wireless systems. With regard to user interface, in addition to car-based or charging station-based approaches, mobile phone-based interfaces have also been proposed [28].

9.9.3 Management of the flexibility provided by EVs stored energy

The flexibility provided by the integration of EVs into Smart Grid needs to be efficiently managed to maximize the benefits gained from such integration. The benefits obtained as a result of such management include (i) load shaping aiming to maximize grid capacity utilization [29]–[31] and (ii) alleviation of peak load increases [31].

9.9.3.1 Load shaping aiming to maximize grid capacity utilization

Deployment of large-scale intermittent renewable energy-based generation such as wind is very likely to introduce stability problems due to wind fluctuations. It has been shown [29] that by using household appliances and electric vehicles it is possible to generate a flexible load that can be applied to smooth out fluctuating wind power. Based on this, the future potential for creating residential load controlled capacities with different electric vehicle penetrations and charging levels has been examined. Also it has been shown that communities with more than 20% of households owning electric vehicles have the flexibility to smooth wind farm fluctuations.

9.9.3.2 Alleviation of peak load increases

As mentioned previously, charging EVs at home could substantially go beyond the home nominal peak load. If the charging process is made at the same time by several customers connected on the same distribution transformer, this will remarkably affect the grid, that is, the peak load of the transformer as a consequence of simultaneously EVs charging can substantially be greater than its nominal rated value. This phenomenon represents a challenge as well as an opportunity to Smart-Grid operation. The way forward to significantly alleviate peak load increases due to residential vehicle charging at home is by adopting intelligent control strategies for the charging process. Additionally, car batteries

that are connected to the grid can be exploited to provide grid services, particularly the stored energy in these batteries may be fed back to the grid to help coping with peak demands due to, for example, household appliances.

A simulation study has been conducted to assess the optimal car battery discharging, that is, V2G, scheduling to achieve peak shaving and reduction of the variability (over time) of domestic load connected to a local distribution network [31,32]. In this study, a three-feeder distribution network feeding 63 houses has been considered. Three scenarios have been contemplated on. This includes (i) V2G without using any intelligent charging. This scenario is referred to as “business-as-usual (BAU)” which is used as reference compared to the results of other two scenarios, (ii) intelligent local charging optimization without V2G, and (iii) charging optimization with V2G. It has been concluded that non-V2G optimized charging obtained from (ii) can reduce the peak demand by 64% compared to BAU case. However, according to scenario (iii), if intelligent charging is applied to V2G, it is possible to achieve peak demand reduction ranging from 29% up to 70% compared to a BAU scenario [32].

9.10 Coordination of multiple plug-in electric vehicle charging in Smart Grids using real-time smart load management (RT-SLM) algorithm

It has been recognized that charging activities of multiple domestic plug-in electric vehicles (PEVs) that are connected to a Smart Grid without proper coordination could introduce several problems to the distribution network to which they are connected [33]. Such problems include potential stresses, performance degradations, and overloads that may occur to the distribution network to which PEVs are connected. Uncontrolled and random PEV charging can also cause increased power losses, overloads, and voltage fluctuations, which are all detrimental to the reliability and security of the associated Smart Grid.

In order to resolve these problems, a real-time smart load management (RT-SLM) control strategy has been proposed and developed aiming at coordinating PEV charging based on real-time performed every 5 min, minimization of total cost of generating the energy and the associated grid energy losses. This is enabled by using the Smart-Grid bidirectional communication infrastructure, which provides an excellent opportunity to manage this problem. This approach proved to reduce generation cost by incorporating time-varying market energy prices and PEV owner preferred charging time zones based on priority selection. To practically achieve this goal, an RT-SLM algorithm has been specifically developed that appropriately considers random plug-in of PEVs and at the same time uses the maximum sensitivities selection (MSS) optimization. Using this approach makes it possible for PEVs to start charging as soon as possible considering priority-charging time zones while complying with network operation criteria, such as losses, generation limits, and voltage profile. This algorithm will be discussed in the following subsections.

- Background and assumptions
- RL-SLM coordination algorithm
- Automation of scheduling PEVs charging using RT-SLM algorithm

9.10.1 *Background and assumptions*

The proposed RT-SLM algorithm has been developed in the context of Smart Grid, whereby it is assumed that communications infrastructure can be used to send and receive signals to individual PEV chargers, which means that PEV charging control would be scheduled automatically and PEV owners have no control whatsoever in this process [33].

In the course of development of the RT-SLM algorithm, the following assumption has been made:

(i) *Load profiles*

To model the domestic load variations in the absence of PEV at each house over a 24-h period, the typical residential load curve shown in Figure 9.3 is used. It is based on actual measurements made on a distribution transformer [33]. It is also assumed that the average peak load per house is equal to 2 kW with a power factor of 0.9.

(ii) *Charging zones and preferred charging periods*

It is possible to minimize the cost of purchasing or producing the energy required for charging PEVs by defining time zones that corresponds with utilities interest in minimizing generation when the peak load occurs. The

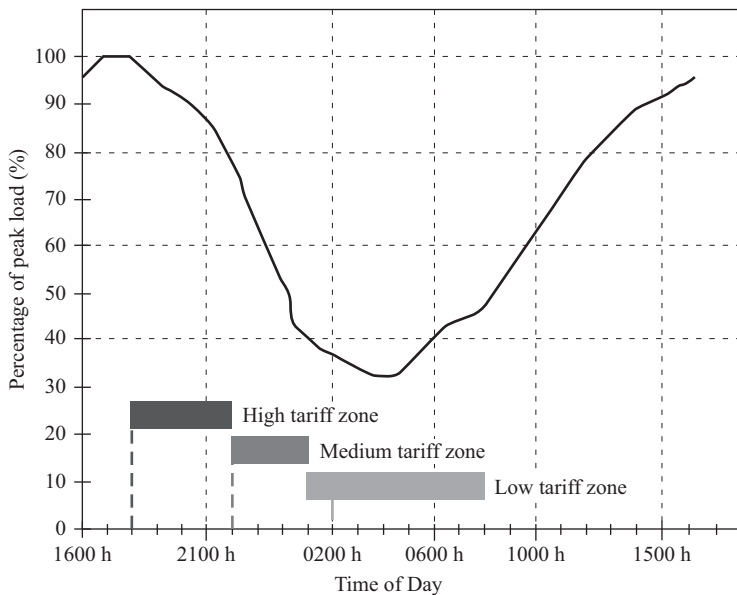


Figure 9.3 Assumed daily residential load curve [33]. Reproduced by permission of IEEE.

way to achieve this is by allowing PEV owners to indicate their preferred charging time zone. Then at each time interval with 5 min length, the RT-SLM algorithm calculates the accommodation of these preferences and at the same time executes the minimization of the cost function subjected to system constraints of (9.2), (9.3a), and (9.3b) (see Section 9.10.2.1), respectively. For the purpose of this study, the following three charging zones, shown in Figure 9.4, have been considered:

- High charging zone extending from 18:00 to 22:00
The time of this zone mostly coincides with the period when the peak load occurs. It is also designated as a “high priority” for PEV owners who want to charge their PEVs as soon as they arrive home back from work in order to have their vehicles ready for use later in the evening. Obviously PEV owners who desire charging their vehicles during this period of high load demand will be charged a higher tariff rate.
- Medium charging zone extending from 22:00 to 01:00
This zone is designated as a “medium priority” that suits consumers who prefer charging their vehicles at partially off-peak load periods and therefore pay a lower tariff rate.
- Low charging zone extending from 01:00 to 08:00
The time of this is the zone coincides with the off-peak load period whereby tariff rate is at its cheapest value. This in turn encourages most consumers charging their vehicles during this zone to ensure their vehicles are fully charged and ready for use throughout the next day. This zone is therefore termed as a “low priority” zone.

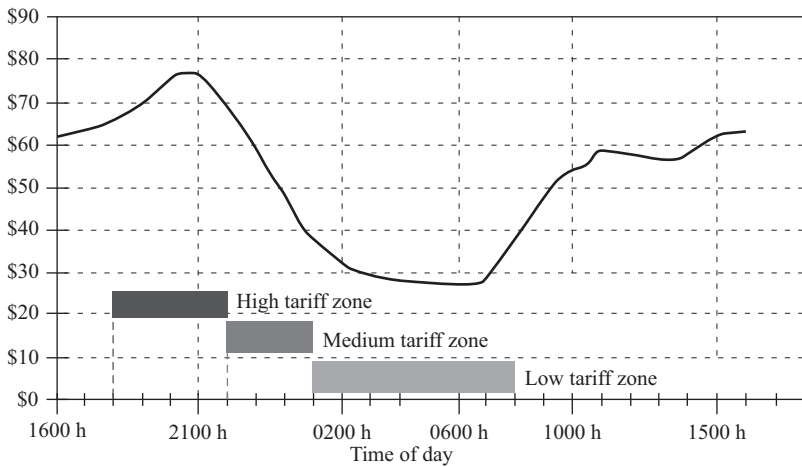


Figure 9.4 Subscription options of charging time zones for PEV owners and variable short-term market energy pricing [33]. Reproduced by permission of IEEE.

9.10.2 RL-SLM coordination algorithm

Figure 9.5 shows the basic components of the RL-SLM coordination algorithm. These are (i) a reading routine for reading the parameters of the grid and recognizing the arrival of a PEV as soon as it is connected to the grid, (ii) an optimization algorithm dedicated to minimize generation and losses during PEVs charging, and

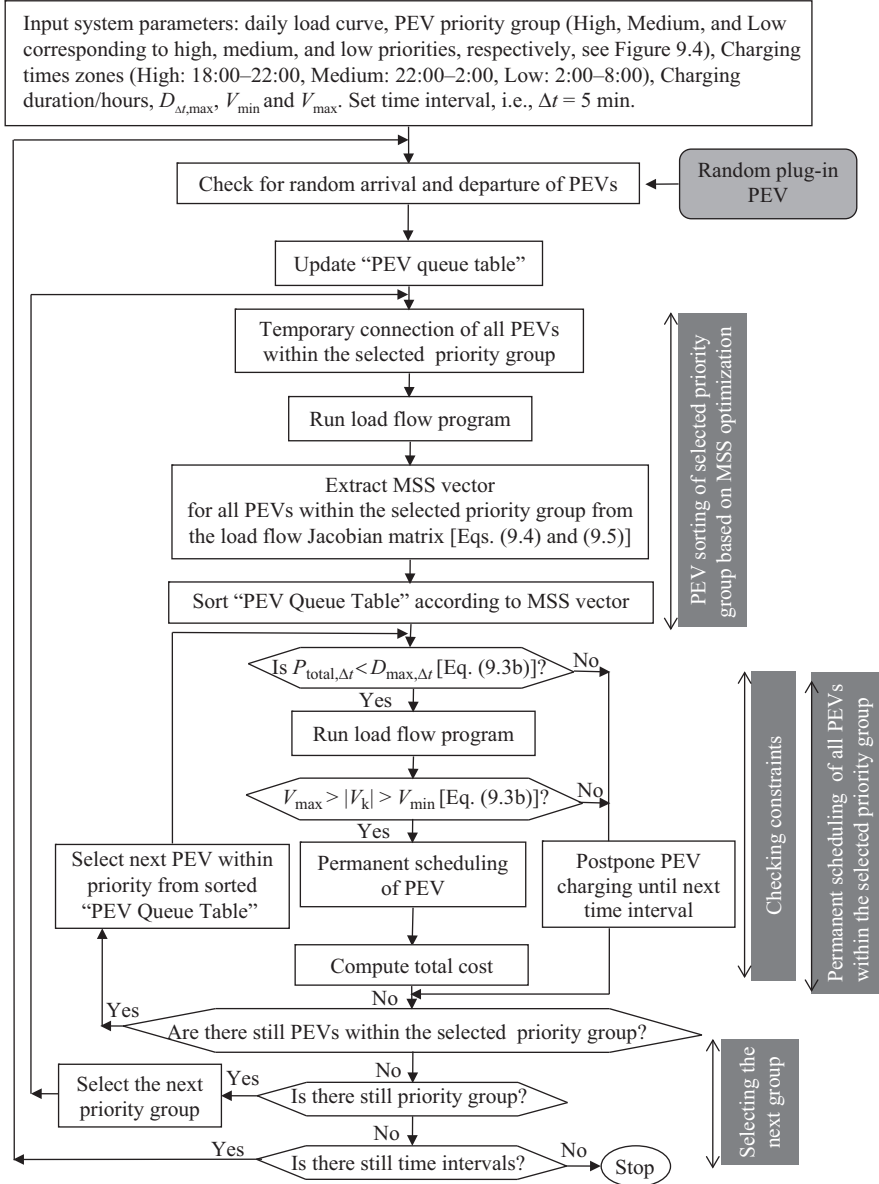


Figure 9.5 Basic components of RL-SLM coordination algorithm [after 33]

(iii) load flow program for assessing the state of the grid to which PEVs charging equipment are connected. The state of the grid is expressed in terms of bus/node voltages, losses, power flows. The purpose of this program is to check that voltage magnitudes remain within their specified boundaries, check the losses sensitivities to PEV charging and that the grid is not subjected to overloading.

9.10.2.1 Formulation of the optimization algorithm to minimize generation and losses during PEVs charging

The problem related to minimization of generation and losses during PEVs charging, which is embedded within the RL-SLM algorithm for coordinating PEV charging, is formulated as an optimization problem. Mathematically, as it is the case for any optimization problem, it consists of an objective function and number of constraints functions as outlined below. Details of mathematical formulation will not be covered in this book. Readers who are interested in such details should refer to [33].

The objective function

The aim of the objective function (F_o) of the coordination algorithm, related to automatically scheduling of PEV charging, is to minimize the total cost of purchasing or producing the energy required for charging PEVs as well as minimizing the associated grid energy losses. This is because the Smart-Grid economy largely depends on the cost of energy, some of which is normally consumed as losses in cables and transformers carrying the energy to PEVs. The objective function takes the following form:

$$\begin{aligned} \text{Min}(F_o) = & \text{Total generation cost } (F_{\text{Gen cost}}) \\ & + \text{Total system losses cost } (F_{\text{loss cost}}) \end{aligned} \quad (9.2)$$

Subjected to the following system constraints:

(a) *Voltage magnitudes of nodes should remain within their limits*

This constraint needs to be included to ensure that voltage magnitudes at all nodes of distribution network remain within the statutory limits adopted by utilities. Therefore, this constraint takes the following form: Voltage at any node:

$$V_{\min} \leq |V_k| \leq V_{\max}, k = 1, 2, \dots, n \quad (9.3a)$$

where k and n are the node index and total number of nodes, respectively. V_k is voltage of k th node, $V_{\min}$ and $V_{\max}$ are the lower and upper statutory limits, respectively.

(b) *Total maximum peak load of distribution network should not exceed its limit*

This constraint is required to ensure that the total maximum peak load of distribution network, within the interval time, Δt , should remain either equal or below a ceiling limit. This can be expressed as follows:

$$P_{\text{total}, \Delta t} = \text{The sum of powers at all nodes} \leq D_{\max, \Delta t} \quad (9.3b)$$

where $P_{\text{total}, \Delta t}$ is the total power consumption at time interval Δt within the 24 h, $D_{\max, \Delta t}$ is the maximum demand level at Δt that would normally occur without having any PEVs are connected to distribution network.

It is important to note that the above algorithm is repeatedly executed during the 24 h of the day at intervals of 5 min length.

Assessing the state of a Smart Grid which is subjected to PEV charging

A modified Newton-based load flow routine is used to assess the state of the Smart Grid, which is subjected to PEV charging, the generation status, voltage profile, and power losses necessary for the objective function (9.2) and examine whether the constraints represented in (9.3a) and (9.3b) are maintained. In this routine, all loads are modeled as constant power loads whereby their real and reactive powers are updated using the daily load curve. The load flow is performed for each time interval.

9.10.2.2 Maximum sensitivities selection (MSS) optimization technique for RT-SLM algorithm

Since the solution of the optimization problem represented by (9.2) and (9.3) needs to be found during each and every step with a short duration of 5 min, it is important that the selected algorithm to be used for this purpose must be computationally efficient and suits real-time applications. Hence, the maximum sensitivities selection (MSS) optimization technique [34–36] has been selected to solve the optimization problem represented by (9.2) and (9.3) embedded in the RT-SLM algorithm.

What the MSS algorithm does? It calculates the objective function sensitivities, in terms of system losses due to PEV charger loads connected to the Smart Grid at a given time step. This is done by temporarily activating the load flow program by considering all PEV charger nodes and assuming the load of each of them is equal to 5% more than its nominal power rating. The results obtained are then put in the queue at the current time step. By subjecting individual PEV charger nodes to small load power perturbations, the sensitivities of system losses due to each PEV node candidate are determined and stored in the MSS vector. The MSS vector prioritizes the selection of a PEV charging. It is arranged such that the PEV which contributes the lowest loss sensitivity is given the high priority to be charged first, that is, scheduled to be charged first. Therefore, the PEV coordination solution is designed based on scheduling first PEVs that result in minimum impact on system losses.

It is possible to compute the sensitivities of the objective function (9.2) to the PEV location and power consumption using the following partial derivatives [34–36]:

$$MSS_j = \frac{\partial P_{\text{loss}}}{\partial P} \quad (9.4)$$

where MSS_j is the sensitivity of PEV at j node, P_{loss} is total power loss and P is the power consumption of PEV. Partial derivatives of P_{loss} can be computed from the Jacobian matrix of the load flow as follows:

$$\begin{bmatrix} \frac{\partial P_{\text{loss}}}{\partial P} \\ \frac{\partial P_{\text{loss}}}{\partial Q} \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial Q}{\partial \theta} \\ \frac{\partial P}{\partial |V|} & \frac{\partial Q}{\partial |V|} \end{bmatrix}^{-1} \begin{bmatrix} \frac{\partial P_{\text{loss}}}{\partial \theta} \\ \frac{\partial P_{\text{loss}}}{\partial |V|} \end{bmatrix} \quad (9.5)$$

where $\partial P, \partial Q, \theta$, and $|V|$ are active power mismatch, reactive power mismatch, bus voltage phase angle, and its magnitude, respectively.

9.10.3 Automation of scheduling PEVs charging using RT-SLM algorithm

Random and unpredictable activities of domestic PEVs could lead to deviation in voltage magnitudes beyond their statutory limits, overloads, and excessive power losses, which would undermine the security and reliability of distribution network to which PEVs are connected. The way forward to solve this problem is by developing a fast and adaptable real-time coordination strategy, represented by real-time smart load management (RT-SLM) that takes into account the time preference of PEV owners at which they charge their vehicles in addition to ensuring the security and reliability of distribution network.

(i) Operating principles of RT-SLM algorithm

The RT-SLM algorithm facilitates the automation of scheduling PEVs charging by communicating individual PEV chargers using Smart-Grid communications infrastructure.

The first step taken by RT-SLM is solving the optimization problem, which consists of the cost function and system constraints represented by (9.2), (9.3a) and (9.3b), respectively. As mentioned previously, the optimization technique used for finding the solution of this problem is maximum sensitivities selection (MSS) algorithm. Additionally, load variations and energy pricing over a 24-h cycle with PEV owner preferences for charging time zone and priority are included (see Section 9.7.1(ii)). This is followed by the second step in which the load flow program is executed. The results obtained from these two steps are used by RT-SLM to assign charging schedules for individual PEVs that ensure maximizing the operational performance of Smart Grid, as discussed previously (see Section 9.7.2.2).

(ii) Implementation of RT-SLM algorithm

Figure 9.5 shows the details of executing the PEV scheduling the RT-SLM algorithm which was implemented using the MATLAB[®] platform. As shown in the figure, the algorithm begins by first reading the input parameters such as impedance data of buses and branches, the nodes at which PEVs are connected, specified priority time zones, load profiles of PEV chargers and residential loads as well as system constraints. This is followed by performing initialization including selecting the highest priority group, time zone, and a PEV.

The algorithm then adds the randomly arriving PEVs to the “PEV Queue Table” followed by sorting the priority of the table from high to low. The queue also includes PEVs from previous time intervals that have not been charged due to constraints violation. PEV coordination is continuously performed during the 24 h of the day at time intervals of 5 min length each. At every time interval, the RT-SLM checks the current state of the Smart Grid, that is, load level, losses, determines MSS vector using (9.4) and (9.5) and consequently rearranging the

“PEV Queue Table” according to the obtained MSS values. PEV chargers are then activated starting from the top of the queue.

9.11 Summary

This chapter is devoted to discussing how the integration of electric vehicles is enabled by the Smart Grid. It started by highlighting the benefits gained from the electrification of transportation and the factors that drive toward transportation electrification. The challenges to EV adoption faced by both customers and utilities are then discussed. This is followed by discussing the types of EV charging stations, which is also known as EV supply equipment (EVSE). Smart charging enabled by Smart Grid is then covered. The load management of EVs using Smart-Grid technologies was then discussed. Under this title, several topics were covered including (i) the difference EVs make to electricity load, (ii) optimizing EV charging scheduling using Smart-Grid technologies, (iii) using EVs to meet peak load, and (iv) management of intermittent renewable energy-based generation using EVs and effect of regulation, electricity pricing business models for EVs charging stations on load management of EVs. This is followed by discussing the flexibility of electric vehicles and their integration into Smart Grid, whereby the definition of flexibility in relation to EV was introduced followed by discussing the components related to EV-Smart-Grid integration and then the management of the flexibility provided by EV-stored energy was covered. Finally, automatic charging scheduling of multiple PEV to be connected to a Smart Grid using real-time smart load management (RL-SLM) algorithm was discussed. Among other things covered under this title include (i) the basic components of the RL-SLM algorithm, outlining the formulation of the optimization algorithm used to minimize generation and losses during PEVs charging and (ii) automation of scheduling PEVs charging using the RT-SLM algorithm, whereby the operating principles of the RT-SLM algorithm and its implementation were explained.

References

- [1] Silver Spring Networks. *How the smart grid enables utilities to integrate electric vehicles, whitepaper* [Online]. 2013. Available from <http://www.silverspringnet.com/pdfs/whitepapers/SilverSpring-Whitepaper-ElectricVehicles.pdf> [Accessed 27 September 2016]
- [2] US Department of Energy. *Hybrid and plug-in electric vehicles-vehicle technologies program* [Online]. March 2012. Available from <https://energy.gov/sites/prod/files/2014/05/f15/52723.pdf> [Accessed 27 September 2016]
- [3] Jung M. and Yeung P. (Silver Spring Networks). *Connecting smart grid and climate change, whitepaper* [Online]. October 2011. Available from http://www.silverspringnet.com/pdfs/SSN_WP_ConnectingSmartGrid-1109.pdf [Accessed 27 September 2016]

- [4] EPRI, NRDC. *Environmental assessment of plug-in hybrid electric vehicles, vol. 1: nationwide greenhouse gas emissions, final report* [Online]. July 2007. Available from http://mistrada.com/yahoo_site_admin/assets/docs/epriVolume1R2.36180810.pdf [Accessed 27 September 2016]
- [5] Hensley R., Knupfer S., and Pinner D. *Electrifying cars: how three industries will evolve* [Online]. McKinsey Quarterly, June 2009. Available from http://www.mckinsey.com/insights/manufacturing/electrifying_cars_how_three_industries_will_evolve [Accessed 27 September 2016]
- [6] Nissan. Available from <http://www.nissan.co.uk/GB/en/vehicle/electric-vehicles/leaf/charging-and-battery/charging-map.html> [Accessed 23 March 2015]
- [7] Zhang X., Wang Q., Xu G., and Wu Z. 'A review of plug-in electric vehicles as distributed energy storages in smart grid'. *Fifth IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*; Istanbul, Turkey, 2014, pp. 1–6
- [8] AeroVironment. *Different types of charging* [Online]. Available from http://evsolutions.avinc.com/electric_vehicles/new_way_to_refuel/different_ways_of_charging/ [Accessed 25 March 2015]
- [9] Morgan T. *Smart grids and electric vehicles—made for each other* [Online]. International Transport Forum, OECD; 2012. Available from <http://www.internationaltransportforum.org/jtrc/DiscussionPapers/DP201202.pdf> [Accessed 16 February 2015]
- [10] Crist P. *Electric vehicles revisited: costs, subsidies and prospects* [Online]. International Transport Forum (ITF); 2012, Discussion Paper No. 2012-3. Available from <http://www.internationaltransportforum.org/jtrc/DiscussionPapers/DP201203.pdf> [Accessed 16 May 2015]
- [11] Leo M., Kavi K., Anders H., and Moss B. *Ancillary service revenue opportunities from electric vehicles via demand response* [Online]. United States: Better Place Master's Project Team; University of Michigan; 2011. Available from <http://www.erb.umich.edu/Research/InstituteReports/11-12/BetterPlaceMastersProjecFinalReport-web.pdf> [Accessed 18 May 2015]
- [12] Eurelectric (Union of the Electricity Industry). *Market models for the roll-out of electric vehicle public charging infrastructure: a concept paper* [Online]. Brussels, Belgium: Eurelectric; September 2010. Available from http://www.eurelectric.org/media/45284/2010-09-21_market_model_final_for_membernet-2010-030-0808-01-e.pdf [Accessed 18 May 2015]
- [13] Robinson J., Brase G., Griswold W., Jackson C., and Erickson L. 'Business models for solar powered charging stations to develop infrastructure for electric vehicles'. *Multidisciplinary Digital Publishing Institute (MDPI) Journal on Sustainability*. 2014;6:7358–87
- [14] Huang S. and Infield D. 'The potential of domestic electric vehicles to contribute to Power System Operation through vehicle to grid technology'. *Proceedings of the 44th International Universities Power Engineering Conference (UPEC)*; Glasgow, 2009, pp. 1–5

- [15] Einwächter F. and Sourkounis C. 'Accessing flexibility of electric vehicles for smart grid integration'. *Ninth International IEEE Conference on Ecological Vehicles and Renewable Energies (EVER)*; Monte-Carlo, 2014, pp. 1–8
- [16] Koyanagi F. and Uriu Y. 'A strategy of load leveling by charging and discharging time control of electric vehicles'. *IEEE Transaction on Power Systems*. 1998;**13**(3):1179–84
- [17] Grahn P. and Soder L. 'The customer perspective of the electric vehicles role on the electricity market'. *Eighth International Conference on European Energy Market (EEM)*; Zagreb, 2011, pp. 141–48
- [18] Rahimi-Eichi H., Ojha U., Baronti F., and Chow M. 'Battery management system: an overview of its application in the smart grid and electric vehicles'. *IEEE Industrial Electronics Magazine*. 2013;**7**(2):4–16
- [19] Glanzer G., Sivaraman T., Buffalo J.L., Kohl M., and Berger H. 'Cost-efficient integration of electric vehicles with the power grid by means of smart charging strategies and integrated on-board chargers'. *Tenth International IEEE Conference on Environment and Electrical Engineering (EEEIC)*; Rome, 2011, pp. 1–4
- [20] Monteiro V., Goncalves H., and Afonso J.L. 'Impact of Electric Vehicles on power quality in a Smart Grid context'. *Eleventh International Conference on Electrical Power Quality and Utilisation (EPQU)*; Lisbon, 2011, pp. 1–6
- [21] Gomez J.C. and Morcos M.M. 'Impact of EV battery chargers on the power quality of distributed systems'. *IEEE Transaction on Power Delivery*. 2003;**18**(3):975–81
- [22] Staats P.T., Grady W.M., Arapostathis A., and Thallam R.S. 'A statistical method for predicting the net harmonic currents generated by a concentration of electric vehicle battery chargers'. *IEEE Transaction on Power Delivery*. 1997;**12**(3):1258–66
- [23] Staats P.T., Grady W.M., Arapostathis A., and Thallam, R.S. 'A procedure for derating a substation transformer in the presence of widespread electric vehicle battery charging'. *IEEE Transaction on Power Delivery*. 1997;**12**(4):1562–68
- [24] Lambert F. *Secondary distribution impacts of residential electric vehicle charging* [Online]. USA: California Energy Commission; May 2000. Available from http://www.energy.ca.gov/reports/2002-01-11_600-00-039/600-00-039_NOAPPENDICES.PDF [Accessed 18 May 2015]
- [25] Rahman S. and Shrestha G.B. 'An investigation into the impact of electric vehicle load on the electric utility distribution system'. *IEEE Transaction on Power Delivery*. 1993;**8**(2):591–97
- [26] Zhang Z., Xu H., Shi L., Li D., and Han Y. 'Application research of an electric vehicle DC fast charger in smart grids'. *IEEE Sixth International Conference on Information and Automation for Sustainability (ICIAFS)*; Beijing, 2012, pp. 258–61
- [27] Marra F., Sacchetti D., Traeholt C., and Larsen E. 'Electric vehicle requirements for operation in smart grids'. *Second IEEE PES International*

- Conference and Exhibition on Innovative Smart Grid Technologies (ISGT Europe)*; Manchester, 2011, pp. 1–7
- [28] Masuch N., Lutzenberger M., Ahrndt S., Heßler A., and Albayrak S. ‘A context-aware mobile accessible electric vehicle management system’. *Federated Conference on Computer Science and Information Systems (FedCSIS)*; Szczecin, 2011, pp. 305–12
 - [29] Schuelke A. and Erickson K. ‘The potential for compensating wind fluctuations with residential load shifting of electric vehicles’. *IEEE International Conference on Smart Grid Communications (SmartGridComm)*; Brussels, 2011, pp. 327–32
 - [30] Shireen W. and Patel S. ‘Plug-in hybrid electric vehicles in the smart grid environment’. *IEEE PES, Transmission and Distribution Conference and Exposition*; New Orleans, LA, 2010, pp. 1–4
 - [31] Mets K., Verschueren T., De Turck F., and Develder C. ‘Exploiting V2G to optimize residential energy consumption with electrical vehicle (dis)charging’. *IEEE First International Workshop on Smart Grid Modeling and Simulation (SGMS)*; Brussels, 2011, pp. 7–12
 - [32] Mets K., D’hulst R., and Develder C. ‘Comparison of intelligent charging algorithms for electric vehicles to reduce peak load and demand variability in a distribution grid’. *Journal of Communications and Networks*. 2012;**14** (6):672–81
 - [33] Deilami S., Masoum A.S., Moses P.S., and Masoum M.A.S. ‘Real-time coordination of plug-in electric vehicle charging in smart grids to minimize power losses and improve voltage profile’. *IEEE Transaction on Smart Grid*. 2011; **2**(3):456–67
 - [34] Wu Z.Q. and Lo K.L. ‘Optimal choice of fixed and switched capacitors in radial distributions with distorted substation voltage’. *IEE Proceedings – Generation, Transmission and Distribution*. 1995;**142**(1):24–8
 - [35] Masoum M.A.S., Ladjevardi M., Fuchs E.F., and Grady W. ‘Optimal placement and sizing of fixed and switched capacitor banks under non-sinusoidal operating conditions’. *IEEE Power Engineering Society Summer Meeting*; Chicago, IL, 2002, pp. 807–13
 - [36] Masoum M.A.S., Ladjevardi M., Jafarian A., and Fuchs E.F. ‘Optimal placement, replacement and sizing of capacitor banks in distorted distribution networks by genetic algorithms’. *IEEE Transaction on Power Delivery*. 2004;**19**(4):1794–1801

This page intentionally left blank

Chapter 10

Smart Grid and energy storage systems

10.1 Introduction

Historically, electrical energy storage (EES) systems have played three important roles [1]: (i) they reduce electricity costs by storing electricity obtained during off-peak load at which the electricity price is low, to be used during peak load times instead of buying electricity whose prices then are high; (ii) they are used to improve the reliability of the power supply, whereby EES systems support users when, for example, an electrical network is subjected to disruption due to natural disasters; and (iii) they maintain and improve power quality, frequency, and voltage.

EES systems are expected to play an important role in solving problems related, for example, to excessive power fluctuation and unstable power supply which are particularly associated with the high penetration of renewable energy-based generation. EES systems are also expected to play significant role in the off-grid domain, that is, transport and mobility. For example, electric vehicles use batteries as EES, as discussed in Chapter 9. The idea is to replace the electricity generated using fossil fuels by that generated from renewable energy sources.

It is expected that dispersed EES systems will be used for load leveling, fluctuation smoothing, uninterruptible power supply (UPS), and emergency power source. Their introduction is considered essential to control the future complicated energy utility networks [2].

Demand side management (DSM) is another area, which is connected to mass EES. The aim is to reduce peak demand and optimize off-peak usage. By combining EES and demand side, whereby the “storage” operates from the supply side while the demand side operates from the “DSM” could potentially lead to operation generation plants (both traditional and renewable) in a more cost-effective way.

As with regard to Smart Grid, EES is considered as one of the key elements that can help in the development and realization of the Smart Grid concept.

10.2 Characteristics of energy storage devices/systems

Energy storage devices are characterized by the following two factors [3]:

(i) Energy density

Energy density is the energy magnitude per unit weight, measured in Wh/kg, a storage device/system can supply. Accordingly, this factor can be used to define the quantity of energy that a device/system can store and deliver.

(ii) Discharge time

Discharge time of a storage device/system is the period of time over which it releases its stored energy. This is obviously related to the rating of the device/system measured in kW or MW.

Energy storage systems (ESSs) may be classified according to the operating range of their discharge times as (a) very short-term where the discharge time is less than 1 minute, (b) short-term where the discharge time is less than 2 hours, (c) long-term for which the discharge time is between 2 and 8 hours, and (d) very long-term for where the discharge time can be from a day to weeks [4].

The energy rating, which is expressed either in kWh or MWh, is considered as an important factor in determining how long a device/system can supply energy for, while the power rating is an important factor in determining how much energy can be released during a fixed time. For example, a 1,000 kWh device rated at 50 kW can supply an output of 50 kW for 20 hours (i.e., $50 \times 20 = 1,000$ kWh).

10.3 Types and characteristics of EES systems

EES systems may be classified according to the form of energy used. Figure 10.1 shows that EES systems are classified into mechanical, electrochemical, chemical, electrical, and thermal energy storage (TES) systems [1].

It will be noted from Figure 10.1 that hydrogen (H_2) and synthetic natural gas (SNG) are classified as chemical ESSs. These gases are secondary energy carriers

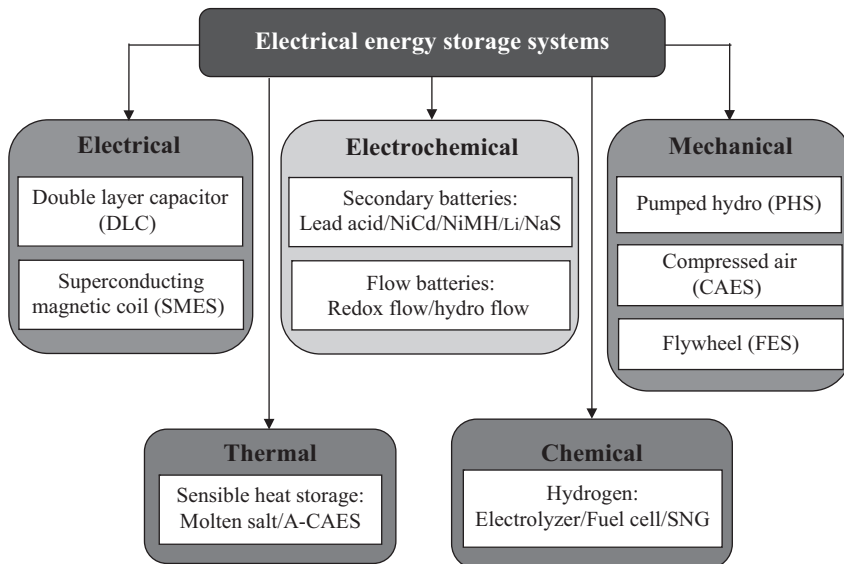


Figure 10.1 Classification of electrical energy storage systems according to energy form [after 1]

but can be utilized to store electrical energy. This, for example, is achieved by producing H_2 via electrolysis of water. The H_2 can then be used as fuel for fuel cells to generate electricity. This combined electrolysis–fuel cell process can be considered as an electrochemical EES.

Figure 10.1 also includes TES systems despite the fact that electricity, in most cases, does not constitute a direct input to such storage systems. However, with the help of TES, the energy from renewable energy sources can be buffered which makes it possible to produce electricity on demand. Examples of such TES include hot molten salts in concentrated solar power (CSP) plants and the storage of heat in compressed air plants using an adiabatic process to gain efficiency.

A brief discussion of each of these types will be given in the following subsections.

10.3.1 Mechanical storage systems

The most common mechanical storage systems include pumped hydroelectric power plants or pumped hydro storage (PHS), compressed air energy storage (CAES), and flywheel energy storage (FES).

(i) **Pumped hydro storage**

The basic structure of a conventional PHS system consists of two water reservoirs which are built at different elevations. During off-peak time, the water is pumped from the lower to the upper reservoir, a process described as “charging.” The process is reversed, when it is required, by allowing the water to flow back from the upper to the lower reservoir. The flow of water is used to power a turbine with a generator to produce electricity, which is described as “discharging.”

PHS power plants represent approximately 99% of worldwide installed electrical storage capacity, which is almost 3% of global generation capacity [1,5].

(ii) **Compressed air energy storage**

The CAES technology has been used for different industrial applications since the nineteenth century. Due to its availability, air is used as storage medium. Initially air is compressed and stored in either an underground structure or an above-ground system of vessels or pipes using electricity. When it is required latter on, the compressed air is mixed with natural gas, burned, and expanded in a modified gas turbine to generate electricity.

The main advantage of CAES is its large capacity. Its disadvantages are low overall efficiency and the limitation of geographic locations.

(iii) **Flywheel energy storage**

The basic idea of storing energy in FES is that rotational energy is stored in an accelerated rotor, a massive rotating cylinder. The main components of a flywheel structure consist of a rotating body/cylinder, which comprises of a rim attached to a shaft, in a compartment, the bearings and the transmission device. The latter comprises of motor/generator mounted onto the stator. The energy stored in the flywheel is maintained by keeping the rotating body at a

constant speed. The amount of energy stored can be increased by increasing the speed.

However, electricity can be extracted from the system by the same transmission device by reducing the rotational speed of the flywheel.

10.3.2 Electrochemical storage systems (batteries)

Under this section, several types of batteries will be covered. Only a brief discussion will be given here. Readers who are interested in a detailed discussion of the subject are advised to refer to [1,5]. They may be classified as secondary battery types and flow battery types. The batteries under secondary battery types include lead acid, nickel cadmium/nickel metal hydride (NiCd/NiMH), lithium-ion, metal air, sodium sulfur, and sodium nickel chloride, while those under flow battery types include a redox flow batteries and hybrid flow batteries.

10.3.2.1 Secondary batteries

(i) Lead acid (LA) battery

LA batteries are considered the world's most widely used battery type. They have been around since approximately 1890. They are used in both mobile and stationary applications. Their typical applications include emergency power supply systems, stand-alone systems with PV, and battery systems for mitigation of output fluctuations from wind power and as starter batteries in vehicles. In the period from 1910 to 1945, many LA batteries were used for storage in grids. Stationary LA batteries are expected to meet far higher product quality standards than starter batteries. LA batteries have the disadvantage of decreasing its usable capacity when high power is discharged. They also sever other drawbacks including lower energy density and the use of lead, which is a hazardous material prohibited or restricted in various jurisdictions. Their advantages include a favorable cost/performance ratio, easy recyclability, and a simple charging technology. Research and development conducted on LA batteries aimed to improve their behavior for microhybrid electric vehicles.

(ii) Nickel cadmium and nickel metal hydride battery

NiCd batteries have been available since nearly 1915. However, NiMH batteries were introduced about 1995. In comparison to LA batteries, nickel-based batteries have a higher power density, a slightly greater energy density, and the number of cycles is higher. NiCd batteries are considered a very successful battery product. They are the only batteries that have good performance even at temperatures as low as -20 to -40°C .

A major application of NiMH batteries is in hybrid vehicles, whereby sealed NiMH batteries are almost exclusively used to operate these vehicles available on today's market.

(iii) Lithium ion battery (Li-ion)

Since around the year 2000 Li-ion batteries have become the most important storage technology in the areas of portable and mobile applications such as laptops, cell phones, electric bicycles, and electric cars. They are characterized

by having high cell voltage levels of up to 3.7 V nominal which means that the number of cells in series with the associated connections and electronics can be reduced to obtain the target voltage. Consequently, it is possible to replace three NiCd or NiMH cells which have a cell voltage of only 1.2 V by one Li-ion cell. Li-ion batteries have several advantages including (a) their high gravimetric energy density, and the possibility of large cost reductions via mass production; (b) generally, they have a very high efficiency, typically in the range of 95%–98%; and (c) they are characterized by the possibility of realizing almost any discharge time ranging from seconds to weeks which makes them very flexible and universal storage technology.

The main problem of Li-ion battery technology is the safety issue. This is because most of the metal oxide electrodes are thermally unstable and can decompose at elevated temperatures, releasing oxygen which can lead to a thermal runaway. A way forward to minimize this risk is to equip Li-ion batteries with a monitoring unit to avoid over-charging and over-discharging.

Li-ion battery technology is currently under further research and development, and there is considerable potential for further progress. The attention is currently focused on the development of cathode materials.

(iv) **Metal air battery**

A metal air (Me-air) electrochemical cell is made of a pure metal anode and a cathode, which is connected to an unlimited supply of air. Only the oxygen in the air is needed in order to have electrochemical reaction. The most attractive Me-air battery is the lithium air battery because of its high theoretical specific energy which is equal to 11.14 kWh/kg, excluding oxygen. This corresponds to almost 100 times more than other battery types and even greater than petrol which is equal to 10.15 kWh/kg. It should be pointed out that oxygen is not stored in the battery. Since the high reactivity of lithium with air and humidity can cause fire, this represents a high safety risk.

Presently, the only technical feasible Me-air batteries are zinc air batteries, with a theoretical specific energy of 1.35 kWh/kg excluding oxygen. These batteries have some properties of fuel cells and conventional batteries, whereby the zinc is the fuel. The reaction rate can be controlled by varying air flow, and oxidized zinc/electrolyte paste can be replaced with fresh paste.

Rechargeable zinc air cells are difficult to design because zinc precipitation from the water-based electrolyte needs to be closely controlled. An acceptable electrically rechargeable ME-air system can potentially offer low materials cost and high specific energy. However, there is still some time to go before it reaches to market stage.

(v) **Sodium sulfur battery (NaS)**

Figure 10.2 shows the basic components of NaS battery. It consists of a positive electrode made of liquid sulfur, a negative electrode made of liquid sodium and an electrolyte separating the two electrodes made of a solid beta alumina ceramic. In order to keep the electrodes in a liquid state (melted), the battery temperature must be kept between 300 and 350°C. The typical life

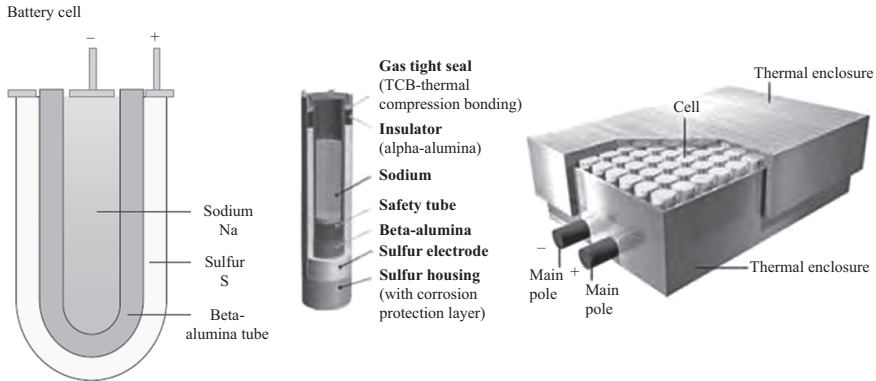


Figure 10.2 (a) Basic components of NaS and (b) 50 kW module [1]. (Reproduced with permission from IEC White Paper, *Electrical Energy Storage—White Paper* © 2011 IEC Geneva, Switzerland. www.iec.ch.)

cycle of NaS batteries is about 4,500 cycles and its discharge time is from 6 hours to 7.2 hours. They have an AC-based round-trip efficiency of about 75% and have fast response. This makes NaS batteries economically viable to be used in combined power quality and time shift applications with high energy density. The main drawback of NaS batteries is the requirement of a heat source to maintain the operating temperatures. Such a source uses the battery's own stored energy, resulting in partially reducing the battery performance. Normally, the temperature of the battery can be almost maintained by just its own reaction heat, by ensuring appropriately dimensioned insulation.

NaS batteries are suitable for applications with daily cycling. NaS battery technology is likely to be very attractive and interesting for both utilities and large consumers because the response time of NaS batteries is in the range of milliseconds and they also can meet the requirements of grid stabilization.

(vi) **Sodium nickel chloride battery (NaNiCl)**

The NaNiCl battery is classified as a high-temperature battery, similar to NaS battery. Its operating temperature is around 270°C. It is better known as the ZEBRA (Zero Emission Battery Research) battery [1,6]. It has been commercially available since around 1995. Its positive electrode is made of nickel chloride compared to sulfur in case of NaS batteries. NaNiCl batteries have the ability to withstand limited overcharge and discharge. Compared to NaS batteries, NaNiCl batteries have potentially better safety characteristics and a higher cell voltage. They have the tendency of developing low resistance when faults occur. The advantage of this is the loss of the voltage from only one cell, instead of premature failure of the whole system, when cell faults in serial connections occur. These batteries have been successfully implemented in several electric vehicle projects such as Think City and Smart EV. This makes them an attractive opportunity for fleet applications.

Current research is focusing on developing advanced versions of the ZEBRA battery with higher power densities that suits hybrid electric vehicles applications, and also high-energy versions suitable for storing renewable energy for load-leveling and industrial applications.

10.3.2.2 Flow batteries

A flow battery is an electrochemical device that converts the chemical energy in the electroactive materials directly to electrical energy, similar to a conventional battery and fuel cells [7]. Unlike conventional secondary batteries, whereby the energy is charged and discharged in the active masses of the electrodes, the energy in a flow battery, which is also a rechargeable battery, is stored in one or more electroactive species that are dissolved in liquid electrolytes. Normally, the electrolytes are stored externally in tanks and pumped through the electrochemical cell that changes chemical energy directly to electricity and vice versa. The power is determined by the size and design of the electrochemical cell, while the energy depends on the size of the tanks. This characteristic makes flow batteries suitable to a wide range of stationary applications. Flow batteries are initially developed by NASA in the early 1970s as EES for long-term space flights. Currently, they are becoming attractive for storing energy for durations extending from hours to days with a power of up to several MWs [1].

Flow batteries may be classified into two namely: redox flow batteries (RFBs) and hybrid flow batteries (HFBs).

(i) Redox flow battery

Redox stands for “reduction/oxidation” [7,8]. RFBs are systems in which all the electroactive materials are dissolved in a liquid electrolyte. Figure 10.3 shows a schematic diagram of a RFB system, whereby a renewable power source (wind/solar) is used to charge an RFB and when required the stored energy is supplied (discharged) to consumers.

Basically a RFB contains two liquid electrolyte dissolutions containing dissolved metal ions as active masses, which are pumped to the opposite sides of the electrochemical cell. The electrolytes at the negative and positive electrodes are called anolyte and catholyte, respectively. During charging and discharging, the metal ions stay dissolved in the fluid electrolyte as liquid, that is, no phase change of these active masses takes place. Anolyte and catholyte flow through porous electrodes, separated by a membrane which allows protons to pass through it for the electron transfer process (see Figure 10.4). During the exchange of charge, a current flows over the electrodes, this is supplied by a battery-powered source as shown Figure 10.4. During discharge, the electrodes are continually supplied with the dissolved active masses from the tanks; once they are converted the resulting product is removed to the tank. Theoretically, an RFB can be “recharged” within a few minutes by pumping out the discharged electrolyte and replacing it with recharged electrolyte. For this reason, RFBs are becoming attractive for mobile applications. However, the energy density of the electrolytes is still too low to be adopted for electric vehicles applications. Several redox pairs

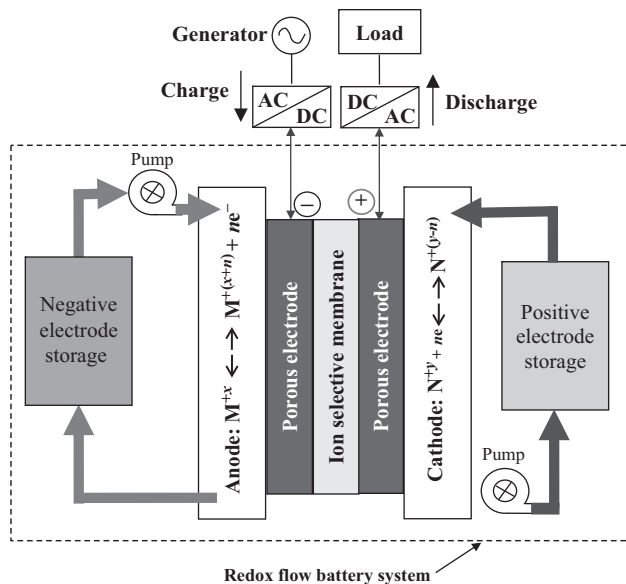


Figure 10.3 A schematic diagram of a redox flow battery system with electrodes shown in a discharge mode [after 7]

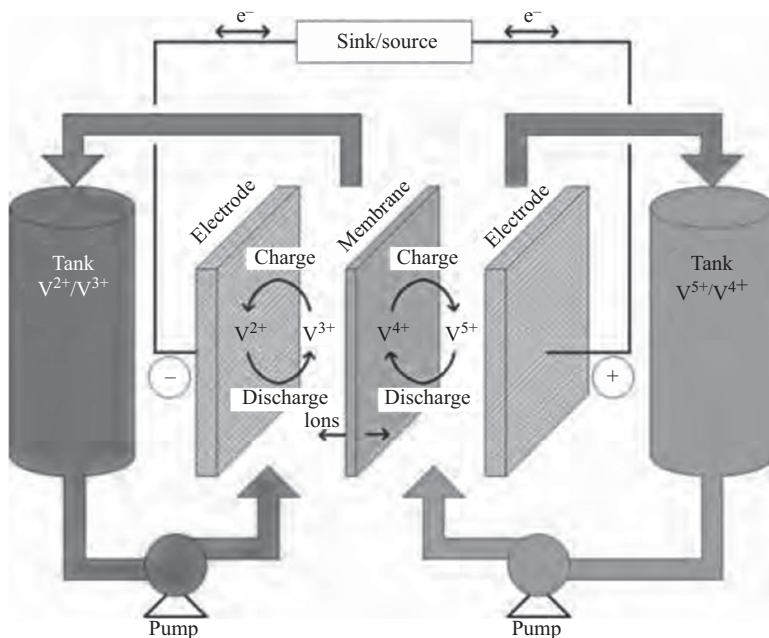


Figure 10.4 A Schematic diagram of vanadium redox flow battery [1].
(Reproduced with permission from IEC White Paper, Electrical Energy Storage—White Paper © 2011 IEC Geneva, Switzerland. www.iec.ch)

have been investigated and tested in RFBs including Fe–Ti system, Fe–Cr system, and poly S–Br system (Regenesys installation in the UK with 15 MW and 120 MWh). The vanadium redox flow battery (VRFB) has been developed the furthest. It has been piloted since approximately 2000 by companies including Prudent Energy in Canada and Cellstrom in Australia. In the vanadium system, V^{+2} is oxidized to V^{+3} at the anode, and V^{+5} is reduced to V^{+4} at the cathode [7]. Thus, the VRFB uses a V^{2+}/V^{3+} redox couple as oxidizing agent and a V^{5+}/V^{4+} redox couple in mild sulfuric acid solution as reducing agent. The main advantage of this battery is the use of ions of the same metal on both sides. It has been recognized that crossing of metal ions over the membrane cannot be prevented completely, which is the case for every RFB. In case of VRFBs, the only result is a loss in energy. For other RFBs, which use ions of different metals, the crossover causes an irreversible degradation of the electrolytes and a loss in capacity. It should be pointed out that the VRFB was pioneered at the University of New South Wales, Australia, in the early 1980s. SEI has been recently installed a VRFB storage system of up to 500 kW and 10 hours in Japan. The same company has also used a 3 MW, 1.5 seconds VRFB in power quality applications.

(ii) **Hybrid flow battery**

A HFB is defined by one or more electroactive species being deposited as a solid [9]. Hybrid flow cells combine features of conventional secondary batteries and RFBs, whereby one of the active masses is internally stored within the electrochemical cell, while the other remains in the liquid electrolyte and is stored externally in a tank. The capacity of the battery depends on the size of the electrochemical cell. Examples of a HFB include zinc–cerium (Zn–Ce) [10] and zinc–bromine (Zn–Br) systems. The anolyte in these examples consists of an acid solution of Zn^{2+} ions. During charging Zn is deposited at the electrode, whereas at discharging Zn^{2+} returns back into solution. A microporous polyolefin material is used for the membrane and for most of the electrodes carbon–plastic composites are used. Many companies are investing on the commercialization of the Zn–Br HFB, which was originally developed by Exxon in the early 1970s. ZBB Energy and Premium Power, in the USA, sell trailer-transportable Zn–Br systems with unit capacities of up to 1 MW/3 MWh for utility-scale applications. Systems of 5 kW/20 kWh for community energy storage are in development as well.

10.3.3 Chemical ESS

Chemical energy storage covered under this section includes H_2 and SNG as secondary energy carriers. These two gases have the ability to store electrical energy in large quantities. This can be achieved by using the “surplus” electricity, generated particularly from renewable energy sources, to produce H_2 via water electrolysis. Once the H_2 is produced, then it can be used as an energy carrier in various ways, for example, as pure H_2 or as SNG. Chemical energy storage is the only concept that allows storage of large amounts of energy, in the range of TWh, and for large

periods of time, even as seasonal storage. This is despite the low overall efficiency of H_2 and SNG compared to other storage technologies such as PHS and Li-ion chemical energy storage.

H_2 and SNG as universal energy carriers have additional advantage. They can be used in different sectors, such as transport, mobility, heating, and the chemical industry.

(i) **Hydrogen**

A H_2 storage system typically consists of an electrolyzer, a H_2 storage tank, and a fuel cell. An electrolyzer is an electrochemical converter whose function is to split water with the help of electricity into H_2 and oxygen. It is an endothermic process, which means that for the reaction to take place heat must be supplied. Once H_2 is produced, it is stored under pressure in gas bottles or tanks, which can be done practically for an unlimited time. To generate electricity using H_2 , both H_2 and oxygen (normally taken from air) are supplied to a fuel cell, where an electrochemical reaction which is the reverse of water splitting, takes place. In this process, the reaction between the H_2 and oxygen produces water, heat, and generation of electricity. It will be noted that due to economical and practical reasons, oxygen produced from electrolysis is normally released, and not stored. However, in the process of electricity generation, the required oxygen is taken from the surrounding atmosphere. In addition to fuel cells, gas motors, gas turbines and combined cycles of gas, and steam turbines are under consideration for electrical generation. Generation plants based on H_2 systems with fuel cells, which is less than 1 MW and gas motors with rating under 10 MW, can be adopted for combined heat and power generation in decentralized installations. However, gas and steam turbines with up to several hundred MW could be used as peaking power plants.

As with regard to the storage of the H_2 different methods are used. It can be stored either as a gas under high pressure, a liquid at very low temperature, adsorbed on metal hydrides, or chemically bonded in complex hydrides. However, for stationary applications, the most popular approach is gaseous storage under high pressure. For smaller amounts of H_2 , they are normally stored in above-ground tanks or bottles under pressures up to 900 bar. However, for larger amounts of H_2 , they are stored in underground piping systems or even salt caverns with several $1,00,000\text{ m}^3$ volumes under pressures up to 200 bar.

During the last 25 years, many R&D projects were initiated. They have successfully demonstrated the feasibility of H_2 technology. One such project is the PURE project in Unst, Shetland, Scotland, and the UK [11]. Other examples include the self-sufficient project in island of Utsira, Norway, and the hybrid power plant from Enertrag in Germany [12]. The common feature of these projects is the use of wind energy to produce H_2 via electrolysis, if the generated electricity cannot be consumed locally or directly it is fed into the grid. On demand, the stored H_2 is either converted back to electricity using fuel cells or as in case of hybrid power plant in Germany the H_2 is added to the biogas to be used to run a gas motor.

(ii) **Synthetic natural gas**

The alternative option to H_2 to store electricity as chemical energy is to synthesis methane, which is known as “synthetic natural gas (SNG).” In this case, after splitting the water into H_2 and oxygen in an electrolyzer, additional step is needed to produce methane in a methanation reactor in which H_2 and carbon dioxide (CO_2) react. Similar to the H_2 , the produced SNG may be stored in pressure tanks, underground, or fed directly into the gas grid. The CO_2 required for the methanation process can be obtained from many sources including fossil-fuel-based power stations, industrial installations, or biogas plants.

Transport of CO_2 and H_2 gases from their sources, that is, the CO_2 source and the electrolysis plant, respectively, to the methanation plant must be avoided in order to minimize energy losses. Accordingly, it is preferred that the production of SNG is done at the locations where both CO_2 and surplus of electricity are available. The use of CO_2 from biogas production processes is particularly promising because it is a widely used technology. In any case, onsite storage of the gases is needed, because the methanation is a continuously running process.

Figure 10.5 shows a comprehensive overview of the concept of the combined use of H_2 and SNG as chemical energy storage.

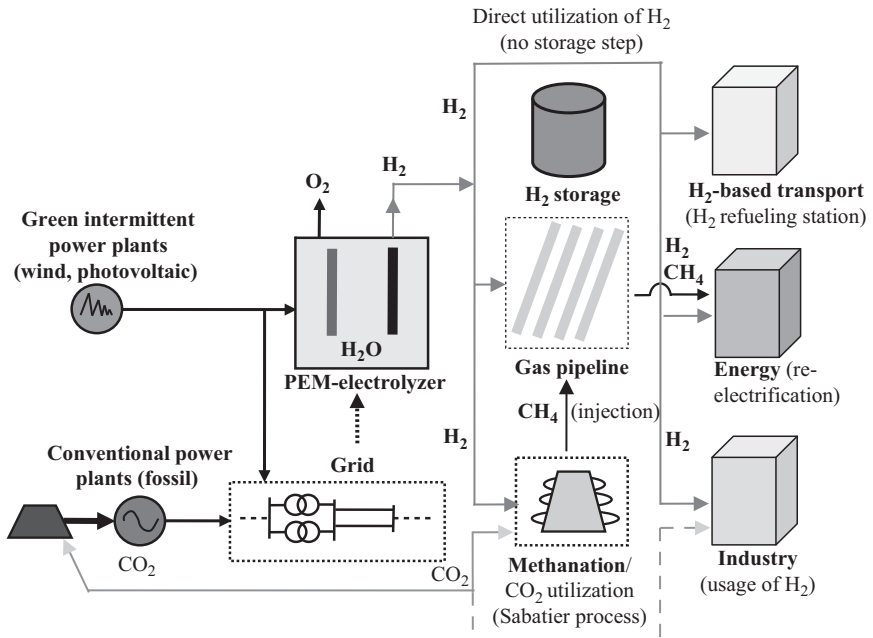


Figure 10.5 A comprehensive overview of the concept of the combined use of H_2 and SNG as a chemical energy storage/carriers [after 1]

10.3.4 *Electrical storage systems*

Double-layer capacitors (DLCs) and superconducting magnetic energy storage (SMES) will be covered under this section as follows.

(i) **Double-layer capacitors**

The technology of electrochemical DLCs, which is also known as super-capacitors, has been around for more than 60 years [1]. DLCs have properties that are intermediate between those of batteries and the classical capacitors, which are widely used in electronics [13]. This is due to their almost unlimited cycle stability, extremely high power capability, and their energy storage capability, which are several orders of magnitude higher than that due to traditional capacitors.

However, the two main characteristics of DLCs are (i) their extremely high capacitance values, which could be in the order of many thousand farads, and (ii) their capability of very fast charge and discharge because of their extraordinarily low inner resistance. They have other advantages including durability, high reliability, no maintenance requirements, long lifetime, and operation over a wide temperature range and in different environmental conditions including hot, cold, and moist conditions. Their lifetime can reach 1 million cycles, which is equivalent to 10 years of operation without any degradation. The only problem is the solvent used in the capacitors, which deteriorates in 5 or 6 years irrespective of the number of cycles.

DLCs are environmentally friendly and easily recycled or neutralized. Their typical efficiency is about 90% and discharge times are in the range of seconds to hours. Their specific power density can reach approximately 10 times more than that of conventional batteries. Exception to this is the very-high-power lithium batteries whose specific power density can be almost the same as that of DLCs. However, the specific energy density of DLCs is almost 10 times lower than that due to conventional batteries.

With regard to application of DLCs, they particularly suit the applications that have large number of short charge/discharge cycles, where their high-performance characteristics can be used. DLCs, however, are not suitable for the storage of energy over longer periods of time, due to their high self-discharge rate, their low energy density, and high investment costs.

Since almost 1980, DLCs have been widely applied in consumer electronics and power electronics. They have also been identified to be ideally suited as UPSs to bridge short voltage failures.

An emerging application of DLCs is electric vehicles, whereby they can be used as a buffer system during the acceleration process and regenerative braking [6].

(ii) **Superconducting magnetic energy storage**

The principles used by SMES systems to store energy are based on electrodynamics [1]. An SMES system stores the electrical energy in the magnetic field within a cooled superconducting coil [14]. The magnetic field is generated by the flow of direct current in a superconducting coil [1], which is

cryogenically cooled beyond its superconducting temperature of -269°C [14]. The resistance of the material to electric currents, at this temperature, collapses, and accordingly the resulted small electrical resistance helps in achieving very high efficiencies of up to 97% in addition to enabling storage almost indefinitely [14].

The main component of SMES systems is a coil made of superconducting material in addition to power conditioning equipment and a cryogenically cooled refrigeration system. Their main advantage is their very fast response time, that is, the required power can be obtained almost instantaneously. They have also very high power output which can be provided for a short period of time. SMES systems have no moving part. However, their overall reliability crucially depends on the refrigeration system. Theoretically, the energy can be stored indefinitely as long as the cooling system is in good operating condition. However, storage for long time is limited by the energy demand of the refrigeration system. Currently, large SMES systems with rated power greater than 10 MW are mainly used in particle detectors for high-energy physics experiments and nuclear fusion. Up till now only a few and rather small SMES systems are commercially available, which are mostly used for power quality control in manufacturing plants such as microchip fabrication facilities [15].

10.3.5 Thermal energy storage systems

TES systems store available heat in an insulated repository using different methods. The stored heat is then used in various industrial and residential applications including space heating or cooling, hot water production, or electricity generation. Similar to other storage systems, the purpose of deployment of TES systems is to overcome the mismatch between demand and supply of energy, which in this case thermal energy. Accordingly these systems are important for effective integration of renewable energy sources.

TES may be classified into three technologies [1] including storage of sensible heat, storage of latent heat, and thermochemical storage, which include adsorption heat storage and reversible chemical reactions [16]. Figure 10.6 shows an overview of major technique of storage of solar thermal energy [17].

(i) Sensible heat storage

Sensible heat storage (SHS) is considered as one of the mature, best-known, and most widespread technologies. Example of this technology is the domestic hot water tank. The storage medium can be a liquid such as water or thermo-oil, or a solid such as concrete or the ground [1]. Thermal energy is mainly stored due to the change of temperature of the storage medium. The capacity of a storage system is defined by the specific heat capacity and the mass of the medium used.

Thermal energy is stored in SHS by raising the temperature of a solid or liquid. During the process of charging and discharging, SHS system utilizes the heat capacity and the change in temperature of the material. The amount

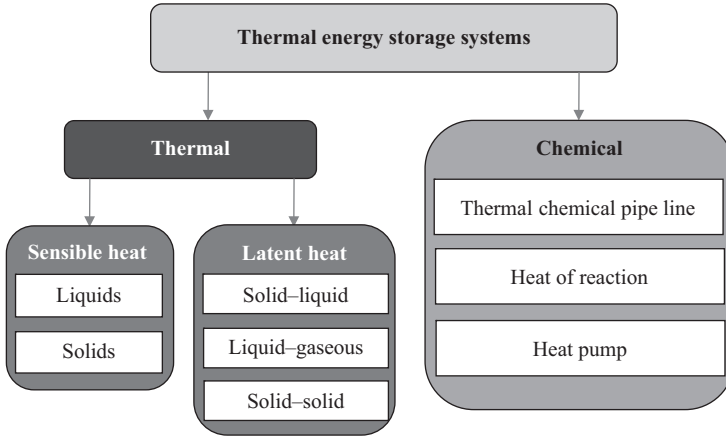


Figure 10.6 Classification of thermal storage of solar energy [after 17]

of heat stored depends on the specific heat of the medium, the temperature change, and the mass of storage material as shown in (10.1) [17]:

$$Q = \int_{T_1}^{T_2} mC_p dT, \text{ or} \quad (10.1)$$

$$Q = mC_p(T_2 - T_1)$$

where Q is the amount of heat charged/discharged to a SHS system, C_p is the specific heat capacity of the storage material, m is the mass of storage material, T_1 is the initial store temperature, and T_2 is the final store temperature.

Water is considered as the best SHS liquid available due to its high specific heat and also because it is inexpensive. However, above 100°C, oils, molten salts, and liquid metals, etc. are usually used. However, rock bed type storage materials are preferred for air heating applications.

(ii) **Latent heat storage**

Latent heat storage (LHS) is realized by utilizing phase change materials (PCMs) as storage media. The available PCMs that can be used for LHS system include organic materials such as paraffin and inorganic materials such as salt hydrates [1].

The principles of LHS are based on the heat absorption or release when a storage material is subjected to a phase change from solid to liquid or liquid to gas or vice versa [17]. Latent heat is also known as “hidden” heat, because the temperature does not change during energy transfer. The ice cooler is considered as the best-known latent heat, or cold, storage system in which ice is used in an insulated container or room for maintaining the low temperature of food during hot climate conditions [1].

Presently most PCMs use the solid-liquid phase change. For example, in concentrated solar power (CSP) plants molten salts are used as a thermal

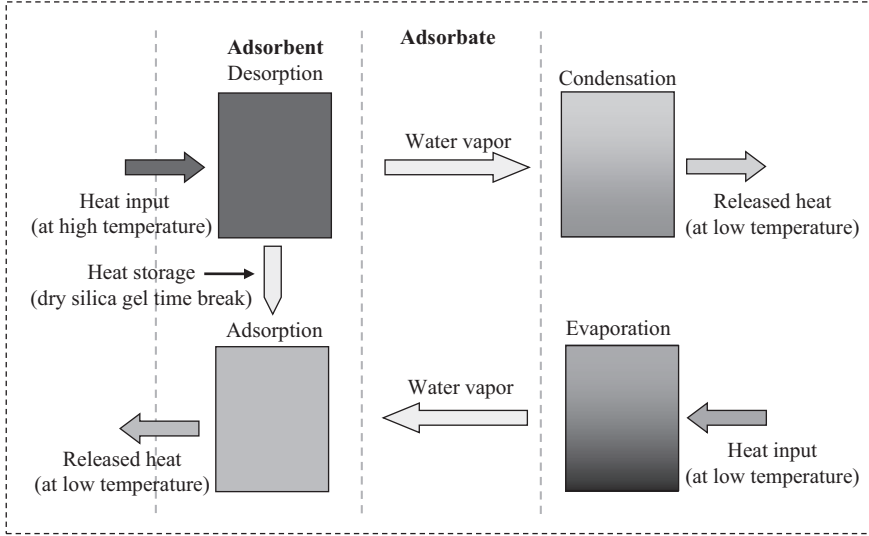


Figure 10.7 Operating principle of a closed-cycle desorption/adsorption heat storage [after 10]

storage medium [18]. LHS has the advantage of its capacity to store large amounts of energy in a small volume and with a minimal temperature change, which allows efficient heat transfer [1].

The storage heat capacity of an LHS system with a PCM medium [17] can be found as follows:

$$Q = \int_{T_1}^{T_m} m C_p dT + m a_m \Delta h_m + \int_{T_m}^{T_2} m C_p dT, \text{ or} \quad (10.2)$$

$$Q = m [C_{sp}(T_m - T_1) + a_m \Delta h_m + C_{lp}(T_2 - T_m)]$$

where Q is the storage heat capacity of an LHS system, m is the mass of heat storage medium (kg), a_m is the fractional melted factor, C_p , C_{sp} , and C_{lp} are the specific heat (J/kg K), the average specific heat between T_1 and T_m (kJ/kg K), the average specific heat between T_m and T_2 (J/kg K), respectively, T_m , T_1 , and T_2 are the melting, initial, and final temperatures, respectively, and Δh_m is the heat of fusion per unit mass (J/kg).

(iii) **Sorption (adsorption, absorption) storage systems**

Figure 10.7 shows the operating principle of a closed-cycle desorption/adsorption heat storage [19]. Desorption is also termed as “absorption.” This figure shows a closed sorption system utilizing water as adsorbate (adsorptive). During the process of desorption, an adsorbent such as silica gel or zeolite is heated up by heat from a high-temperature source. A working fluid, such as water vapor, is desorbed from the adsorbent and condensed in a

condenser at low temperatures. The resulting heat of condensation is withdrawn from the system. It is possible to store the dried adsorbent and the separated working fluid as long as desired. Desorption mode stops when the adsorbent is dried out. This depends on the heat magnitude supplied to the adsorber, that is, adsorbate is condensed in the condenser, or when the adsorbent and adsorbate are separated.

During the process of adsorption, adsorption heat must be discharged from the adsorber. This occurs when the working fluid takes up low-temperature heat in an evaporator. Subsequently, the vapor of the working fluid adsorbs on the adsorbent and heat of adsorption is released at high temperatures. If this does not happen, this means that sorption process has reached its thermodynamic equilibrium and the flow of water vapor stops. When the adsorbent is saturated with water vapor, the process ends and the tank is discharged. When this happens, it needs to be recharged again (desorption). The temperature of the released heat can reach up to 200 °C depending on the adsorbent/working fluid pair, while the energy density may reach up to three times that of SHS with water. Sorption storage systems (SSSs), however, are more expensive due to their complexity.

10.4 Benefits of ESSs

Energy storage can potentially provide several benefits to the future Smart Grid that will enhance its performance, operability, and security as well as reducing the cost of energy production, and delivery. The potential benefits of energy storage include [20,21]:

- offset additional need for peak generating capacity,
- enhance optimal operation of existing generation facilities,
- provide ancillary services such as load following, area regulation, and spinning reserve,
- reduce transmission congestion,
- defer transmission and distribution upgrades and provide an alternative to inflexible lumpy transmission, and distribution capacity additions,
- support and enhance demand response resources,
- improve power quality,
- help in peak shaving and load leveling,
- reduce reverse power flows,
- minimize network losses,
- help in restoration of power after the occurrence of a fault,
- support the network when subjected to islanding conditions,
- help in meeting regulatory requirements, and
- instrumental in facilitating the integration of intermittent renewable energy sources-based generation plants and the growth of its penetration into grid. This is particularly important as energy storage can be used to reduce the power fluctuation caused by the intermittent renewable energy sources-based generation plant.

Energy storage can also be used to time shift renewable energy-based generation from off-peak to on-peak times. This in turn would lead to reduction in potential transmission bottleneck by storing the energy close to the end user or by using underutilized transmission paths at night.

10.5 Applications of ESSs

Applications of ESSs may be broadly divided into two areas, namely (i) electrical network energy storage and (ii) transport/mobility energy storage [14].

Figure 10.8 shows time versus power operational range of the different energy storage technologies [22]. The same figure also shows suitability of various ESSs for both electrical networks (utility) and transport applications. It can be seen from the figure that time and power ranges for transport applications are from seconds to hundreds of minutes and from tens of kilowatts to tens of megawatts, respectively, while those related to utility-scale applications are from tens of minutes to hours and from MWs to GWs.

It will be noted that key performance criteria used in case of electrical networks and integration of renewable energy are energy storage capacity, power output, and life cycle. Due to their long life cycle, storage systems that are based on reversible physics such as CAES or pumped hydro have been preferred in

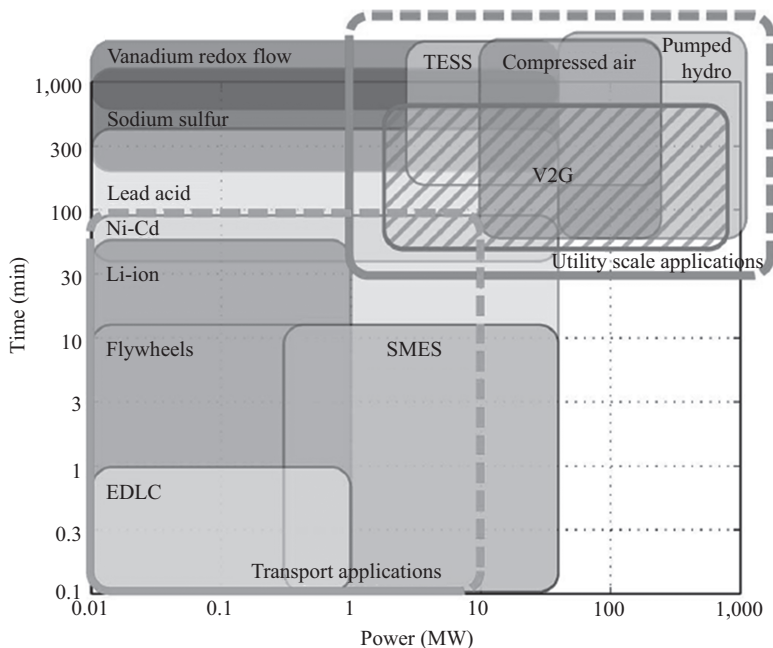


Figure 10.8 Time versus power operational range of different energy storage technologies [22]. Reproduced with the permission from IEEE

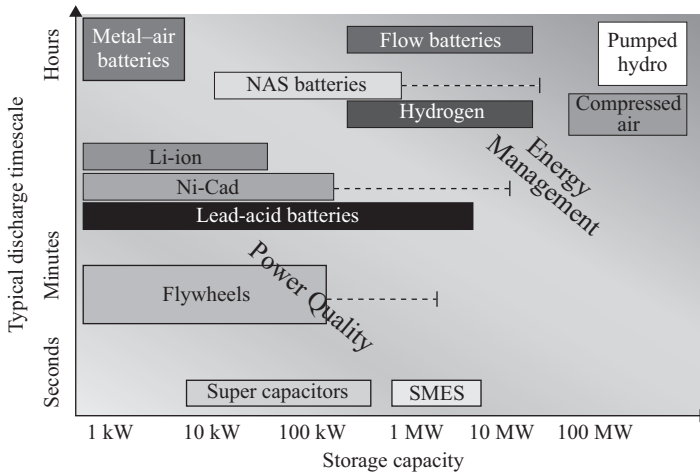


Figure 10.9 Typical storage capacity versus discharge times for energy storage systems [14]. Reproduced by permission of Publications Office of the European Union

comparison to electrochemical batteries that suffer from ageing problems and are difficult to recycle.

In case of transport applications, the key performance criteria are portability, scalability, and energy and power densities. Because of their modularity and portability, batteries are considered the most viable option for transport applications, despite many restrictive issues, including limited life.

10.5.1 Electrical network energy storage applications

Applications of electrical network energy storage involve systems/devices that are suitable for power quality applications, energy management applications or for both. Figure 10.9 [14] shows the typical capacity of several ESSs plotted against discharge time to identify which of them are suitable for power quality application and which are suitable for energy management.

10.5.2 Transport and mobility energy storage applications

It has been recognized that energy storage can be an attractive option for reducing fuel consumption, or for providing an alternative form of motion power to the gasoline-fueled internal combustion engine.

Application of energy storage to the transport and mobility sector can lead to improvement in system efficiency as well as reduction in greenhouse gas emission. Several storage systems have been considered for transport purposes, including batteries, super capacitors, H_2 , and flywheels. It will be noted that there is an overlap between the storage systems that have potential applications in the transport area with those that are used in electrical network. Table 10.1 shows an

inventory of energy storage technologies that have potential use for both transport and electrical network energy storage applications [14].

10.6 Energy storage systems and integration of wind power-based plants

In this section, the application of ESSs to facilitate effective and efficient integration of wind power-based generation (WPBG) into Smart Grid distribution networks will be discussed in detail. This will include (i) mitigation of power fluctuation caused by WPBG and (ii) improvement in low-voltage-ride-through (LVRT) capability

10.6.1 Mitigation of power fluctuation

It is well-known that power output of WPBG is fluctuating in response to wind speed variation [23,24]. Fast fluctuations of wind generators power output that falls in the time range of up to a minute can cause network frequency and voltage variations, particularly in isolated power systems which in turn lead to the deterioration of the power quality [25,26]. The effect of power fluctuations can be mitigated by using ESSs. Storage technologies that are suitable for mitigating power fluctuations are characterized by having high ramp power rates and high cycling capability. This is due to the requirements of fast power modulation and continuous operation. Such requirements can be met by ESSs including batteries (apart from conventional LA batteries), flow batteries, and particularly short time scale energy storage such as super-capacitors, flywheels, and SMES, which are considered very suitable for this kind of application.

Doubly fed induction generators (DFIGs) are widely used in generating electricity from wind power due to its various favorable characteristics including the flexibility features of variable speed operation, reduced converter size, and the ability to control the real and reactive power outputs [27]. In this context, it has been proposed by many researchers that ESS may be integrated into the DC-link of wind turbine-driven DFIG to improve, among other things, their power output fluctuations [26–30]. This is achieved by using the storage element to smooth the generator's power output by injecting real power (using the stored energy) during low wind conditions while storing energy during high wind conditions [27].

Figure 10.10 shows a typical configuration of a wind turbine-driven DFIG equipped with a super-capacitor-based ESS [29]. The high-speed DFIG is driven by a low-speed wind turbine through a gearbox. The DFIG is a wound-rotor induction machine. As the figure shows the DFIG is connected to the grid at both stator and rotor terminals. The stator is directly connected to the grid, while the rotor is fed through a variable-frequency converter. The latter consists of a rotor-side converter (RSC) and a grid-side converter (GSC) connected back to back through a DC link. The converter usually has a rating which is a fraction (25%–30%) of the DFIG nominal power. Consequently, the wind turbine generator (WTG) system rotates at a speed in the range of $\pm(25\%–30\%)$ around its synchronous speed, and its active

Table 10.1 An inventory of energy storage technologies* [14]. Reproduced by permission of Publications Office of the European Union

Technology type	System energy density	Efficiency of recovery	Development	Deployment	Illustrative economic costs	Current investment		Advantages	Disadvantages	Suitability for		
						EU	Rest of world			Energy management	Power quality	Transport
Advanced battery systems												
Super-capacitors	0.1–5 Wh/kg	85%–98%	Developing	Widespread (small scale)	2002: 200–1,000 (€/kW)	3.6M€ under Joule III FP4	Unknown	Long life cycle, high efficiency	Low energy density Toxic and corrosive compounds	✓✓	✓✓✓	✓✓✓
Nickel batteries	20–120 Wh/kg	60%–91%	Available	Limited	200–750 (€/kWh)			High-power and energy densities Good efficiency	Ni–Cd: cadmium Highly toxic Ni–Zn, NiMH and Na–NiCl ₂ require recycling	✓✓	✓✓✓	✓✓✓
Lithium batteries	80–150 Wh/kg	90%–100%	Available	Growing for small-scale applications	150–250 (€/kWh) [high energy, industrial application]	5M€ under FP6	USA, Japan, Taiwan	High power and energy densities High efficiency	High cost Lithium oxides and salt require recycling Polymer solvents and carbon must be made inert	✓✓	✓✓✓	✓✓✓
Lead-acid batteries	25–45 Wh/kg	60%–95%	Available	Widespread	50–150 (€/kWh)			Low capital cost	Lead requires recycling	✓✓	✓✓✓	✓✓✓
Zinc–bromine flow batteries	37 Wh/kg	75%	Early phase of commercialization	Limited	2 MWh battery (1.8m€)			High capacity	Low energy density	✓✓✓	✓✓	
Vanadium flow batteries		85%	Early phase of commercialization	Limited	1,280 €/kW			High capacity	Low energy density	✓✓✓	✓✓	

Metal-air batteries	110–420 Wh/kg	~50%	Electrically rechargeable cells – developing	Limited (large scale)				High energy density Low cost Environmentally benign	Poor electrical recharge ability Short recharge lifetime	✓✓✓	✓	✓
Sodium–sulfur batteries	150–240 Wh/kg	>86%	Available	Mainly in Japan	170 €/kWh		Japan	High power and energy densities High efficiency High production costs Na requires recycling	High production costs Na requires Recycling	✓✓✓	✓✓	✓
Fluid storage												
Pumped hydro-electric	N/A	75%–85%	Available	Widespread—90 GW world-wide	140m€–>680m€ for a 1,000 MW plant	Limited	Limited	High capacity, relatively low cost per unit capacity	Disturbs local wildlife and water levels	✓✓✓	✓✓	×
Compressed air energy systems	N/A	80% (Alabama plant)	Available	Limited, one site in the USA and one in Germany	400 €/kWh at plant in Alabama	Limited testing (Italy)	Planned 2.7 GW Plant (Norton, Ohio)	High capacity, relatively low cost per unit capacity	Problematic in obtaining sites for use: Norton, Ohio site is experiencing several legal proceedings	✓✓✓	✓✓	×
Mechanical systems												
Flywheels	30–100 Wh/kg	90%	Available		3,000–10,000 (€/kW)			High power	Low energy density	✓✓✓	✓✓	✓

(Continues)

Table 10.1 (Continued)

Technology type	System energy density	Efficiency of recovery	Development	Deployment	Illustrative economic costs	Current investment		Advantages	Disadvantages	Suitability for		
						EU	Rest of world			Energy management	Power quality	Transport
Electromagnetic systems												
Superconducting magnets		97%–98%	Developed up to 10 MW, potential to increase this to 2,000 MW	In power quality applications, potential for diurnal storage	350 €/kW		Japan, USA	High power	Health impacts for large-scale sites	✓	✓✓✓	×
H ₂												
H ₂ fuel cell	N/A (system outputs <1 kW–3 MW)	25%–58%	Research/developing/ marketed	Limited	6,000–30,000 €/kWh	H ₂ and fuel cell technology platform	Freedom CAR (USA)	H ₂ can be stored for long term Range of cell types for different applications	Expensive catalysts or processing often required	✓✓✓	✓✓✓	✓✓✓
H ₂ internal combustion engine (ICE)	N/A	N/A	Developing	Limited		BMW	Ford/California			✓	✓	✓✓✓

*Values are representative of stationary and transport applications.

Key: ✓✓✓ = Suitable; ✓✓ = Partially suitable; ✓ = Limited suitability; × = Unsuitable

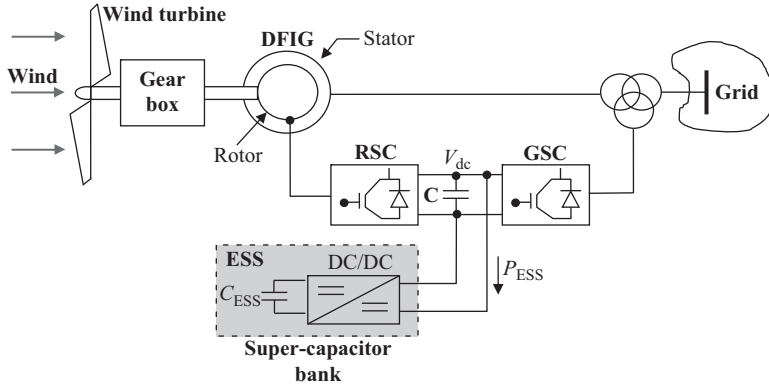


Figure 10.10 A typical configuration of a wind turbine driven DFIG equipped with a super-capacitor-based ESS

and reactive powers can be controlled independently. The ESS shown in Figure 10.10 consists of a super-capacitor bank and a two-quadrant DC/DC converter that is connected to the DC link of the DFIG converters. The way ESS is designed is to act as either a source or a sink of real power and therefore contributes to the control of generated real power output of WTG. The capacitance of the super-capacitor bank can be calculated as follows:

$$C_{\text{ESS}} = \frac{2P_r T}{V_{\text{SC}}^2} \quad (10.3)$$

where C_{ESS} is the capacitance of the super-capacitor bank in farads, P_r is the rated power of the DFIG in watts, V_{SC} is the rated voltage of the super-capacitor bank in volts, and T is the desired time period in seconds that the ESS can supply/store energy at the rated power (P_r) of the DFIG.

An ESS is installed in each WTG rather than a large single central ESS for the entire wind farm. This is because (i) this arrangement ensures a high reliability as the failure of a single ESS unit does not affect the ESS units in other WTGs and (ii) installing an ESS in each WTG ensures the reinforcement of the DC bus of the DFIG converters during transients and consequently enhancing the LVRT capability of the WTG [31].

The super-capacitor is equipped with a control which interacts with WTGs and other controls in order to optimize the net power delivered to the external grid by the entire system. A two-layer constant power control (CPC) scheme is used, which consists of a high-layer wind farm supervisory controller (WFSC) and low-layer WTG controllers. The function of the high-level WFSC is to generate the real power references for the low-layer WTG controllers of individual DFIG wind turbine in response to the real power demand from the grid operator. Low-layer WTG controllers accordingly regulate each DFIG wind turbine to generate the desired

amount of real power. The difference between the available wind energy input and desired active power output is supplied or absorbed by the ESS [29].

10.6.2 Improvement in LVRT capability

10.6.2.1 Grid codes requirements for wind power plants to withstand voltage dips

The voltage of renewable energy-based power plants which are connected to a smart distribution network may be subjected to voltage dips due to various reasons such as faults that occur on the network. In order to maintain the stability of the smart distribution network to which renewable energy-based power plants are connected, it is vitally important to be able to control the voltage of these plants at the common coupling point (CCP) with the network. To achieve this objective grid codes make it a requirement that wind power plants must withstand voltage dips down to a certain percentage of the nominal voltage (0% in some cases) and for a specified duration [31]. These requirements are commonly known as “Low-voltage ride through (LVRT) requirements”. ESS may be applied to improve LVRT capability. Similar to mitigation of power fluctuation case, the suitable ESSs that can be applied to this case are those with high ramp-up rates, which enable a fast power modulation. Therefore, the most suitable ESSs for this application include batteries, flow batteries, and short time scale energy storage such as super-capacitors, flywheels, and SMES.

10.6.2.2 How an ESS can help improving LVRT capability

To explain how an ESS can help improving LVRT capability, let us consider the wind turbine driven DFIG shown in Figure 10.10. As discussed in the previous section, this figure shows an energy storage device is integrated into the DFIG’s bidirectional DC/DC converter, which is coupled with the DC bus. In this topology, the DC bus voltage is controlled by either the GSC or the storage converter. However, the RSC is used to regulate [32] the storage power stored in the ESS.

During normal operating condition when the machine run at super-synchronous speed, the power flows from the rotor windings to the converter, whereby some energy is stored in the ESS while the remainder is exported onto the grid via the GSC. However, when the DFIG operates at subsynchronous speed, there is a deficiency in the power generated by the generator and the difference between the required and generated powers is obtained from the ESS by discharging its stored energy.

When a fault occurs on the grid to which DFIG is connected, the magnitude of the voltage at the terminals of DFIG drops to a value that depends on the severity of the fault. Under this condition, the power output of DFIG delivered to grid is reduced. This in turn leads to unbalanced between the input and output powers of DFIG. The difference between the two powers causes the acceleration of DFIG, which could lead to its isolation from the grid even if the fault is properly cleared.

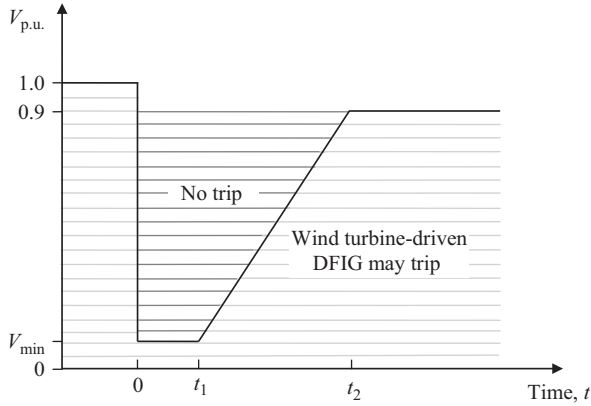


Figure 10.11 Typical LVRT characteristics [after 32]

In order to minimize transients upon reclosing or reestablishment of system connection, it is preferred to maintain the speed constant at its pre-fault value.

Figure 10.11 shows a typical LVRT characteristic [33] that dictates the voltage profile for which a DFIG must remain connected to the system. To be able to meet this requirement, the control system and the hardware need to be modified to manage the energy produced by the WTG during the low-voltage event, otherwise without such management, the power produced by the DFIG under fault conditions will remain within the electric machine, resulting in an increased mechanical speed as stated earlier.

The options that can be used to handle the energy that cannot be delivered to the grid during low-voltage events are as follows [32]:

1. Dumping the energy in a resistor, which is normally connected to the dc bus, to regulate the dc bus to within $\pm 10\%$ of its nominal value.
2. Shorting the rotor windings through a resistor to operate the machine as a conventional induction machine.
3. Dumping the energy in an electrical storage device such as super-capacitor, SMES, and batteries.

The third option is of particular interest as it is very relevant to our discussion related to the application of ESS to improve LVRT. In this context, it is important to work out the size of the storage device that must be able to absorb the energy produced under the worst conditions, which is represented by a three-phase fault. If such fault is assumed to occur time at $t = 0$ (refer to Figure 10.11) and cleared at $t = t_1$, that is, its duration $= t_1$, then the approximate required energy storage capability, E_s , can be determined such that:

$$E_s = V \cdot t_1 = t_1 \text{ per unit (p.u.)} \quad (10.4)$$

where V is the p.u. voltage.

However, the precise energy of the storage device required to determine the precise size of energy storage capacitance can be calculated as equal to the area above the LVRT curve and below 0.9 p.u. line as given in (10.5):

$$E_{LVRT} = P_{base} \{ (0.9 - V_{min})t_1 + (1/2)(t_2 - t_1)(0.9 - V_{min}) \} \quad (10.5)$$

where V_{min} , t_1 , and t_2 are the parameter shown in the LVRT profile curve shown in Figure 10.11.

The energy E_{LVRT} basically equal to the amount of energy that must be managed during the fault. If the maximum voltage across the storage device is equal to V_{DC0} , then the required value of the capacitance can be determined as follows:

$$C_{ESS} = \frac{2E_{LVRT}}{V_{DC0}^2} \quad (10.6)$$

10.7 Summary

This chapter is devoted to ESSs. The characteristics of energy storage devices/systems are discussed in Section 10.2. This is then followed by discussing types and characteristics of EES systems in Section 10.3. The types covered include (i) mechanical storage systems, (ii) electrochemical storage systems (batteries), (iii) chemical ESSs, (iv) electrical storage systems, and (v) TES systems. Section 10.4 is devoted to highlight the potential benefits to Smart Grids in terms of enhancing its performance, operability and security as well as reducing the cost of energy production and delivery. Applications of ESSs are then introduced in Section 10.5. Such applications may be broadly divided into two areas: (i) electrical network energy storage and (ii) transport and mobility energy storage. The application of ESSs to facilitate effective and efficient integration of WPBG into Smart Grid distribution networks is discussed in detail in this Section 10.6. The discussion has focused on (i) mitigation of power fluctuation caused by WPBG and (ii) improvement in LVRT capability.

References

- [1] IEC. *Electrical energy storage, White Paper* [Online]. 2011. Available from <http://www.iec.ch/whitepaper/pdf/iecWP-energystorage-LR-en.pdf> [Accessed 15 June 2015].
- [2] Kondoh J., Ishii I., Yamaguchi H., *et al.* 'Electrical energy storage systems for energy networks'. *Energy Conversion and Management*. 2000;**41**:1863–74.
- [3] European Parliament. *Outlook of energy storage technologies* [Online]. 2008. Available from <http://4dlab.info/energy/energy-storage-outlook-of-energy-storage-technologies.pdf> [Accessed 21 June 2015].
- [4] US DOE (Schoenung S.M.). *Characteristics and technologies for long- vs. short-term energy storage, Sandia Report – SAND2001-0765* [Online].

- March 2001. Available from <http://prod.sandia.gov/techlib/access-control.cgi/2001/010765.pdf> [Accessed 21 June 2015].
- [5] REA (Renewable Energy Association). *Energy storage in the UK: an overview* [Online]. Winter 2015/16. Available from http://www.r-e-a.net/upload/rea_uk_energy_storage_report_november_2015_-_final.pdf [Accessed 10 September 2016].
 - [6] IEA (Espinar B. and Mayer D.). *The role of energy storage for mini-grid stabilization-report IEA-PVPS T11-02* [Online]. 2011. Available from http://www.iea-pvps.org/index.php?id=227&eID=dam_frontend_push&docID=744 [Accessed 13 September 2016].
 - [7] Nguyen T. and Savinell R.F. *Flow batteries* [Online]. *The Electrochemical Society Interface*, Fall 2010. Available from http://www.electrochem.org/dl/interface/fal/fal10/fal10_p054-056.pdf [Accessed 25 June 2015].
 - [8] US Department of Energy. *Vanadium redox flow batteries – improving the performance and reducing the cost of vanadium redox flow batteries for large-scale energy storage* [Online]. October 2012. Available from http://www.kigeit.org.pl/FTP/PRCIP/Literatura/081_Vanadium_Redox_Battieries.pdf [Accessed 13 September 2016].
 - [9] Rose D.M. and Ferreira S.R. *Performance testing of zinc–bromine flow batteries for remote telecom sites* [Online]. Available from <http://www.sandia.gov/ess/publications/SAND2013-2818C.pdf> [Accessed 13 September 2016].
 - [10] Walsh F.C., Ponce de Leon C., Berlouis L., *et al.* *The development of Zn–Ce hybrid redox flow batteries for energy storage and their continuing challenges* [Online]. 2015 Available from <http://eprints.soton.ac.uk/373749/> [Accessed 25 June 2015].
 - [11] Gazey R., Salman S.K., and Aklil-D'Halluin D.D. 'A field application experience of integrating hydrogen technology with wind power in a remote island location'. *Journal of Power Sources*. 2006;**157**(2):841–47.
 - [12] Enertrag. *The hybrid power plant* [Online]. Available from <https://www.enertrag.com/en/project-development/hybrid-power-plant.html> [Accessed 14 September 2016].
 - [13] Cahela D.R. and Tatarchuk B.J. 'Overview of electrochemical double-layer capacitors', *23rd International Conference on Industrial Electronic, Control and Instrumentation (IECON 97)*; New Orleans, LA, 1997, pp. 1068–73.
 - [14] European Parliament (Naish C., McCubbin I., Edberg O., and Harfoot M.). *Outlook of energy storage technologies* [Online]. 2008. Available from <http://4dlab.info/energy/energy-storage-outlook-of-energy-storage-technologies.pdf> [Accessed 21 June 2015].
 - [15] IEA. *Prospects for large scale energy storage in decarbonised grids, report* [Online]. 2009. Available from https://www.iea.org/publications/freepublications/publication/energy_storage.pdf [Accessed 7 July 2015].
 - [16] Eames P., Loveday D., Haines V., and Romanos P. *The future role of thermal energy storage in the UK energy system: an assessment of the technical feasibility and factors influencing adoption, research report* [Online]. 2014.

Available from <https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&ved=0ahUKEwjMxPPI25HPAhViDMAKHXS-D18QFggiMAE&url=http%3A%2F%2Fwww.ukerc.ac.uk%2Fasset%2F82664E2B-6533-4019-BF5140CEB7B9894D%2F&usg=AFQjCNH7-uvbshW0xml-MxwCb4ljvgt8mg> [Accessed 21 June 2015].

- [17] Sharma A., Tyagi V.V., Chen C.R., and Buddhi D. 'Review on thermal energy storage with phase change materials and applications'. *Renewable and Sustainable Energy Reviews*. 2009; **13**(2):318–45.
- [18] Fairley P. *Largest solar thermal storage plant to start up* [Online]. 2008. Available from <http://spectrum.ieee.org/energy/environment/largest-solar-thermal-storage-plant-to-start-up> [Accessed 17 September 2016].
- [19] Stritih U. and Bombač A. *Description and analysis of adsorption heat storage device* [Online]. *Journal of Mechanical Engineering*; 2014. pp. 619–28. Available from http://www.sv-jme.eu/data/upload/2014/10/01_2014_1814_Stritih_04.pdf [Accessed 17 September 2016].
- [20] US DOE (Hoffman M.G., Sadosky A., Kintner-Meyer M.C., and DeSteele J.G.). *Analysis tools for sizing and placement of energy storage in grid applications: a literature review, report PNNL-19703* [Online]. USA: US Department of Energy; 2010. Available from http://www.pnl.gov/main/publications/external/technical_reports/PNNL-19703.pdf [Accessed 17 September 2016].
- [21] Koochi-Kamai S., Tyagi S.S., Rahim N.A., Panwar N.L., and Mokhils H. 'Emergence of energy storage technologies as the solution for reliable operation of smart power systems: a review'. *Renewable and Sustainable Energy Reviews*. 2013; **25**:135–65.
- [22] Vazquez S., Lukic S.M., Galvan E., Franquelo L.G., and Carrasco J.M. 'Energy storage systems for transport and grid applications'. *IEEE Transaction on Industrial Electronics*. 2010; **57**(12):3881–95.
- [23] Salman S.K. and Rida I. 'Investigating the electrical integration of wind power based embedded generation into utilities' network'. *Proceedings of the Third International Association of Science and Technology for Development (IASTED) International Conference on Power Energy Systems*; Las Vegas, USA, November 1999. IASTED; Paper No. 301-058, pp. 134–40.
- [24] IEA. *Variability of wind power and other renewables—management options and strategies, report* [Online]. France: International Energy Agency; 2005. Available from http://www.uwig.org/iea_report_on_variability.pdf [Accessed 20 September 2016].
- [25] Díaz-González F., Sumper A., Gomis-Bellmunt O., and Villafafila-Robles R. 'A review of energy storage technologies for wind power applications'. *Renewable and Sustainable Energy Reviews*. 2012; **16**(4):2154–71.
- [26] Muljadi E., Butterfield C.P., Chacon J., and Romanowitz H. 'Power quality aspects in a wind power plant'. *IEEE Power Engineering Society General Meeting*; 2006. pp. 1–8.

- [27] Abbey C. and Joos G. 'Integration of energy storage with a doubly-fed induction machine for wind power applications'. *IEEE 35th Annual Power Electronics Specialists Conference*; Aachen, Germany; 2004, pp. 1964–68.
- [28] Bhuiyan F.A. and Yazdani A. 'Multimode control of a DFIG-based wind-power unit for remote applications'. *IEEE Transactions on Power Delivery*. 2009;**24**(4):2079–89.
- [29] Qu L. and Qiao W. 'Constant power control of DFIG wind turbines with supercapacitor energy storage'. *IEEE Transactions on Industry Applications*. 2011;**47**(1):359–67.
- [30] Baros S. 'A novel ectropy-based control scheme for a DFIG driven by a wind turbine with an integrated energy storage'. *Proceeding of the American Control Conference (ACC)*; Chicago, IL, 2015, pp. 4345–51.
- [31] Tsili M. and Papathanassiou S. 'A review of grid code technical requirements for wind farms'. *IET Journal on Renewable Power Generation*. 2009; **3**(3):308–32.
- [32] Abbey C. and Joos G. 'Supercapacitor energy storage for wind energy applications'. *IEEE Transaction on Industrial Applications*. 2007;**43**(3): 763–76.
- [33] E. ON Netz GmbH. *Grid code for high and extra high voltage* [Online]. Bayreuth, Germany. April 2006. Available from http://www.pvupscale.org/IMG/pdf/D4_2_DE_annex_A-3_EON_HV_grid_connection_requirements_ENENARHS2006de.pdf [Accessed 12 August 2015].

This page intentionally left blank

Chapter 11

Smart transmission grid

11.1 Introduction

Much of the work done on Smart Grids in recent years was mainly focused on distribution networks and the consumer interaction with the grid [1]. However, transmission system is considered as the backbone of electric power system, which is used to transfer electricity from generation system to consumers via distribution networks. Therefore, it is important to recognize that the smart transmission grid (STG) resulted from transforming conventional transmission system must deal with more diversified challenges than ever before [2]. These challenges are due to unpredicted uncertainties caused by high penetration of renewable and variable energy sources, limited investments in transmission assets, and an ever higher demand for a more secure supply of electric energy at the lowest possible cost [1].

In this context, the term “Smart Transmission Grid” is a collective term that includes the physical network as well as the controls and devices supporting the function of the physical network [2]. This makes the work related to STG fall in line with the ongoing Smart Grid initiative.

This chapter will be dedicated to discuss research activities currently underway, particularly in Europe and the USA, aiming at the development of STG.

STG is considered as an integrated system that consists of three interactive smart components. These are smart control centers, smart transmission networks, and smart substations [2].

11.2 Why transmission grids need to be smart?

Although current conventional transmission system is well equipped in terms of automaton, protection, and control compared to conventional distribution networks, it can be further improved to make it as integral part of Smart Grid. The aim is to make the power system operating more reliable and efficient. It is also anticipated [3] that time synchronized measurements will be ubiquitously available in the future at all high-voltage substations at very high rates. The information obtained from such measurements can be utilized more effectively for real-time operation as well as for subsequent decision making. However, it has been recognized that the current transmission system is not capable to handle future real-time data. Thus, it has been contemplated that an information infrastructure is needed to store and

communicate the data. Therefore, the requirements for realizing such infrastructure that can handle ubiquitous phasor measurements, taking into consideration the huge volume and rate of data that makes it impossible to store all the data centrally, as it is currently practiced, have been investigated and identified [3].

This in turn has opened the opportunity to the introduction of new and improved applications, which may be classified into two categories. The first one is the set of automatic wide-area controls and the second one is the set of control center energy management system functions with particular attention to the state estimator.

11.3 Challenges and requirements of future STG

The challenges and requirements of future smart transmission system may be classified into four aspects as follows [2].

11.3.1 Environmental challenges

Future smart transmission systems face several environmental challenges; some of which are similar to those faced by other parts of electric power system, for example, smart distribution network. Such challenges include the necessity to reduce carbon oxide emission. This may be achieved by making smart transmission systems more adaptable to manage renewable energy sources (RESs) and therefore less dependable on fossil energy resources. Other important environmental challenge that faces future smart transmission systems is its ability to cope with natural disasters such as hurricanes, earthquakes, and tornados that can easily destroy the transmission systems. Continued shortage of suitable lands to be used for building the future of transmission systems poses further challenge to these systems.

11.3.2 Market/customer requirements

To ensure the transparency and liberty of a competitive market, a fully technologically based operated system together with power market policies must be developed. It is also important that customer satisfaction with electricity consumption should be improved. This may be achieved by providing high-quality/price ratio electricity as well as customers' freedom to interact with the transmission system.

11.3.3 Infrastructure challenges

Infrastructure challenges are imposed due to the aging of existing transmission systems and sometimes due to lack of investments. The situation is made even worse due to the pressure caused by increasing load demands and network congestion. A way forward to overcome these types of challenges is by equipping future smart transmission systems with the necessary tools that are required to improve their reliability. Such tools include fast online analysis tools, wide-area monitoring, measurement and control systems, and fast and accurate protection systems.

11.3.4 *Adaptation of innovative technologies*

An efficient and a proactive adaptation of innovative technologies is considered one of the challenges that faces the development of smart transmission systems. Innovative technologies include the state-of-the-art technological advances in the areas of sensing, communications, control, computing, and information technology. The effort so far made in making transmission systems to be more intelligent and therefore transforming them to “smart systems” has been demonstrated in several projects including IntelliGrid, GridWise, FutureGrid.

11.4 The essential aspects of the STG

In the context of enabling a practical “Smart Grid” implementation in the European power system, an emphasis is placed on three essential aspects of the STG. These are [1] (i) integration of synchrophasor measurement technology into transmission system operation and control, (ii) compatibility of the Information and Communication Technology (ICT) infrastructure, and (iii) operational and coordination issues.

11.4.1 *Integration of synchrophasor measurements technology into transmission system operation and control*

Conventionally, transmission system operation and control depend on performing most of the monitoring and control actions within an Energy Management System (EMS), which makes use of a supervisory control and data acquisition (SCADA) system [1]. However, it has been recognized the need for a real-time wide-area monitoring, protection, and control (WAMPAC) system [4]. The backbone of this system is the synchronized measurement technology (SMT). The SMT is a collective term that includes the set of phasor measurement units (PMUs) and their enabling information and communication infrastructures [1]. SMT has several advantages: (i) it is possible to synchronize the measurements obtained from widely dispersed locations to a global positioning system (GPS) clock; (ii) it is possible to directly measure voltage phase angles, which was technically not feasible; (iii) multiply the improvement of the accuracy and speed of EMS applications (e.g., state estimation).

Synchrophasor system provides the opportunity to extensively apply the time-stamped measurement data and higher resolution provided by PMUs in transmission system.

It is important that STG should make use of this data to take the advantage of all the available “observability” and “controllability” in a power system through closed-loop feedback control and to coordinate system control with protection. This in turn would result in STG behaving as a “self-healing” system or at least utilizing the system more securely through increased awareness. It will be noted that all measurement devices should have the ability of producing synchronized and high-resolution time-stamped data that capture the dynamic behavior of the power system and can provide system observability.

In order to achieve these objectives, STGs need to be equipped with more than the high-resolution measurements provided by PMUs. Figure 11.1 illustrates

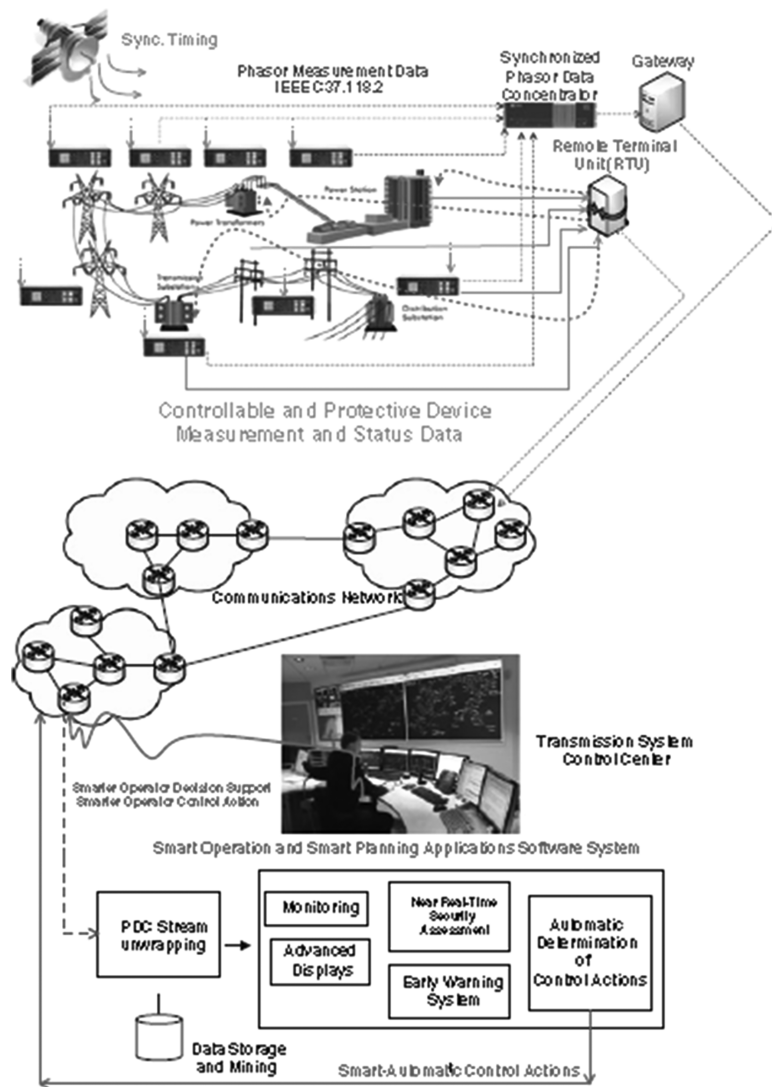


Figure 11.1 The concept of a “centralized model” for a smart transmission grid [5]. Reproduced with permission from Springer.

the concept of a “centralized model” for an STG. This figure shows that the synchronized measurements for STG are taken at transmission substations through time synchronized measurements not only from PMUs but also from other highly accurate measurement systems retrieving data from controllable devices and protective device, which may be termed as “information sets”, that is, all available information from within a protective relay. The obtained huge amount of data is sent via communication networks to a decision and control support system whose

task is to determine appropriate preventive, corrective, and protective measures that need to be taken. Such support system is considered as the foundation that enables STGs using synchrophasor data. In such support system, it is expected that the newly developed analysis techniques will produce “smarter” decisions, leading to operate the power system under consideration more securely, efficiently, and reliably. It is also envisaged that the decisions produced by this support system are used to support operators at control centers to take “smarter operator control actions” or even device “smart-automatic control/protective actions.”

It will be noted that beside the centralized model shown in Figure 11.1, it is possible to have more decentralized models for STGs. It has been proposed that a “decentralized model” of an STG is based on dividing the system into “focal area” systems with different operational functions and a “wide-area” system [1,5]. For example, some of these systems might not include a focal area control center, which means that in such systems only specific functions are executed that require only small amount of data with perhaps lower quality of service (QoS).

11.4.2 Compatibility of ICT infrastructure

The ICT infrastructure constitutes a fundamental requirement that need to be met in order to realize Smart Grid as well as STG, as it has been previously established. However, not every ICT system can adequately meet all the requirements of power systems. Also methods that cater for the interdependence between power systems and ICT infrastructures are not commonly available, which creates an overarching research challenges. Some of such challenges that require further investigation to make ICT infrastructure compatible to power systems include [1] (i) market model implications, (ii) ICT impact on observability and controllability, (iii) optimal information exchange, (iv) agent-based distributed control, and (v) real-time performance in WAMC.

Resolving these issues would lead to an optimized use of ICT infrastructure, which in turn ensures cost-efficient deployment of STGs.

11.4.3 Operational and coordination issues

Prior to electricity market liberalization era, generation, transmission, and distribution systems usually belong to same company and therefore have the responsibility to maintain and operate these systems as one entity. This type power system structure has facilitated the means to make the necessary investment decisions based on a coordinated planning. In other words, generation investments are usually coordinated with necessary transmission system reinforcements. Therefore, generation investments used to be mainly based on adopting traditional large generating units following the principle of economy of scale. This kind of structure has also enabled system operators to control all aspects of the power system operations such as generation dispatch, coordinating the operation of transmission system by deciding which line(s), capacitor(s) to be switched on/off, etc. to ensure controlling system’s power flows and therefore avoid line overloads.

After electricity market liberalization, which led to the break of power systems into independent entities including generation system, transmission system, and

distribution systems, each owned and managed by completely independent organization/company. Transmission system operators (TSOs) continue to make the investment decisions and manage their own transmission system. However, under the new deregulated structure they faced new challenges and experienced several limitations. For example, generation investments are no longer coordinated with transmission system expansion as they are performed by different organizations. However, the newly installed generation capacity is often of a different type than it was before. For example, generation from RES has become a commonplace. Additionally, small-scale generation such as CHP (combined heat and power) has emerged. These kinds of generation units are not only unpredictable; they are also not under the control of the operator. This has led to unpredictable power injection pattern, which in turn has led to a higher uncertainty of the energy flows in the system. Further instability in the energy flows, particularly cross-border, has been caused by the liberalization of electricity market.

TSOs are still able to control transmission system to manage its power flows. However, redispatching generation is more difficult and costly. Due to the increase in variable energy flows, the limited investments in transmission system, and the reduced control options for the system operator, the operation of transmission system is becoming closer and closer to its limits. This in turn has led to potentially serious consequences for the security of transmission system.

Therefore, new and more advanced operating principles are needed to control transmission systems, through interzone coordination and implementation of enhanced security measures.

11.5 Vision of future STG

Figure 11.2 shows a vision of STG proposed by [2]. This vision has been developed following the identification of the challenges and requirements of future smart transmission systems. Based on this vision, the major smart characteristics and performance features required to deal with new challenges have been identified.

According to this vision, the STG is considered as an integrated system that functionally consists of three main interactive components as shown in Figure 11.2. These are (i) smart transmission networks, (ii) smart substations, and (iii) control centers.

11.5.1 Characteristics of future STG

The characteristics of future STG that enable such a grid to deal with the identified challenges and requirements of future smart transmission systems discussed in Section 11.3 according to this vision, include digitalization, flexibility, intelligence, resilience, sustainability, and customization as discussed below [2].

11.5.1.1 Digitalization

STG will be characterized by extensively using digital technologies, which is considered a fundamental characteristic that will facilitate the realization of

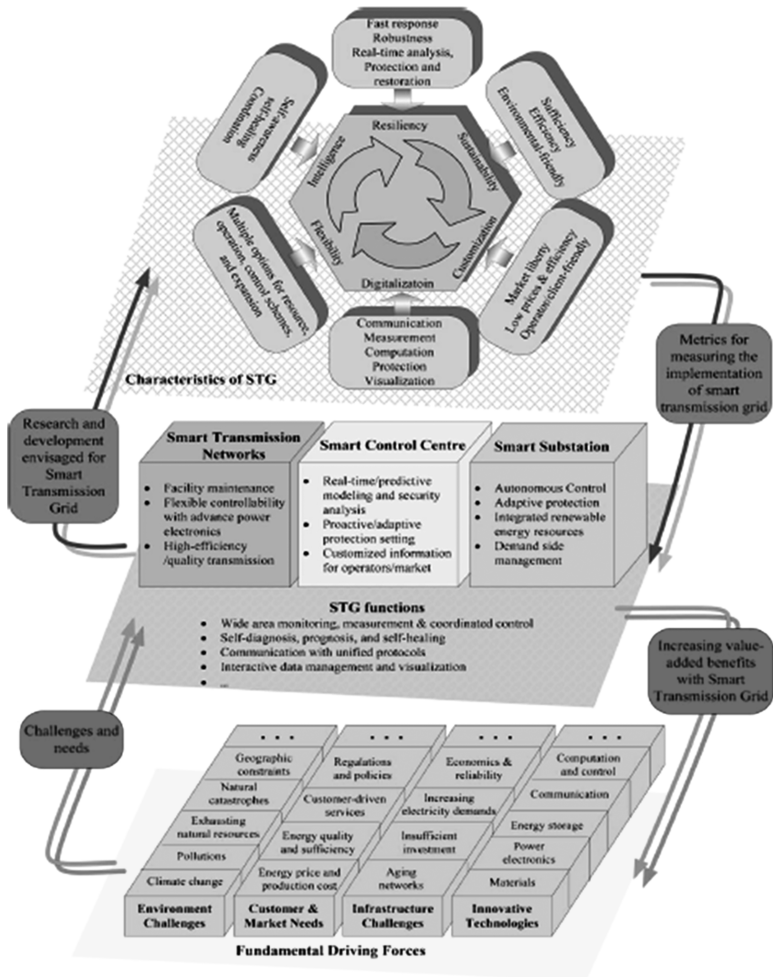


Figure 11.2 Vision of smart transmission grid [2]. Reproduced with permission from IEEE

the other smart features. This ensures fast and reliable sensing, measurement, communication, computation, control, protection, visualization, and maintenance of the entire transmission system. Digitalization is featured with user-friendly visualization for sensitive situation awareness and a high tolerance for man-made errors.

11.5.1.2 Flexibility

The second characteristic of STG is flexibility. This is exhibited in four aspects: (a) expandability in terms accommodating the penetration of renewable energy-based generation and other innovative and diverse generation technologies, (b) adaptability to various geographical locations and climates, (c) ability to accommodating

multiple control strategies to ensure the coordination of decentralized control schemes between various substations and control centers, and (d) seamless compatibility with different market operation styles and plug-and-play capability to ensure accommodating progressive technology upgrades that have hardware and software components.

11.5.1.3 Intelligence

STG will be characterized by being intelligent. This is achieved by incorporating and embedding intelligent technologies into future STG. This in turn makes self-awareness of the system operation state available with the help of online time-domain analysis such as voltage/angular stability and security analysis. It will also make it possible to achieve self-healing feature which will help to enhance the security of transmission grid through coordinated protection and control schemes.

11.5.1.4 Resiliency

Resiliency is the characteristic whereby STG has the capability of securely and reliably delivering electricity to customers, while the grid is subjected to external or internal disturbances or hazards. This is achieved by STG fast self-healing capability, which enables it to dynamically reconfigure itself in such a way that makes it possible to recover from attacks, natural disasters, blackouts, or network component failures. In terms of practical implementation, online computation and analysis can be used, for example, to enable fast and flexible network operation and control such as executing an intentional islanding in the event of an emergency.

11.5.1.5 Sustainability

In the context of STG, the sustainability is perceived as sufficiency, efficiency, and environment-friendly. Practically this means that the growth of electricity demand must be met with the implementation of affordable alternative energy resources, increased energy savings via utilization of appropriate technology that manages the electricity delivery and system operation and mitigation of network congestion. It also means that the criteria of using innovative technologies are based on such use should lead to reduction in pollution or emission and decarbonization that considers the environment and climate changes.

11.5.1.6 Customization

This is the characteristic whereby STG is client-tailored for the operators' convenience while maintaining its functions and interoperability. It is expected that STG will also meet the needs of customers who are looking for more energy consumption options that satisfy a high quality/price ratio. It is also expected that STG will further liberate electricity market by increasing the transparency and improving market competition.

11.5.2 Basic components of STG

The STG consists of three main components as shown in Figure 11.2. These are smart transmission network, smart control center, and smart substations as discussed below.

11.5.3 Smart transmission network

Development of smart transmission network is based on the reinforcement of existing transmission networks with the emerged new technologies. Such technologies include advanced materials, power electronics, sensing devices, communication information and technologies, signal processing, and computing. Application of these technologies helps in transforming existing transmission networks to be smart, which should lead to increase in the utilization, efficiency, quality, and security of existing systems.

11.5.3.1 Characteristics of smart transmission network

The expected characteristics of smart transmission network are outlined below [2].

High-efficiency and high-quality

This is achieved by using ultra-high-voltage (UHV), high-capacity transmission corridors, controllable high-capacity alternating current (AC) and direct current (DC) facilities, advanced conductors, including high-temperature composite conductors for overhead transmission and high-temperature superconducting cables. These conductors have the properties of greater current-carrying capacity, lower voltage drops, reduced line losses, lighter weight, and greater controllability.

Flexible controllability, improved transmission reliability, and asset utilization

This is achieved by utilizing advanced flexible AC transmission systems (FACTS), high-voltage DC (HVDC) devices, and other power electronics-based devices. FACTS devices enable providing a flexible control of the transmission network and increase power transfer levels without having to build new transmission lines. These devices also improve the dynamic performance and stability of the transmission network.

Self-healing and robust transmission of electric power

This is achieved by extensively incorporating smart transmission networks with advanced sensing equipment, signal processing devices, and communication technologies that assist in real-time monitoring of operating conditions of transmission lines, transformers, and circuit breakers. For example, it has been suggested [6] that it is possible to install a cost-effective distributed power line condition monitoring system, which is based on a distributed power line wireless sensor net in which each distributed intelligent sensor module is incorporated with advanced signal processing and communication functions. Such system should have the capability to perform several useful tasks including (a) continuously measuring line parameters and (b) continuously monitoring line status in the immediate vicinity of the sensor that are critical for line operation and utilization. This includes measurement of overhead conductor sags, estimation of conductor temperature profile, estimation of line dynamic thermal capacity, detection of vegetation in the proximity to the transmission line, detection of ice formation on lines, detection of galloping lines, estimation of mechanical strength of towers, prediction of incipient failure of

insulators and towers, identification of the critical span limiting line capacity, and determination of fault location on the line.

Provision of advanced transmission line maintenance and diagnostic technologies

Future smart transmission networks will be equipped with advanced line maintenance and diagnostic technologies such as live-line maintenance to clean and deice conductors, clean and lubricate moving parts that open and close, replace spacer/dampers, tighten or replace bolts, and install sensors and measuring devices, without having to take out the line out of service. Introducing advanced maintenance and transmission line condition monitoring technologies also allows for prioritized equipment ranking, condition-based maintenance, prevention programs, smart equipment replacement programs, and right-of-way maintenance. This in turn reduces disastrous failures and maintenance costs and improves the overall reliability of the transmission system [7].

Extreme event facility hardening system

Extreme event facility hardening technologies encompasses devices used for (i) detecting potential extreme contingencies that cannot easily detected from a single cause; (ii) diagnosis; (iii) containment; (iv) mitigation; (v) restoration; (vi) development of various extreme event scenarios that include floods, extreme weather, tsunamis and the like; and (vii) development of modular equipment designs for lines, substations, and novel configurations to manage failures and enable rapid system restoration under catastrophic events [7].

11.5.4 Smart transmission substations

Existing comprehensive automation technologies currently applied to substations are used as basis to achieve the smart substation concept. The smart concept related to transmission substation is expected to enhance the reliability and efficiency of monitoring, operation, control, protection, and maintenance of equipment and apparatus installed in the substation. As far as the operation is concerned, a smart substation should quickly respond and must provide a high level of operation safety. This requires that a smart substation must have the major characteristics discussed in the following subsection.

11.5.4.1 Characteristics of a smart substation

The major characteristics of a smart substation are as follow.

Fully equipped with advanced digital technologies

A smart transmission substation will be fully equipped with advanced digital technologies. This provides a platform for fast and reliable sensing, measurement, communication, control, protection, and maintenance of all the equipment and apparatus installed in the substation.

Autonomous

The smart substation operates independently from control centers and other substations, that is, it is autonomous. However, it has the ability to communicate with

each other to enhance the efficiency and stability of power transmission. Individual components within the smart substation also operate independently to ensure fast and reliable response, particularly, under emergency conditions.

Coordination and communication capability

The smart substation will be characterized for having the capability to easily communicate and coordinate with other substations and control centers. It is also important that in order to improve the security of the entire power system, adaption of protection, and control schemes should automatically be carried in coordination with control centers.

Self-healing capability

This is the characteristic by which a smart substation has the ability to dynamically reconfigure itself to recover from attacks, natural disasters, blackouts, or network component failures.

11.5.4.2 Example of a practical smart substation

The practical smart substation example discussed in this section is related to a 500 kV substation that was installed in Chinese transmission system, which was commissioned in 2011 [8]. It consists of ten 500 kV lines, sixteen 220 kV lines, and four 1,000 MVA transformers. It is considered as a milestone on the road to transform Chinese electricity transmission system to a Smart Grid.

The substation is considered as a fully digital high-voltage substation. The concept of digital substation is based on utilizing intelligent primary equipment and networked secondary devices, to share digital information and realize distributed protection and control functions via common Ethernet network.

Intelligent primary devices include (i) electronic CT/VT (also called non-conventional instrument transformers—NCITs) and (ii) intelligent circuit breakers. The electronic CT/VTs are connected to the intelligent electronic devices (IEDs) through merging units. The latter are used to convert analog signals to International Electrotechnical Commission (IEC) 61850-9-2 digital format. Time synchronization has been achieved in this project using IEEE 1588 version 2 [8].

In this context, the main aspects that will be covered regarding this example include (i) the architecture of IEC 61850 substation automation system (SAS) using station and process buses, (ii) IEEE 1588 standard for precise time synchronization, and (iii) the communication network within the substation.

Architecture of IEC 61850 SAS using station and process buses

Figure 11.3 shows the conceptual architecture of an IEC 61850 compatible SAS [8]. The aim of this figure is to show the logical view of IEC 61850 substation architecture rather than the actual topology of the substation. According to this figure, the substation has four levels: (i) Level 0: process intelligent switchyard, sensors, I/Os; (ii) Level 1: bays IEDs; (iii) Level 2: substation SAS; and (iv) Level 3: dispatch center.

The IEC 61850 standard includes two busses based on the Ethernet technology. These are (i) the station bus and (ii) the process bus. It can be seen from Figure 11.3

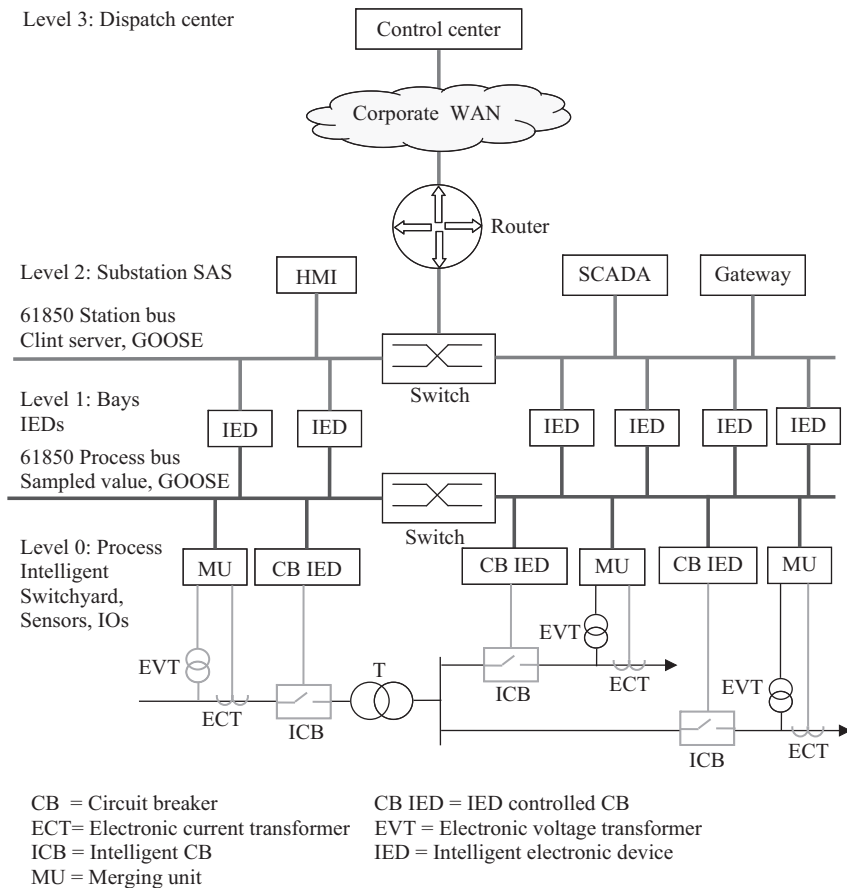


Figure 11.3 Conceptual architecture of an IEC 61850 compatible substation automation system using station bus and process bus [after 8]

that the networks for the station and process buses are physically separated from each other and the IEDs are connected to both networks via independent network interfaces. However, it is possible that station and process buses are connected to the same physical network and sharing a common set of Ethernet switches.

As illustrated in Figure 11.3, the IEC 61850 station bus is used to interconnect all bays to the station supervisory level and also to transfer control information such as measurement, interlocking, and operations. It will be noted that several benefits can be gained from using station bus including the use of GOOSE messages ensuring the speedy transfer of critical protection information. The reason for using GOOSE in this project is to exchange interlocking and blocking signals between IEDs. The use of Ethernet network greatly helps in reducing copper wiring traditionally used for exchanging binary information between relays.

Figure 11.3 also shows that the IEC 61850 process bus is used to interconnect the IEDs that belong to a bay. These IEDs transfer sampled values (SVs) of

protection real-time measurements. Compared to the station bus, the process bus goes a step further as it provides digital link to the primary equipment such as switchgear and instrument transformers. In doing so it reduces copper wiring within the switchyard. Additionally it eliminates high-voltage signals. This in turn makes the maintenance of IED panels in the control building a lot safer and easier. Also the relay panels, which have much less wiring, can help standardize the design of the interfaces between secondary and primary systems. It can also result in having less effort for drafting, installation and testing of such system.

IEEE 1588 standard for precise time synchronization

Smart substation precise time includes time synchronization and application data transmission time delay or time performance of intelligent equipment. The precise time ensures a stable and safe operation of power system. Time deviation and data transmission time delay are usually introduced by IEDs and communication networks, which lead to unsafe operation of substations. It is, therefore, extremely important to take these factors into account when designing a smart substation to ensure precise time synchronization. The most popular time synchronization technologies used in smart substation applications include [9] pulse per second (PPS), inter-range instrumentation group-B (IRIG-B), network time protocol (NTP), and precise time protocol (PTP) (IEEE 1588). Table 11.1 summarizes the main features of these technologies.

The IRIG-B time protocol is widely used by electric utilities, industrials, and others to ensure precise time synchronization of power system devices, such as breakers, relays, and meters [10]. It requires special type of cables for time synchronization. The time accuracy can reach up to 10 μ s and it employs point-to-point directional synchronous technology [9].

The NTP is considered as the most popular time transfer protocol of Internet. The simplified version of NTP, which is called as simple network time protocol (SNTP), has been adopted by IEC61850 standard. The drawback of NTP is its inability to meet the high-precision device requirements of substation. However, NTP/SNTP is considered an easy network technology that can be easily implemented. Currently, they are used at smart substation to perform time synchronization at the station level.

The PTP is considered the most up-to-date network time protocol of Internet [9]. It is named as IEEE 1588 standards by IEEE standard committee at the end of 2002. It employs hardware and software technologies to implement time

Table 11.1 The most popular time synchronization technologies and their main features [9]

Characteristic	Type of time synchronization technology		
	IRIG-B	NTP	PTP
Accuracy	Ms	Ms	Ns
Channel	Special	Network	Network
Time synchronized mode	Single	Double	Double
Calibration	Fixed	Dynamic	Dynamic

synchronization between master clock and slave clock. Hardware is used to mark time tag, while the software is used to calculate time offset and time delay. It has the capability to dynamically calibrate time based on calculation result. Following the approval of IEC61588 standards, there is a possibility that these standards together with IEEE 1588 standards might be used at smart substation to perform time synchronization at bay level and process level.

In the example under consideration IEEE 1588 version 2 is preferred to be used because it allows submicrosecond time accuracy and also because it uses common Ethernet network for distributing the clock signal to all devices in the substation [8]. One of the benefits of using IEEE 1588 version 2 is the elimination of the extra cabling requirements of 1PPS or IRIG-B to propagate highly accurate timing signals.

IEEE 1588 can also handle process bus applications better than SNTP as it has the ability to guarantee microsecond accuracy required for synchronized IEC 61850-9-2 SVs. IEEE 1588 is similar to SNTP in providing time synchronization over a user datagram protocol (UDP) packet [11] in Ethernet network. However, the two are different from each other in that IEEE 1588 allows for hardware assisted time stamping.

One of the fundamental problems of time synchronization addressed by IEEE 1588 is path delay, which is the time required by a message to propagate from the grandmaster to the slave. The delays that are introduced on the path include cable delay, encoding, and decoding of symbols on the wire, switch fabric latency, store, and forward of switches and most troublesome, queuing from switches.

The path delay is corrected by IEEE 1588 using one of two methods: end to end (E2E) or peer to peer (P2P). Path delay correction is carried by E2E method based on measuring the delay across the entire path from master to slave. However, path delay correction used by P2P is performed by measuring the multiple delays between each hop between network nodes (i.e., switches and devices). It will be noted that P2P has an important advantage over E2E in an Ethernet local area network (LAN) where the measured path delay does not change from message to message due to network topology change.

Communication network inside the substation

The communication network inside the substation was realized using IEC 61850 standard. It consists of two separate Ethernet networks: one for process bus and another for station bus as shown in Figure 11.3. To ensure time synchronization, a time synchronization signal needs to be propagated to all devices through the network using IEEE 1588 version 2 in the process bus and SNTP protocol in the station bus. To ensure simultaneous connection to both networks related to station bus and process bus, the IEDs as well as time clocks are equipped with dual Ethernet cards.

The devices connected to process bus include:

- 139 x Ethernet switches with IEEE 1588 in the process bus
- Electronic CTs and VTs
- IEEE 1588 master clocks with GPS
- Merging units
- Protection and control IEDs

The electronic instrument transformers CTs and VTs as well as merging units are used to publish sampled measured values (SMV) data streams in accordance with IEC 61850-9-2LE (Light Edition) [12] frame format at sampling rate of 80 samples per cycle. The SMV traffic is received by protection and control IEDs according which they generate GOOSE messages containing switching commands to intelligent breaker controllers connected to the process bus. Manufacturing Message Specification (MMS) traffic are not used in the process bus. The IEDs are dynamically subscribed to the SVs multicast traffic using GMRP protocol [13].

11.5.5 Smart control centers

11.5.5.1 Review of control centers development

In this review, the development of power systems control centers will be covered under four periods namely: (i) during the 1950s, (ii) during the 1960s, (iii) during the 1970s and 1980s, and (iv) during the 1990s as discussed below [14].

Development of control centers during the 1950s

In the 1950s, real-time data of power outputs from generation plants as well as power flows over tie-lines were collected employing analog communication technologies. These data are passed to control centers operators to perform load frequency control (LFC) and economic dispatch (ED) [2]. System frequency is used as indication of power balance between generation and load within a control area. When generation exceeds the load, the frequency of system goes beyond its nominal value, and when the load exceeds generation, the frequency goes below its nominal value. Thus, an LFC is used to control generation in order to maintain system frequency and interchange schedules between control areas. However, an ED is used to optimize the minimum total cost of the system while meeting load demand. This is achieved by adjusting the power outputs of generators at equal incremental cost. Transmission losses are taken into account by introducing penalty factors to compensate such losses using the *loss formula*. This is considered as the introduction or the first step toward the development of modern control center.

Development of control centers during the 1960s

The 1960s have seen the introduction of digital computers. This has led, among other things, to the development of remote terminal units (RTUs), which are employed to collect real-time measurements of voltage, real, and reactive powers and status of circuit breakers at transmission substations. These measurements are sent to a central computer that has the capability to perform necessary calculation for automatic generation control (AGC). An AGC is basically a combination of LFC and ED. This has led to the introduction of SCADA system through which command signals are remotely sent from the control center to control generation levels and the switching operation of circuit breakers. Real-time operations of the interconnected power systems have greatly benefited from the extensive and effective application of digital computers, particularly after the USA northeast blackout of 1965.

Development of control centers during the 1970s and 1980s

In the 1970s, the capability of control centers has been further improved by introducing the concept of system security, covering both generation and transmission systems. *Security* of a power system is defined as the ability of the system to withstand disturbances or contingencies, such as generator or transmission line outages. Nowadays *power system reliability* is preferred to be used instead of the traditional *power system security* to avoid confusion, since security gives the impression “security against intrusion,” which is not necessary the case.

The security control system may be defined as the system responsible for monitoring, analysis, and real-time coordination of the generation and the transmission systems. It works by first processing the real-time measurements received from SCADA, which are passed through a *state estimator* to eliminate possible measurements and communications errors. The output of the state estimator is then processed by the contingency analysis system to answer “what-if” questions. Contingencies are defined as the disturbances to which generators or transmission lines are subjected to such as generator failure or transmission line outages. Contingency analysis is carried out using a steady-state model of the power system, that is, power flow calculations. *Optimal power flow* (OPF) programs, which are efficient algorithms for large nonlinear programming problem, have been developed specifically for transmission-constrained ED, preventive control, and security-constrained ED (SCED).

The daily and weekly variations in load demands make it necessary to schedule the start-up and shutdown of generators beforehand to ensure that there is always adequate generating capacity online at minimum total costs. This is achieved by optimization routines, known as unit commitment (UC) programs, specifically used to perform such scheduling.

Control centers are also equipped with state estimation and other network analysis software, called advanced application software, in addition to the generation control software, called EMSs.

The computers used in the early control centers are specialized computers used to be offered by vendors whose business was mainly tied up with the utility industry. However, later on, general purpose computers ranging from mainframe to mini were used to perform SCADA, AGC, and security control.

Minicomputers were gradually replaced by a set of UNIX workstations or PCs running on an LAN in the late 1980s. At the same period, SCADA systems were installed in substations and distribution feeders, which are equipped with *distribution management systems* (DMSs). As time progresses, more functions were added to these DMS.

Development of control centers during the 1990s

The second half of the 1990s has seen the restructuring or deregulation of the electric power industry. This has led to unbundling of vertically integrated utilities and consequently the separation of generation, transmission, and distribution systems from each other. The restructuring principles are based on the idea that a competitive market is more efficient in overall allocation of resources.

Thus, competitive generation markets have emerged as a new phenomenon, which replaced regulated monopolies. However, transmission system remained largely regulated.

Two types of markets have been introduced to cover the restructured power industry. The first one is the bilateral contracts between suppliers and consumers, while the second one is an auction market in which generators submit bids to a centralized agent which determines the winning bids and the price. Different schemes are used to determine the price. For example in the USA, the price is determined using what is called a uniform pricing scheme, which is based on the highest bid price that is deployed to serve the load, while in the UK the price is determined using a nonuniform pricing scheme, which is based on the bid price, that is, pay-as-bid. To facilitate transactions, a market operator is needed to run the auction market. The role of market operator may be dedicated to an *independent system operator* (ISO), a *regional transmission organization* (RTO), or other entities with similar functions. With the introduction of electricity markets, some control centers such as those belong to an ISO or an RTO have assumed the responsibility of running market operation in addition to maintaining system reliability. The two aspects are usually run separately but with close coordination.

It is important to note that the sale of electricity is subjected to the condition that the balance between electric power generation and load has to be maintained at all times. This requirement has made market structure rather complex. Consequently, most electricity markets run different types of markets including a day-ahead energy market, a real-time balancing market, and an ancillary service market. The day-ahead market is the market in which hourly clearing prices are calculated in advance for each hour of the next day based on generation and demand bids, and bilateral transaction schedules. Thus, in cases where the most economical generation is conflicting with the reliability of the transmission system, which lead to transmission congestion, *congestion management* needs to be initiated.

One of the options to execute congestion management is based on the pricing differences between the nodes of the network, which is called *location marginal prices* (LMPs). The LMPs are obtained from the nodal shadow prices of an OPF or SCED. The day-ahead market makes it possible for participants to purchase and sell energy at these binding day-ahead LMPs.

As far as bilateral transactions are concerned, a *security-constrained unit commitment* (SCUC) is usually conducted, based on the bids submitted by the generators, to schedule the start-up and shutdown of generators in advance. The transmission customers may schedule bilateral transactions at binding day-ahead congestion charges based on the difference in LMPs at the generation and the demand sides.

Figure 11.4 shows the principles of control centers in electricity market environment. The market clearing prices, which are represented by a new set of LMP, under real-time energy market environment, are calculated using SCED every 5 min or so based on revised generation bids and the actual operating condition from state estimation.

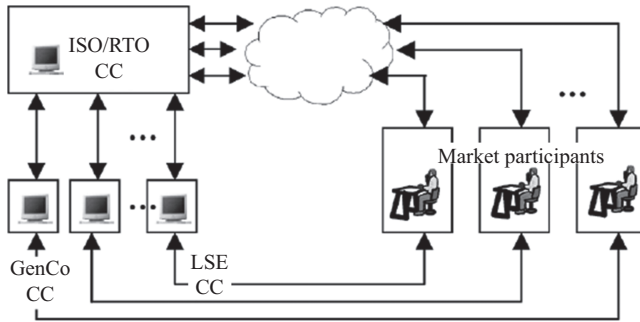


Figure 11.4 Principles of control centers (CCs) in the market environment [14].
Reproduced with permission from IEEE

Any generation, load, or bilateral transaction that deviates from the day-ahead schedule must pay the balancing market LMP. There are number of measures that can be executed to ensure reliable delivery of electricity to consumers. For example, possible generator failure and/or sudden load increase is taken into account by making available additional generation capacity reserve. Such generation reserve is standby to be used immediately as the situation arises.

In order to maintain voltage at an acceptable level for proper operation of the system, adequate reactive power resources are needed. Such resources are all grouped under the term *ancillary services*. An ancillary service can either be self-supplied by users of the transmission system or system-wide management by the ISO/RTO. Markets have also established mechanism to manage ancillary services.

Restructuring of electrical industry has introduced two major changes to the structure of the control centers. According to the first one, functions of control centers have been widened to include business management of electricity market in addition to their traditional energy management function. The second major change is the transformation of traditional centralized utilities' control centers that differ only in size to a variety of control centers run by different entities including ISOs or RTOs, transmission companies (Transcos), generation companies (Gencos), and load serving entities (LSEs) whose market functions are different from each other.

Control centers that are designed to operate under electricity market environment are structured hierarchically in two levels, as shown in Figure 11.4. In this figure, the ISO/RTO control center that operates the electricity market of a region coordinates the LSE and other control centers for system reliability provided that market requirements are satisfied. Market participants are the entities including ISO, RTO, LSE, and Genco. In order to perform market functions, control centers of these entities are usually equipped with business functions. The part of control center functions that performs business applications is called *business management system* (BMS). The ISO and RTO are usually functioned as market operators. Therefore, their BMS is also called *market operations system* (MOS). EMS and BMS are closely interacted with each other. For other types of control centers that do not operate a market, a BMS is added to the traditional EMS to *interact* with the market.

11.5.5.2 Vision of functions for future smart control centers

The envisaged future smart control centers is expected to be equipped with facilities that have the capabilities of collecting data in a much wider and faster scale compared with ones that are currently employed. This in turn enables smart control centers to have much expanded applications both in power system operations and business operations [14]. The infrastructure of the future smart control center is expected to consist of large number of computers and embedded processors, for example, IEDs, spread out all over the system, and a flexible communication network in which computers and embedded processors interact with each other using standard interfaces. It is also envisaged that the data and data processing, as well as applications, will be distributed and therefore ensuring cooperative processing at local and global levels. Being a distributed system, locations of hardware, software, and data will be transparent to the user.

The vision of future smart control centers is developed based on advancement of the existing control centers, which are originally developed several decades ago. The new functions that are expected to be incorporated into smart control centers include monitoring/visualization, analytical capability, controllability, and communication facilities that facilitate the interaction with electricity market [2]. A brief discussion of these functions is given below.

Monitoring/Visualization

The monitoring system currently utilized in control centers depends mainly on state estimators, which are based on data collected using SCADA systems and RTUs. The information collected at system level of the imagined smart control center is assumed to be obtained from the state measurement modules based on PMUs. It is anticipated that PMU-based state measurements are more efficient than the current state estimation method, because synchronized phasor signals provide the information related to state variables, particularly, voltage angles. A drawback of the current state estimation method is its requirement for additional running time and being less robust. This is because the data collected from the RTUs is not synchronized which requires significant effort to be made for topology checking and bad data detection.

As with regarding visualization, the existing visualization technology displays the system configuration using one-line diagrams that can illustrate interconnections among buses without matching it to the geographic location. Additionally, only buses in the control area, together with some boundary buses, are normally displayed by the monitoring system. Whereas in the future, it is expected that the results obtained from state measurement are combined with a wide-area geographical information system (GIS) for visual display on the screens of the smart control center. It is anticipated that the wide-area GIS will cover a vast region including the control center's own service area as well as all interconnected areas. This obviously helps in increasing the situational awareness across a broad scope and consequently prevents improper operations compared to the situation where a neighboring system is not fully known.

As the visualization and monitoring technology that suit smart control centers applications are expected to cover a much broader scope, an increased information

exchange is required. The existing technology employed for interarea communications uses a mix of obsolete and current technologies, such as telephone lines, wireless, microwave, and fiber optics. This obviously needs to be changed and updated. Future communication channels are expected to be more dedicated. For example, they employ a fiber optic network for communications with QoS implemented, which requires using a unified protocol to ensure better communications among different control areas.

Analytical capability

Online analytical tools currently used in existing control centers normally perform steady-state contingency analysis. For example, power flow analysis programs are utilized to determine line flow violations when a contingency event occurs. It is expected that online time-domain-based analysis, such as voltage stability and transient angular stability, will be incorporated in the future smart control centers.

Existing analysis tools are based on predefined generator and transmission models, which do not represent the real-time dynamic characteristics of the system. It is therefore important that future online analysis tools incorporated in the future smart control centers should have the capability of performing dynamic model updating and validation. Using such tools together with an updated and validated data to perform, for example, online stability analysis should give accurate results compared to the ones obtained from existing practices. The currently employed online security analysis for the next operational time interval is conducted for, say every 5 minutes. This does not cover possible short- to midterm system variations, that is, within 1 hour. Security online analysis applications to be designed for future smart control centers is expected to have look-ahead simulation capability so that future system conditions can be considered.

Controllability

The ultimate control action of existing control centers, such as switching on/off operations, is performed based on offline studies. In order to improve the utilization of dynamic system conditions, control tools designed for future smart control centers should have the capability of performing system switching operations in real time. Similarly, restoration actions are currently performed based on offline studies. This needs to be replaced by online restorative actions.

Another important aspect in this context is related to the protection and control systems. Currently the settings of such systems are fixed whose values are determined based on offline studies. In the future, determination of these settings needs to be made in real time in a proactive and adaptive approach (see Chapter 7). This helps in improving the utilization of generation and transmission assets when the system is not stressed while improving protecting the system when it is subjected to extremely stressed conditions.

Also coordinations of protection and control systems calculated using existing tools are far from perfect. Under this scenario, each component takes actions based on its own decision. Such uncoordinated control actions can lead to an unnecessary action under the present contingency plan such as unnecessary tripping of certain power system components. Therefore, it is extremely important that future smart

control centers should be equipped with appropriate tools that have the capability of coordinating multiple control devices distributed over the system such that optimal coordination can be achieved simultaneously to ensure better controllability.

Electricity market interface

As it has been discussed in Chapter 3, the electricity market constitutes one of the basic components of the future Smart Grid.

The continuous change to which electricity market is subjected to requires control centers that has the ability to be adaptable to the dynamic nature of electricity market. Normally the control center associated with a market actively interacts with other control centers, existing market participants, and new entrants as discussed previously. Consequently, it is important that modern control centers should have the ability to cope with the changing business architecture. This requires that more sophisticated tools should be incorporated into the control centers to make it possible for system operators to efficiently monitor and manage electricity market.

Additionally due to continuous interest in utilizing RESs as well as controllable loads to meet future demand, future smart control centers should have the flexibility to include such energy resources into the unit dispatch. This in turn requires that market clearing algorithms must be robust enough to accommodate the volatile nature of certain renewables such as wind generators with finer forecasting and scheduling methods. It is also important that demand-side participants should have access to the market through certain communications, control, and information channels.

Another important characteristic of future smart control centers is its ability to have congestion management. Accordingly control centers must be able to forecast and identify potential congestions in the network and accordingly put in place the necessary measures to alleviate them using wide-area GIS systems.

11.6 Current research activities on STG

As it has been stated previously in this book, Smart Grids have attracted significant attention in recent years. However, most of the attention has been focused on networks at distribution level and the consumer interaction. In this section, the discussion will be focused on research activities that are currently underway in Europe, the USA, and China aiming at the development of STG.

11.6.1 Smart transmission grid research in Europe

As it has been stated previously much of the attention related to Smart Grid activities was focused on the distribution networks and the consumer interaction. In Europe, the STG has remained in the background. However, synchronized PMU, their supporting ICT infrastructures, and PMU data applications are remarkable exception, despite that they are less common in Europe than in the USA [1].

However, there are several important improvements at transmission level that can be achieved through visionary and careful intelligent grid design and

implementation. Such improvements are essential for the operation of future power systems that will face challenges due to unpredicted uncertainties caused by high penetration of renewable and variable energy sources, limited investments in transmission assets, and an ever higher demand for a more secure supply of electric energy at the lowest possible cost.

Many of the required improvements are not ready to be immediately implemented in the current conventional system. This is due to a specific need for research on some key aspects of the smart transmission system which are considered essential for the full development and utilization of the future grid.

In Europe, three essential aspects have been emphasized regarding the development of STG [1]. These are (i) the evolution of synchrophasor measurement technology and the limitations related to its full integration into power system operation and control. In order to achieve this full integration, it is extremely important to test and integrate any proposed solution in an open and transparent environment; (ii) the IT, data and communication systems; and (iii) the key questions that are open to the transmission system operators particularly related to the coordination within the pan-European power system and its security.

11.6.1.1 Pan-European transmission grid research activities

The targets for the future European energy system were declared in the 2030 policy framework for climate and energy proposed by the European Commission on 22 January 2014 [15]. It has been recognized that the decarbonization of energy supply with an increasing share of electricity generation from intermittent RESs presents European transmission and distribution grid operators with a number of research and development (R&D) challenges. Such challenges have been addressed at the European level via the European Electricity Grid Initiative (EEGI), including the European Association of Transmission System Operators (ENTSO-E), together with the European SmartGrids Technology Platform. An R&D roadmap, together with an implementation plan and a strategic research agenda, has been developed based on these initiatives. They are also used to coordinate the R&D activities to efficiently develop the technologies, tools, and competences necessary to implement the pan-European grid.

The focus has been on smart electricity transmission grids. This includes the interactions with distribution grids. The R&D activities are covered under seven subthemes as follows.

Subtheme 1: grid architecture

The objective of this subtheme is to devise a set of validated methods aiming at developing future network infrastructures and to analyze pan-European grid expansion scenarios to assess, for example, the impact of offshore grids or of HVDC networks on the operation of the whole system. It is important that the new pan-European grid should have the ability to host massively expanded RESs while coping with new uses of electricity, increased cross-border market flows, demand

growth, and maintenance costs beyond 2020. The R&D tasks specifically identified under this subtheme include the following:

- Developing a planning methodology for the pan-European electricity network scenarios for the period 2020–2050.
- Developing dedicated simulation software that helps TSO to analyze pan-European grid expansion scenarios.
- Assessing novel and known technologies to be used for the cross-border connections.
- Evaluating the impact of offshore grids, HVDC networks that operate alongside the existing infrastructure, as well as extra- and UHV AC solutions.
- Developing a suitable method that can be used to assess the social and environmental impact of grid development, including the public acceptance of new technologies and grid expansion measures.

Subtheme 2: power technologies

The main objective of subtheme 2 is to address the affordability and technical performance of emerging technologies that can significantly improve transmission systems. Other aspects that are considered under this subtheme include new sensors, storage technologies, and developing the expertise in hybrid AC/DC power systems and in advanced power technologies, examples of which are listed below:

- Power transfer capacity: HVDC and high-voltage AC cable, AC/DC converter, multiterminal and vendor-independent HVDC voltage source converter (VSC), superconducting, gas insulated line (GIL) and “low-sag” conductors.
- Power control devices: FACTS, phase-shifting transformers, HVDC back-to-back.
- Monitoring devices and systems: PMU, wide-area monitoring systems (WAMS), real-time thermal rating (RTTR), and combined digital fault recording and PMU devices.
- Control devices and systems: PMU data concentrators (PDC), wide-area control systems (WACS), wide-area protection systems (WAPS).

Subtheme 3: network operation

The continued increase in cross-border electric power flows and the large share of variable RES generation, operational planning, and online operation of the power system is changing. The main objective of this subtheme is to operate the transmission system as close to its physical capacity as possible and maintain high security and reliability at reasonable costs. The specific aims include the following:

- Development of new simulation techniques that improve observability and controllability.
- Development of new methodologies that improve the flexibility of the system. Such methodologies should increase controllability, while coping with possible stability-related issues.

- Development of interfaces and tools that enable operators evaluating network status, make real-time decisions, and coordinate their operations across control zones.
- Improving methodologies for forecasting the amount of renewable electricity generation, particularly from wind and solar powers.
- Improving and developing training methodologies for operators, especially those related to cross-border coordinated responses to major contingencies.

Subtheme 4: market design

It is important that wholesale market designs must be analyzed to ensure that they can cope with the variability of renewable energy-based generation, as well as with demand-side management and energy storage. Hence the aim of subtheme 4 is to create simulation platforms and demonstrations for new market mechanisms, such as price signals and mobilization of flexible resources for balancing and reserve purposes. This in turn will be used to support the design of new markets for balancing and ancillary services at the transmission level, the analysis of cross-border interactions, and a more efficient congestion management. Therefore, the R&D activities here include:

- Development of large-scale market simulation tools that takes into consideration RESs, demand side response, and storage systems at the transmission voltage level.
- Analysis of cross-border interactions, including more efficient congestion management and allocation of transfer capacities.
- Designing new markets for balancing and ancillary services at the transmission voltage level and with a European dimension.

Subtheme 5: scaling-up and replication activities

Normally large-scale deployment of successfully demonstrated innovations requires scaling-up and replication. This must be done within a technical risk coverage that satisfies both regulated and free-market players. Thus, R&D activities under this subtheme are designed to bridge the gap between demonstration and industrial application. The aim is to address potential problems in advance. For example, numerical modeling techniques are used to evaluate uncertainties and subsequently propose solutions prior to industrial deployment of a technology. This also serves addressing the concerns of, especially regulators, regarding the following:

- The possibility of economic risk of deployment is not under control, although ensuring the technical risk being under control (lack of economic scaling).
- The conflict between satisfying regulatory environments in control zones. For example, the regulatory environment, which may be favorable in one control zone (economic scaling is then managed), may no longer be favorable in another control zone (lack of replication potential).

Subtheme 6: asset management

The aim of asset management is to maintain robust and cost-effective network infrastructures with reliable performances. This in turn requires understanding and

predicting of the deterioration of main grid components to be able to determine failure probability and manage maintenance, replacement and investments, in order to ensure the reliability of power systems. This can be achieved by adopting improved monitoring of grid's health status and improved preventative maintenance decisions that are suited to local network conditions. R&D activities in this area include:

- Validation of new monitoring concepts for primary and secondary components in terms of scheduling maintenance that maximizes network flexibility.
- Utilization of conditional maintenance to enhance network flexibility.
- Invention of novel maintenance methodologies for new power technologies such as HVDC links, AC/DC converters, underground cables.
- Better understanding of how a network's working conditions impact the ageing of critical components, using subsequent analysis of assets that have been removed from the grid.

Subtheme 7: transmission/distribution grid interactions

This subtheme deals with issues related to interaction between transmission and distribution networks. For example, changes in the architecture of the transmission grid such as using HVDC can also affect distribution network. However, active components employed in the distribution networks, for example, power electronic converters, can provide services to the transmission system, such as virtual power plants (VPP) or "aggregators" organized at the distribution system level (see Chapter 8).

Therefore, the overall aim of this subtheme is to develop complementary roles of TSO and DSO together with the necessary methods and tools to jointly manage a power system that have an increasing number and share of generation units connected to distribution networks. The proposed R&D activities include:

- Developing short- and long-term forecasting tools and designing a communications infrastructure in line with the relevant feedbacks from TSO and DSO that ensure better coordination of system operations.
- Investigating the behavior of customers connected at the distribution system level and integrating them to ensure their active participate in system management.
- Developing and identifying a set of relevant ancillary services shared by the DSO and the TSO that allow the deployment of emerging technologies. For example, integration of electric vehicles and microgeneration.
- Improving the current TSO/DSO interface with respect to protection and restoration processes.
- Developing a common framework for interoperability in the field of Smart Grids. This includes communication protocols, information models, semantic models, and connection requirements.

The priority areas that have been identified are the observability and control of the grids that also support the increased flexibility of future grids through new technologies. Such technologies include information and communication

technologies, and new market mechanisms. The EEGI has identified the integration of the many different technological elements, stakeholders, and business models represented in the new panorama offered by Smart Grids as the main technological challenge. Challenges related to system integration include validation of technologies for real-time operations, for market architectures, and for long-term planning. In order to achieve a truly pan-European grid, it is important to ensure a close coordination among transmission operators.

11.6.2 Smart transmission grid research in USA

To facilitate the discussion of this section, the definition of the following terminologies needs to be introduced first [16].

11.6.2.1 Balancing authority

Balancing authority (BA) is the responsible entity that integrates resource plans ahead of time, maintains demand and resource balance within a BA area, and supports interconnection frequency in real time.

11.6.2.2 Balancing authority area

BA area is the collection of generation, transmission, and loads within the metered boundaries of the BA. The BA maintains load-resource balance within this area.

11.6.2.3 Reliability coordinator

Reliability coordinator (RC) is the entity that is the highest level of authority who is responsible for the reliable operation of the bulk electric system, has the wide-area view of the bulk electric system, and has the operating tools, processes, and procedures, including the authority to prevent or mitigate emergency operating situations in both next-day analysis and real-time operations. The RC has the purview that is broad enough to enable the calculation of interconnection reliability operating limits, which may be based on the operating parameters of transmission systems beyond any transmission operator's vision.

Recently progress has been made in phasor measurements techniques which led to the generation of voluminous data at high-voltage substations. However, relevant applications for handling such data are not yet fully developed. Thus, the idea of developing an "Information infrastructure" is considered as an important step toward the realization of the STG. The aim of developing such infrastructure is to efficiently gather, move, and process the data generated by phasor measurements.

The measured data at high-voltage substations are of two types: (i) change of the open/close statuses of switches and (ii) analog variables, the most important of which are the measurements the currents and voltages sampled at a rate more than 100 times a second synchronized to an absolute time standard and thereby termed as "synchronized phasor measurement." Currently, the amount of data being gathered at a substation is so huge that most of it cannot be transmitted out of the substation at the rates at which they are gathered, and therefore very little is used.

The approach used is to determine how substation collected data can be organized locally for local as well as for global applications uses. Local use of the data at substations is mainly for protection and control. As far as protection is concerned, fast sampling of data is required to enable relays clearing faults milliseconds time range. With regard to control, the most common local control is voltage control which is usually slow. Additionally some local calculations are made and stored separately for certain applications such as digital fault recording (DFR) and sequence of events (SOE). A subset of all the substation data is also collected at the RTU which makes it available to the control center over communication channels.

Second the same data is considered from the viewpoint of monitoring and operating the grid. The aim is to determine which data is needed, where and for what purpose. Currently, the only real-time data that exist in a substation through the RTUs are collected at the control center where the SCADA-EMS can display and further analyze the data for the operator to take manual (supervisory) control actions. According to the USA practices, the only closed-loop control done at the control center is AGC.

However, if the synchronized phasor measurement data increasingly available at the substations become available for broadcast, they will not be needed to be all collected centrally at the control center. Instead, the present-day control center functions and any expected new ones must be considered in terms of their data needs and accordingly the communication system has to be designed to transfer only the necessary data to the appropriate functions which may not all reside at a central control center.

11.6.2.4 Existing information infrastructure

The existing information infrastructure uses the SCADA system to collect all the data by polling the RTUs located at various substations as shown in Figure 11.5 [17]. As the figure shows this system is based on star communication with round-robin polling that centralizes all data from all substations at the control center. The rate of collecting such data is rather slow. It is done every 2–10 s. Additionally, the data at the RTU does not necessarily cover all the measurements that are taken at the substation.

It is not difficult to recognize that the existing information system would be completely overwhelmed by the huge volume of data that is being collected at substations today. This would be true even if the microwave communication currently in use would be replaced with all high-speed fiber.

Recently a parallel communication configuration has been used to collect data from PMUs as shown in Figure 11.6. As it can be seen from this figure, this configuration is also a star. It is used to collect all the PMU data from a utility to a single PDC and then the data from all PDCs are sent to a super-PDC. It is now acknowledged that this system is already overwhelmed with data, although the total number of PMUs in any of the large interconnections is significantly below 100. It is anticipated that the PDC configuration becomes useless when the total PMUs in each substation becomes, which is very likely to happen, more than 100 PMUs.

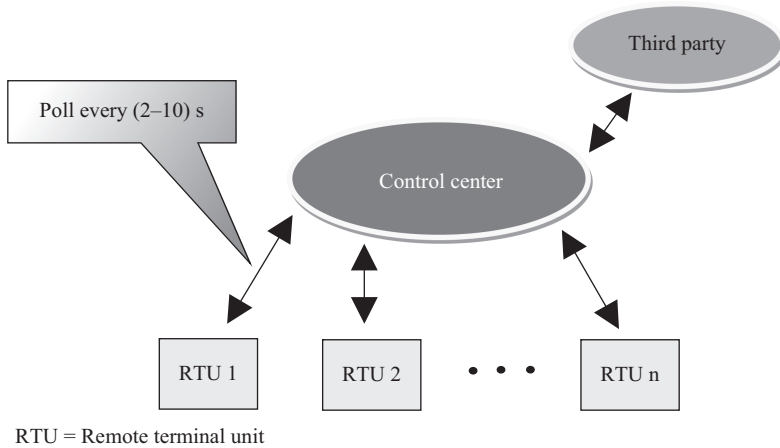


Figure 11.5 The existing supervisory control and data acquisition (SCADA) configuration according which substations data are collected at the control center [after 17]

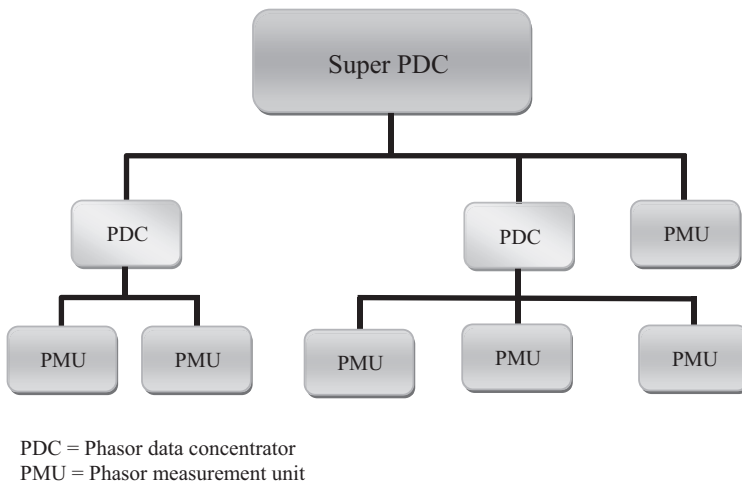


Figure 11.6 Existing arrangement of phasor measurement unit (PMU) data concentrators (PDCs) used to collect the data from PMUs [after 17]

The data obtained from all substations are used by the control center to perform several functions which may be separated into three classes of applications:

1. Monitoring of the system by the operator, which requires various displays (visualization) and alarms.
2. Analysis of how vulnerable the grid is to contingencies which requires state estimation, contingency analysis, and optimal power flow (OPF) (EMS applications).
3. Automatic controls such as AGC.

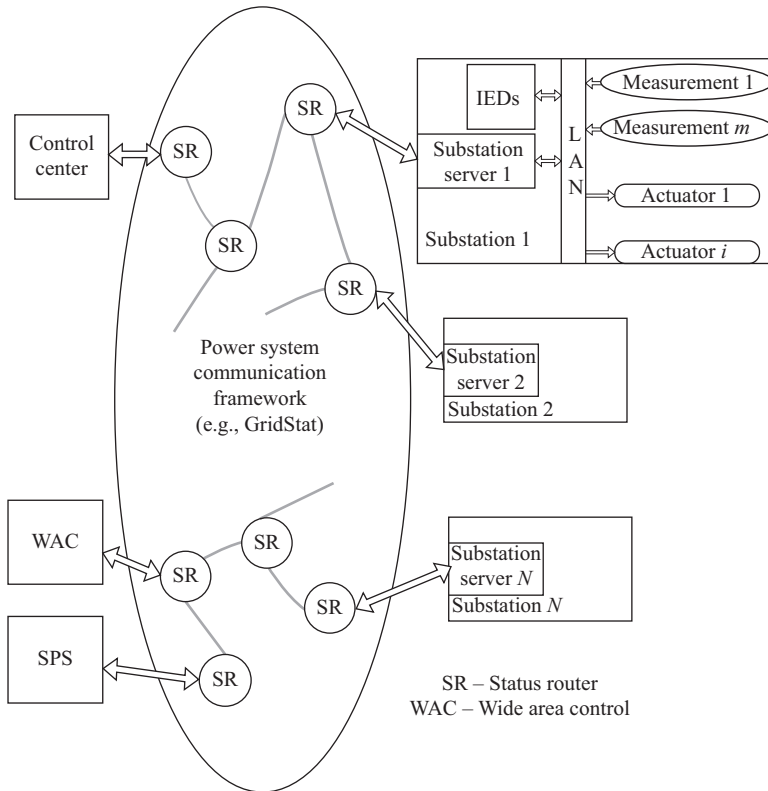


Figure 11.7 The proposed configuration of a real-time information infrastructure for smart transmission grid [17]. Reproduced with permission from IEEE

The existing EMS applications are geared to the data rates currently used by control centers. There will be opportunities to enhance these applications as will be discussed in the next section.

Similarly conventional AGC controller is characterized by being slow. It matches the existing slow information collection data system. Again there will be many new opportunities for improving such AGC as will be discussed in the next section.

11.6.2.5 Future real-time information infrastructure

Figure 11.7 shows the proposed future generic communication architecture that connects all substations to an information network. This is based on the assumption that the latest technologies of computers and communications become available at HV substations and up through the hierarchy.

Figure 11.7 shows the proposed communication infrastructure as a two-level hierarchy, that is, low and high levels. Each substation has its own high-speed LAN

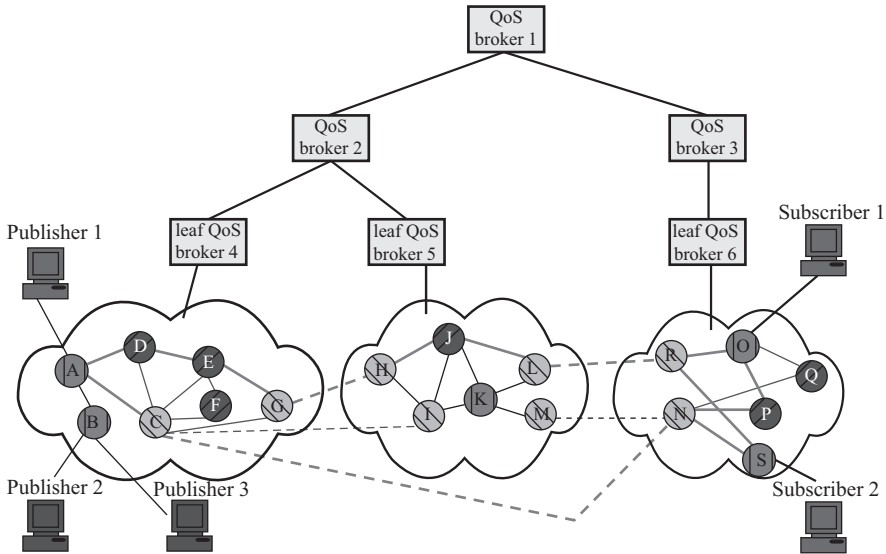


Figure 11.8 Detailed configuration of the proposed information infrastructure showing the management of the router network, including some pathways between publishers and subscribers [17]. Reproduced with permission from IEEE

which brings together all the measurements and local applications. Each substation also has a server that connects to the high level communication network through a router. Therefore, all applications that require data from more than one substation, that is, applications that are not local, have to use the high level network for collecting inputs and sending outputs.

The high level network shown in Figure 11.7 is a network of routers that feed all the wide-area applications of which the most important and common application is the control center (SCADA-EMS). Although the network of routers shown in Figure 11.7 is configured as one level, it has no hierarchies. Each substation will have at least one router and all of them are connected in a network of high-speed communication lines. If the transmission corridors between substations also have fiber optic cables, these may provide convenient channels although other channels may also be used. Additionally, certain applications such as the control center may not be at the same location as a substation and therefore may have its own router(s).

Figure 11.8 shows a detailed configuration. This figure shows that the routers may be grouped for management purposes. The figure also shows that a hierarchy of computers may also be created to control the actual movement of the data. They are shown as QoS brokers. The grouping of routers can be made by jurisdiction such as control area or BA area. It is not recommended to channel all the data that belong to a single area through one router as it is the case for existing information infrastructure, whereby all the data are channeled through the area's control center. The reason is to avoid the introduction of significant latency to the communication

paths. Instead, it is proposed that all routers in all areas are to be kept at the same level and the QoS brokers will find the most efficient path as shown in Figure 11.8.

The router network described above does not exclude setting up functional hierarchies. For example, it is possible to set up an RC control center that can have higher level functions than that of the BA control centers. Obviously this requires different sets of information, but all these control centers can be supported by the same router network.

In the information system proposed in Figure 11.7, the concept of the RTU, currently used in existing systems, has been replaced by the server–router that can access all substation data through the substation LAN. Also in order to resolve the difficulty of handling the expected huge volume of data by existing system, the star configuration used by existing system, is replaced by the network configuration shown in Figure 11.7 and polling, used by existing system, is replaced by a publisher–subscriber system that only moves data from substation to application and vice versa as required.

The configuration of the proposed communication infrastructure shown in Figure 11.7 is also expected to have the ability to handle the high demand for information movement. For instance, a fast wide-area controller (WAC) or special protection scheme (SPS) may require only a small number of synchrophasor inputs from a few different substations and may send out a small number of output control signals to different substations. This can be achieved by using routers to route the data under consideration directly from substations to the controller instead of the controller having to look for some central storage to deal with this fast sampled data.

The advantages expected from adopting the proposed communication infrastructure include:

- The new configuration will provide many opportunities for improving AGC.
- The new configuration will provide further opportunities to enhance EMS applications. Similar to the AGC, these applications can also be separated from the operator monitoring in terms of data requirements as long as the results are channeled to the operator.
- The new configuration will be ideally suited to handle monitoring as well as WAC/SPS applications as long as they are separated as shown in Figure 11.7, whereby the data specifically used for monitoring at the control center is system wide and usually at slow rates, whereas the data specifically used for WAC/SPS are exactly reversed, are fast sampled data (synchrophasors measure at rates up to 100 per second), and are sourced from only few measurements.

11.6.3 Smart transmission grid research in China

China has undertaken ambitious efforts to provide the energy services demanded by its growing economy while mitigating China's contribution to climate change. The Chinese government is committed to (i) reduce the carbon intensity of its GDP by 40%–45% in 2020 in comparison to its level in 2005 and (ii) increase nonfossil energy to 15% of primary energy consumption by 2020 [18]. Both of these commitments require introduction of substantial changes to China's electric power

system. Accordingly, China has decided to replace its traditional energy intensive power grid by Smart Grid [19]. This is particularly emphasized in China's "12th Five-Year Plan of the Electricity Industry," where the development of renewable energy and Smart Grids is highlighted.

The first step toward implementation of Smart Grids in China was made by the East China Power Grid (ECPG). ECPG has carried out its first feasibility study on Smart Grids in 2007 in which advocated promoting deployment of power systems, constructing digital substations, and building a unified enterprise data platform. The aim is to improve security and management of power grid [19]. This is followed by investigating the key technologies required to build Smart Grid, which was undertaken by the National Science and Technology Board, Chinese Academy of Sciences, and Chinese Academy of Engineering.

11.6.3.1 Smart Grid pilot projects

Some regions in China such as Jiangsu and Shanghai have launched Smart Grid pilot projects as early as the 1990s [19]. The aim is to introduce Smart Grid technologies. They began by their pilot constructing a pilot project related to power information collection system encompassing loading management and meter reading technologies. They have also accumulated a lot of practical experience on demand side automatic meter reading, interoperation, and demand side response.

During the period 2010–2011, the State Grid Corporation of China (SGCC) has launched 228 pilot projects covering 21 technological categories. This has led to a breakthrough in six areas, including smart substation, automatic power distribution, power consumption information collection, electric vehicle charging infrastructure, technical supporting system on Smart Grid deployment, and power fiber to the home (PFTTH).

The construction of the Integrated Demonstration Project of Smart Grid in Sino-Singapore Tianjin Eco-City has been completed in 2011. It is considered as the most complete pilot project, which has a wide coverage. Table 11.2 shows some Chinese' Smart Grid pilot projects related to power transmission, distribution, and substations.

11.6.3.2 Transmission system projects

The majority of natural resources in China are distributed in the western regions of the country, while most of the electricity consumption is in developed cities located in the eastern region of the country such as Beijing and Shanghai. This spatial imbalance of energy sources has presented a challenge for energy planners in China as, "How to redirect the electrical energy generated in remotest provinces to power-hungry cities in the east?" The way forward to overcome this challenge was by initiating an Electricity Transfer Project by which much of the electricity converted from new energy source and/or traditional power plants located in the west are transferred to the heavy power users in the east [20].

Accordingly, a project to build a nationwide transmission system with an approximate cost of USD 100bn (CNY 612bn) has been embarked on. This involves the construction of 20 UHV transmission lines. Upon the completion

of the country's west-to-east and north-to-south electricity transmission projects, the SGCC should be able to transmit 450 GW of electricity nationwide by 2030. However, the National Energy Administration (NEA) has planned to complete 12 UHV transmission projects in 2017.

Table 11.2 Pilot projects of Smart Grid in China [19]

Year	Location	Pilot project description
2010	Yangzhou	Yangzhou city of Jiangsu Province was selected as the first "Smart Grid industrial base" by Chinese National Science and Technology Ministry in its "Torch Program" in August, 2010.
2011	Tibet	This project is related to the Qinghai-Tibet cross DC networking engineering, which was completed at the end of 2011.
2011	Tianjin	Construction of the Integrated Demonstration Project of Smart Grid in Sino-Singapore Tianjin Eco-City has been accomplished.
2012	Fujian	This pilot project involves 13 Smart Grid programs including distribution network, charging infrastructure for electric vehicles and smart community. Additionally it also involves the construction of 17 smart substations and putting into operation 4 smart substations. According to the same project 1.78 million smart meters have been installed. The aim is to realize a full-scale automatic information collection process.
2012	Shandong	Installation of online monitoring devices to observe the performance of transmission lines and transformers operating at 220 kV and above. Additionally the project involves accelerating the construction of 6 existing charging stations and the construction of 17 new ones.
2012	Jiangsu	This project was executed between 2012 and 2015, according to which 580 smart substations operating at 110 kV and above, and more than 13,500 km transmission lines were constructed in Jiangsu province.
2012	Liaoning	Building an automatic, interactive Smart Grid equipped with a highly sophisticated information system. The Smart Grid is developed such that it is adaptive to the large scale access to nuclear-, thermal- and wind-based power plants, and also meeting the requirements of AC/DC power transmission.
2012	Guangxi	This project known as "Guangxi Grid." It is dedicated to modernization of rural power grids. It involved building up a set of demonstrating projects in counties, power supply administration projects, and substations with Smart Grid distribution system, digital and unattended substations, and remote meter reading systems. A 184 demonstration projects have been initiated under this project.
2012	Xinjiang	This project was executed under the Chinese 12th Five-Year Plan. It involves building thousands of kilometers of transmission lines to connect hydro- and thermal-based power plants to the grid.
2012	Shanxi	This project is related to smart substation, power consumption information collection, smart community, charging infrastructure for electric vehicles, and PFTTH. Under this project it is planned to install 1.2 million smart meters.

Also, in an effort to improve transmission system, the following transmission lines were planned to be completed by the end of 2009 [18]:

- 640 km of 1,000 kV UHV, AC transmission lines with a total capacity of 6 GVA,
- 1,438 km of ± 800 kV UHV DC transmission lines with a total capacity of 2.5 GVA,
- 1,388 km of 750 kV transmission lines with a total capacity of 16.5 GVA,
- 1,21,868 km of 500 kV transmission lines with a total capacity of 628 GVA, and
- 2,55,657 km of 220 kV transmission lines with a total capacity of 945.6 GVA.

11.7 Summary

This chapter concerns with the development of STG. The reasons for the need of STG are discussed in Section 11.2. This is then followed by discussing the challenges and requirements of future STG in Section 11.3 which include environmental challenges, market/customer requirements, infrastructure challenges, and adaptation of innovative technologies. The essential aspects of the STG are then highlighted in Section 11.4. These include integration of synchrophasor measurements technology into transmission system operation and control, the necessity of having compatible ICT infrastructure, and resolving the operational and coordination issues.

The vision of future STG is then discussed in Section 11.5. Topics covered under this section include the characteristics of future STG, basic components of STG, smart transmission network, smart transmission substations, and smart control centers. An example of a 500 kV practical smart transmission substation is given. The discussion covered includes (i) the applied architecture of IEC 61850 SAS using station and process buses, (ii) IEEE 1588 standard for precise time synchronization, and (iii) the communication network used inside the substation.

The smart control centers are discussed under Section 11.5.5. It started by giving a review of the development of the control centers over the period expanding from the 1950s till the 1990s. Then the vision of functions that future smart control centers should have was highlighted. Such functions include (i) monitoring/visualization, (ii) analytical capability, (iii) controllability, and (iv) electricity market interface.

Finally, this chapter is concluded by Section 11.6 which is devoted to discussing research activities that are currently underway in Europe, the USA, and China aiming specifically at the development of STG.

References

- [1] Vanfretti L., Van Hertem D., Nordstrom L., and Gjerde J.O. 'A smart transmission grid for Europe: research challenges in developing grid enabling technologies'. *IEEE Power & Energy Society General Meeting*; San Diego, CA, 2011, pp. 1–8

- [2] Li F., Qiao W., Sun H., *et al.*, ‘Smart transmission grid: vision and framework’. *IEEE Transactions on Smart Grid*. 2010;**1**(2):168–77
- [3] Bose A. ‘Smart transmission grid applications and their supporting infrastructure’. *IEEE Transaction on Smart Grid*. 2010;**1**(1):11–19
- [4] Chakrabarti S., Kyriakides E., Bi T., Cai D., and Terzija V. ‘Measurements get together’. *IEEE Power and Energy Magazine*. 2009;**7**(1):41–49
- [5] Vanfretti L., Van Hertem D., and Gjerde J.O. *Smart transmission grids vision for Europe: towards a realistic research agenda* [Online]. 2014. Available from https://lirias.kuleuven.be/bitstream/123456789/458845/1/312442_1_En_10_Chapter_OnlinePDF.pdf [Accessed 30 June 2016]
- [6] Yang Y., Divan D., Harley R.G., and Habetler T.G. ‘Power line sensornet – a new concept for power grid monitoring’. *IEEE Power Engineering Society General Meeting (PES 2006)*; Montreal, Canada, 2006, pp. 1–8
- [7] Bonneville Power Admin (Technology Innovation Office). *Transmission technology road map agenda* [Online]. 2006 (Updated 2011). Available from <http://www.rcgsas.com/Documentos/Roadmaps/BPA.pdf> [Accessed 20 July 2016]
- [8] Moore R. and Goraj M. ‘New paradigm of smart transmission substation – practical experience with Ethernet based fiber optic switchyard at 500 kilovolts’. *Second IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies*; Manchester, 2011, pp. 1–5
- [9] Bing H., Xuyang Z., and Jing L. ‘Smart substation precise time research and analysis’. *IEEE International Symposium on Precision Clock Synchronization for Measurement, Control, and Communication (ISPCS)*; Austin, TX, 2014, pp. 93–6
- [10] Cyber Sciences. *Overview of IRIG-B Time Code Standard*. [Online]. 2016. Available from http://www.cyber-sciences.com/documents/TN-102_IRIG-B.pdf [Accessed 9 Aug 2016]
- [11] How to Geek. *What is the difference between TCP and UDP?* [Online]. 2014. Available from <http://www.howtogeek.com/190014/htg-explains-what-is-the-difference-between-tcp-and-udp/> [Accessed 13 Aug 2016]
- [12] Schaub P. and Kenwick A. ‘An IEC 61850 process bus solution’. *Protection, Automation and Control Magazine*. Summer 2009. pp. 38–44
- [13] Fouad A., Molinero-Fernández T.P., and Karam M.J. *Study of IEEE 802.1p GARP/GMRP timer values* [Online]. 1997. Available from <http://klamath.stanford.edu/~molinero/papers/garp-gmrp-timers-1997.pdf> [Accessed 15 August 2016]
- [14] Wu F.F., Moslehi K., and Bose A. ‘Power system control centers: past, present and future’. *Proceedings of the IEEE*; 2005;**93**(11):1890–1908
- [15] Energy Research Knowledge Centre (ERKC) consortium (European Commission). *Smart transmission grids* [Online]. 2014. Available from https://setis.ec.europa.eu/energy-research/sites/default/files/library/ERKC_%20TRS_Smart_Transmission_Grids.pdf [Accessed 2 June 2016]
- [16] NERC. *Glossary of terms used in NERC reliability standards* [Online]. USA: NERC; 2016. Available from http://www.nerc.com/files/glossary_of_terms.pdf [Accessed 21 June 2016]

- [17] Bose A. 'Smart transmission grid applications and their supporting infrastructure'. *IEEE Transaction on Smart Grid*. 2010;**1**(1):11–19
- [18] Wu J., Wu Jiang, and Yu Y. *The smart grid in China: a discussion paper* [Online]. 2012. Available from <http://www.etransition.org/2012.02.05.The%20Smart%20Grid%20In%20China.Final%20Draft.pdf> [Accessed 3 September 2016]
- [19] Yu Y., Yang J., and Chen B. 'The smart grids in China – a review'. *Energies (Open Access)*. 2012;**5**(5):1321–38
- [20] Inside Industrial Infrastructure Corp. *China's electricity grid industry* [Online]. 2015. Available from <https://roko-mobi.s3.amazonaws.com/a0ba76ce-a608-4c3c-8c34-de96329df92e/c790f066-5a61-4691-8ef2-aa57a75f10a8> [Accessed 3 September 2016]

Index

- absorption 207–8
- Abstract Communication Service
 - Interface (ACSI) models 114
- action table 134–5
- active distribution networks with full integration of demand and distributed energy resources (ADDRESS) 152
- architecture 153–4
- concepts 154
- interoperability of data exchanges 157–8
- participants and AD services 155–7
- adaptive, Smart Grid being 5
- adaptive protection system 132–5
- administrative communication systems 83
- administrative operational communication systems 82
- adsorption 207
- advanced application software 238
- advanced metering infrastructure (AMI) 2, 32, 94, 96, 173
 - communication infrastructure 37
 - communication technologies
 - adapted for 37
 - wired communication technologies 38
 - wireless communication technologies 39
- definition of 33
- main components of 33
 - communication network 34–5
 - data reception and management system 35
 - smart meters 33–4
- Advanced Security Acceleration Project for the Smart Grid (ASAP-SG) 96–7
- advanced transmission line
 - maintenance, provision of 232
- AGC controller 251
- agent communication language (ACL) 145
- agents 130, 136, 145
- all-electric vehicles 164
- American National Standards Institute (ANSI) 68–9
- AMI/Enterprise Bus interface 76
- ancillary services 240
- Asea Brown Boveri Ltd (ABB) 3
- automatic generation control (AGC) 237
- background and history of Smart Grid evolution 1–3
- balancing authority (BA) 248
- basic components of Smart Grid 56–8
- battery management system (BMS) 178
- benefits of Smart Grid 9
 - electricity marketing benefits 10
 - environment benefits 10
 - technical benefits 9–10
- business area networks (BANs) 87
- business-as-usual (BAU) 181
- business management system (BMS) 240
- carbon emissions, reduction in 10
- cellular communication 39
- centralized adaptive protection system (CAPS) 133–4

- characteristics of Smart Grid 5–9
 - as defined by EU and US Smart Grid visions 29
 - accommodating all generation and storage options 31
 - anticipating and responding to system disturbances 32
 - enabling active participation by consumers 30
 - enabling new products, services, and markets 31
 - operating resiliently against attack and natural disaster 32
 - optimizing asset utilization and operating efficiently 31–2
 - providing power quality for digital economy 31
- chemical electrical energy storage 201–3
- China
 - Smart Grid efforts 18–20
 - smart transmission grid research in 253–6
- CHP (combined heat and power) 228
- Cigré 72
- CIM Users Group (CIMug) 71–2
- circuit breaker (XCBR) 111–12
- climate change benefits 10
- closed-cycle desorption/adsorption heat storage 207
- commercial virtual power plant (CVPP) 149–50
 - practical implementation of 151–2
- Common Data Classes (CDCs) 106
- communication and information system 59
- communication infrastructure, AMI 37
- communication network technologies 34–5, 50
- communication systems, future 104–5
- communication technologies adapted for AMI 37
 - wired communication technologies 38
 - fiber optic communications 38
 - power line carrier (PLC) 38
 - wireless communication technologies 39
 - cellular communication 39
 - 900 MHz band 40
 - WLAN 39–40
 - ZigBee 39
- complex naming and services models 114
- composition of Smart Grid 46
 - based on conceptual reference model perspective 52
 - use cases 54–6
 - based on standards adaptation 46–7
 - based on technical components' perspective 47
 - advanced control systems 50
 - integrated communication technologies 49–50
 - new and advanced grid components 47–8
 - programs for decision support and human interfaces 50
 - smart devices and smart metering 48
 - based on technical perspective 51
 - smart infrastructure system 51–2
 - smart management and control system 52
 - smart protection system 52
- compressed air energy storage (CAES) 195, 209
- Computer Society Smart Grid Vision Project (CS-SGVP) 11, 13
- concentrated solar power (CSP) plants 195
- configured IED description (CID) 115
- constant power control (CPC) scheme 215
- contingencies 238
- conventional distribution network (DN) 143–4
- conventional electrical networks 25
 - characteristics of 26
 - comparison between Smart Grid and 28

- coupled with emergence of new applications 27
- infrastructure of 25
- Critical Cyber Assets 70
- Critical Infrastructure Protection (CIP) Standards 70
- critical peak prices (CPP) 175
- cyber infrastructure 89
- cyber interoperability standards 64–5
- cyber security 89–90
- Cyber Security Coordination Task Group (CSCTG) 91
- cyber security of power systems: *see* power systems, cyber security of
- cyber systems, defined 63
- data acquisition systems (DASs) 104
- data centers 87
- data element 111
- data name 111
- defense in depth (DID) 93
- definition of Smart Grid 3–5
- delayed auto reclosing (DAR) 138
- demand response (DR) programs 30
- demand side management (DSM) 48, 193
- Department of Energy in USA 3
- desorption 207–8
- digitalization 228–9
- digital signal processing (DSP) unit 109
- direct load control 173
- distributed energy resources (DERs) 10, 28, 128, 143
- distributed generation (DG) 15, 59, 127
- Distributed Network Protocol 3 (DNP3) 91, 98
- distributed system operators (DSOs) 146
- distribution management (DM) 96
- distribution management systems (DMSs) 238
- distribution system operators (DSOs) 146, 148, 155
- distribution systems 25
- double-layer capacitors (DLCs) 204
- doubly fed induction generators (DFIGs) 211, 215–17
- dynamic tariffs 175
- East China Power Grid (ECPG) 254
- economic dispatch (ED) 237
- electrical energy storage (EES) systems 193–208
- electrical power system 59
- electrical storage systems 204–5
- electricity marketing benefits of Smart Grid 10
- Electricity Transfer Project 254
- Electric Power Research Institute (EPRI) 4
- IntelliGrid program 73–4
- electric power system communication infrastructure and its limitation 83
- current PSC systems characteristics 83 shortcomings of 83–5
- future PSC systems, characteristics of 85–6
- electric vehicles (EVs) 27
- all-electric vehicles 164
- challenges faced by customers 166
- anxiety due to unavailability of public rapid charging infrastructure 167
- high cost 166–7
- inconvenience due to long waiting time 167
- potentially long charging times 167
- challenges faced by utilities 167
- additional administrative burden, impacts due to 168
- billing issues related to charging EVs 168–9
- high costs of upgrading the infrastructure 167
- local distribution system, impact on 168
- peak load, impact of 168

- charging systems 169
 - L1 AC charging systems 169
 - L2 AC charging systems 169
 - L3 DC charging stations 169–70
- communication system 180
- EV-Smart-Grid integration,
 - components related to 177–80
- flexibility, definition of 177
- flexibility provided by EVs
 - integration into Smart Grid 180
- hybrid electric vehicles (HEVs) 164
- integrated on-board charger 178–9
- load management, using Smart-Grid technologies 172
 - business models for EVs charging stations 175
 - difference EVs making to electricity load 172
 - effect of electricity pricing/tariffs 174
 - effect of regulation 174
 - EVs in meeting peak load 173
 - intermittent renewable energy-based generation, management of 173–4
 - optimizing scheduling of EV charging 172–3
- off-board charger 178
- on-board charger 178
- plug-in hybrid electric vehicles (PHEVs) 164
- power quality controller 179
- real-time smart load management (RT-SLM) algorithm 181, 182
 - automation of scheduling PEVs charging using 187
 - background and assumptions 182–3
 - implementation of 187
 - maximum sensitivities selection (MSS) optimization technique 186–7
 - operating principles of 187
 - optimization algorithm, formulation of 185–6
- Smart Grid enabling smart charging 170–2
- transportation electrifications
 - benefits of 165
 - driving factors toward 165
- electrochemical storage systems (batteries) 196–201
- electrolyzer 202
- end to end (E2E) system 236
- energy efficiency improvement 9
- energy management systems (EMS) 82, 103
- energy services interface (EIS) 57
- energy storage systems (ESSs) 176, 193
 - applications 209
 - electrical network energy storage applications 210
 - transport and mobility energy storage applications 210–11
 - benefits of 208–9
 - characteristics of 193–4
 - electrical energy storage (EES) systems 194
 - chemical ESS 201–3
 - electrical storage systems 204–5
 - electrochemical storage systems (batteries) 196–201
 - mechanical storage systems 195–6
 - thermal energy storage systems 205–8
 - and integration of wind power-based plants 211
 - improvement in LVRT capability 216–18
 - mitigation of power fluctuation 211–16
- Enterprise Bus (EB) 76
- environmental challenges 224
- environment benefits, of Smart Grid 10
- E-terra control 146
- E-terra trade 146, 151
- Ethernet network 233–4, 236

- Ethernet switch 108–9
- Europe
 - Smart Grid concept in 1
 - smart transmission grid research in 243–8
- European Association of Transmission System Operators (ENTSO-E) 244
- European level via the European Electricity Grid Initiative (EEGI) 244
- European Smart Grid efforts 15–18
- European Technology Platform (ETP) SmartGrids 15
- European Technology Platform for the Electricity Networks of the Future 1
- event table 134–5
- EV-Smart-Grid integration, components related to 177–80
- EV supply equipment (EVSE) 163, 167–72
- existing communication infrastructure (ECI) 83
- eXtensible Markup Language (XML) 70, 115
- extreme event facility hardening system 232
- fault circuit indicator (FCI) 123
 - intelligent fault circuit indicator for Smart Grid applications 124
 - operating principles of 123
- fiber optic cables 108–9
- fiber optic communications 38
- flexibility
 - definition of 177
 - provided by EVs integration into Smart Grid 180
- flexible AC transmission systems (FACTS) 231
- Flexible Electricity Networks to Integrate the eXpected Energy Evolution (FENIX) 147
- commercial virtual power plant (CVPP) 149–50
 - practical implementation of 151–2
- large-scale VPP (LSVPP) 151
- technical virtual power plant (TVPP) 150–1
- virtual power plant (VPP), concept of 148–9
- flow batteries 199–201
- flywheel energy storage (FES) 195
- functionality approach, Smart Grid characteristics based on 5
- future real-time information infrastructure 251–3
- generation system 25
- Generic Object Oriented Substation Event (GOOSE) 114, 121
 - messages 234, 237
- Generic Substation Status Event (GSSE) 114
- geographical information system (GIS) 241
- German Standards Institute DIN (*Deutsches Institut für Normung*) 71
- global positioning system (GPS) 19
- Grid 2030 3
- grid reliability improvement 9
- grid-side converter (GSC) 211
- grid-to-vehicle (G2V) 174
- GridWise™ Alliance 72–3
- GridWise vision 14
- hidden heat 206
- high-performance low-cost computers 104
- high-speed wide area network (WAN) 104
- high voltage alternating current (HVAC) systems 15
- home area networks (HANs) 35–6, 87, 170
- home building energy system (HBES) 36

- home energy management system (HEMS) 36
- HomePlug Powerline Alliance 74
- HTML 70
- Human Machine Interface (HMI) 117
- hybrid electric vehicles (HEVs) 164
- hybrid flow battery (HFB) 201
- hydrogen storage system 202
- ICT infrastructure, compatibility of 227
- IEC 61850 91
 - aim and objectives of 105
 - comprehensive modeling approach of 110–13
 - historical background 103–5
 - mapping process approach to protocols 114
 - merging unit 109–10
 - process bus 107–8
 - practical implementation of 108–9
 - Smart Grids and 117–18
 - structure of 105
 - substation architecture 116–17
 - substation automation system (SAS) 233–5
 - substation configuration language 115–16
 - Users Group 71
- IEC TC 57 66, 71
- IED capability description (ICD) 115
- IEEE 1588 standard 235–6
- IEEE Computer Society Smart Grid Vision Project (CS-SGVP) 11
 - architectural concepts layer 1 12
 - functional concepts layer 2 12–13
 - technological concepts layer 3 13
- improved connection and access of the grid 10
- independent system operators (ISOs) 146, 239–40
- index numbers 114
- information and communication system (ICS) 144
- information system integration project 19
- infrastructure, of Smart Grid 58
 - communication and information system 59
 - electrical power system 59
- infrastructure challenges 224
- in-home display (IHD) unit 36
- innovative technologies, adaptation of 225
- Institute of Electrical and Electronic Engineers (IEEE) 66–7
- Integrated Demonstration Project of Smart Grid 254
- intelligent electronic devices (IEDs) 3, 85, 121, 147
- intelligent primary devices 233
- Intelligent technologies 229
- IntelliGrid 4, 14, 73–4
- International Council on Large Electric Systems 72
- International Electrotechnical Commission (IEC) 3, 66
- International Society of Automation (ISA) 75
- Internet Engineering Task Force (IETF) 67–8
- internet protocol (IP)-based networks 58
- interoperability standards 63
 - analogy between interoperability of digitally based device and human interoperability 63–4
 - cyber interoperability standards 64
 - aim 64–5
 - characteristics 65
 - types of 65
 - development organizations 65
 - electrical power industry standards development organizations (SDOs) 66
 - American National Standards Institute (ANSI) 68–9
 - German Standards Institute DIN 71
 - Institute of Electrical and Electronic Engineers (IEEE) 66–7

- International Electrotechnical Commission (IEC) 66
- Internet Engineering Task Force (IETF) 67–8
- National Institute of Standards and Technology (NIST) 69–70
- North American Electric Reliability Corporation (NERC) 70
- World Wide Web Consortium (W3C) 70–1
- users groups and collaborative efforts within the power industry 71
- Cigré 72
- Electric Power Research Institute (EPRI)'s IntelliGrid program 73–4
- GridWise™ Alliance 72–3
- National Rural Electric Cooperative Association (NRECA)'s MultiSpeak 72
- Utilities Communication Architecture (UCA)
 - International Users Group (UCAIug) 71–2
- Utility Standards Board (USB) 76–7
 - vendor collaborations 74–5
- intersystem interfaces 46–7
- intrusion detection systems (IDSs) 94
- IRIG-B time protocol 235
- ISA 100 75
- ISA SP100 75
- L1 AC charging systems 169
- L2 AC charging systems 169
- L3 DC charging stations 169–70
- large-scale VPP (LSVPP) 151
- latent heat storage (LHS) 206–7
- lead acid (LA) battery 196
- lithium ion battery (Li-ion) 196–7
- load frequency control (LFC) 237
- load management of EVs
 - using Smart-Grid technologies 172
- business models for EVs charging stations 175–6
- difference EVs making to electricity load 172
- effect of electricity pricing/tariffs 174
- effect of regulation 174
- EVs in meeting peak load 173
- intermittent renewable energy-based generation 173–4
- optimizing scheduling of EV charging 172–3
- local-area networks (LAN) 50, 236, 238
- location marginal prices (LMPs) 239–40
- logical connections (LCs) 128
- logical devices 110
- logical nodes (LNs) 111, 128–9
- Long Term Evolution (LTE) 93
- low-speed low-rate wireless area personal network (LR-WPAN) 124
- low-voltage-ride-through (LVRT) capability 216–18
- Manufacturing Message Specification (MMS) 106
- market/customer requirements 224
- market operations system (MOS) 240
- maximum sensitivities selection (MSS) optimization 186–7
- mechanical storage systems 195–6
- merging unit 109–10, 116
- message payload 158
- metal air battery 197
- meter data management system (MDMS) 35
- microgrid central controller (MGCC) 134–5
- minicomputers 238

- motives behind developing the Smart Grid concept 26
 - aging of conventional electrical networks coupled with emergence of new applications 27
 - electricity market, liberalization of 28
 - motivation and inclusion of customers 28
 - political and environmental factors 27
- multiagent systems and IEC 61850 129
- multiagent technology, application of 129
- MultiSpeak 72
- National Institute of Standards and Technology (NIST) 52, 69–70
 - NIST SP-800-53 69
 - NIST SP-800-82 70
- National Rural Electric Cooperative Association (NRECA) 72
- neighborhood area network (NAN) 35, 87, 170
- network automation 118
- network protection 128
- network time protocol (NTP) 235
- nickel cadmium battery 196
- nickel metal hydride battery 196
- 900 MHz band 40
- North American Electric Reliability Corporation (NERC) 70
 - NERC CIP- 002 through CIP-009 70
- off-line fault analysis 134
- on-line fault analysis 134
- Open System Interconnect (OSI) communication system 105
- operational efficiency improvement 9
 - operational gateways 36–7
 - optimal power flow (OPF) programs 238
 - pan-European transmission grid
 - research activities 244
 - asset management 246–7
 - grid architecture 244–5
 - market design 246
 - network operation 245–6
 - power technologies 245
 - scaling-up and replication activities 246
 - transmission/distribution grid interactions 247–8
 - peak time rebates 175
 - peer to peer (P2P) 236
 - phase change materials (PCMs) 206–7
 - phasor measurement units (PMUs) 19, 85, 122, 225, 241, 249–50
 - physical connections (PCs) 128
 - physical devices (PDs) 110–11, 128
 - “plug-and-play” approach 31
 - plug-in electric vehicles (PEVs) 165
 - plugin hybrid electric vehicles (PHEVs) 10, 164
 - power line carrier (PLC) 38
 - power line communication (PLC) 38
 - PowerMatch 146, 152
 - power system communication (PSC), classification of 81
 - administrative communication systems 83
 - administrative operational communication systems 82
 - real-time operational communication systems 81
 - power system protection under Smart Grid environment 121
 - architecture of Smart Grid protection system 128
 - multiagent systems and IEC 61850 129
 - multiagent technology, application of 129

- protection system architecture based
 - on IEC 61850 137
 - new opportunities offered by
 - introduction of IEC 61850
 - standard 138–9
 - traditional practices 138
- protection systems under Smart Grid
 - environment 122
 - adaptability to power system
 - configuration changes 123
 - fault circuit indicator (FCI)
 - 123–5
 - intelligently collecting protection
 - relay data 123
- smart adaptive protection systems
 - 131
 - adaptive protection for smart
 - distribution networks 135–7
 - for microgrids 132–5
- Smart Grid communication
 - infrastructure that suits
 - protection requirements 125–6
- Smart Grid era, protection prior to
 - 122
- Smart Grid requiring smarter
 - protection 126–8
 - efficient use of information at the
 - local bay level 126–7
 - integration of substation
 - information 127
 - use of integrated wide-area
 - information 127–8
- power system reliability 238
- power systems, cyber security of 89
 - basic definitions 89
 - cyber infrastructure 89
 - cyber security 89–90
 - communication-based attacks 93
 - compliance versus security 95
 - emerging Smart Grid cyber-security
 - technologies 93–5
 - security of power systems and cyber
 - attacks 90–1
 - Smart Grid cyber-security
 - challenges 92
 - due to potential infrastructure
 - attacks 92
 - faced by grid operators 92–3
- Smart Grid cyber-security
 - standards 95
 - managing encryption key of field
 - devices 98
 - network segmentation design 96
 - policy security controls 96
 - protection of field devices 97
 - securing communications 97–8
 - Smart Grid cyber-security
 - standards challenges 98–9
 - technical security controls 97
- practical smart substation 233–7
- precise time protocol (PTP) 235
- primary communication 117
- process bus 107–8
 - practical implementation of 108–9
- process layer, defined 116
- programmable logic controllers
 - (PLCs) 3
- protection system architecture based on
 - IEC 61850 137
 - new opportunities 138–9
 - traditional practices 138
- Protocol Specification for Electric
 - Metering (PSEM) 69
- provision of advanced transmission
 - line maintenance and
 - diagnostic technologies 232
- pumped hydro storage (PHS) 195, 209
- PURE project 202
- quality of supply 10
- real-time operational data
 - communication 82
- real-time operational voice
 - communication 82
- real-time prices (RTP) 175
- real-time smart load management
 - (RT-SLM) algorithm 181–8
 - automation of scheduling PEVs
 - charging using 187

- background and assumptions 182–3
- implementation of 187
- maximum sensitivities selection (MSS) optimization technique 186–7
- operating principles of 187
- optimization algorithm, formulation of 185–6
- real-world implementation 71
- redox flow battery (RFB) 199–201
- regional transmission organization (RTO) 239–40
- Regional Transmission Organization/Independent System Operator (RTO/ISO) systems 45
- regional transmission organizations (RTOs) 146, 239
- register numbers 114
- reliability coordinator (RC) 248–9
- remote clients 117
- remote network access 117
- remote terminal units (RTU) 3, 147, 237
- renewable energy-based generation (REBG) 165, 176
- renewable energy sources (RESs) 10, 27, 143, 224
- Request for Comment (RFC) 67–8
- return on investment (ROI) 92
- robust transmission of electric power 231–2
- rotor-side converter (RSC) 211
- sampled measured values (SMV) 237
- security and safety improvement 9–10
- security-constrained unit commitment (SCUC) 239
- security control system 238
- security of a power system 238
- self-healing 5, 32, 231, 233
- semantic object models 117
- simple network time protocol (SNTP) 235
- Simple Object Access Protocol (SOAP) 70–1
- single point status (SPS) 113
- small-scale generation 228
- smart adaptive protection systems 131
 - adaptive protection for smart distribution networks 135–7
 - for microgrids 132–5
- smart aggregation 118
- smart distribution, pillars of 118
- smart distribution network (SDN) 121, 143
 - building blocks of 144
 - agents 145–6
 - E-terra control 146–7
 - E-terra trade 146
 - PowerMatch 146
 - versus conventional distribution network 143–4
 - need for 144
- Smart Grid communication system
 - infrastructure (SGCS) 86
 - architecture of 87
 - challenges 87
 - dealing with huge volume of data 87
 - energy sources 88
 - highly varying traffic 88
 - interoperability 88
 - quality of service (QoS) 88
 - security 88
 - fundamental functions of 87
 - standardization efforts by industry 88–9
- Smart Grid Cyber Security
 - Coordination Task Group (CSCTG) 91
- Smart Grid enabling smart charging 170
 - demand response (DR) system 171
 - demand side management (DSM) system 170–1
 - distributed automation (DA) system 172
 - distributed intelligence 171
 - renewable energy-based generation, coordination with 172

- robust, reliable, and secure
 - connectivity 170
- separate meter at EVSE integrated into AMI 171
- Smart Grid protection system (SGPS) 121, 128–31
- Smart Homes 75
- smart metering system (SMS) 36, 118
- smart meters (SMs) 33–4, 48, 87
- smart transmission grid (STG) 223
 - adaptation of innovative technologies 225
 - “centralized model” for 226–7
 - compatibility of ICT infrastructure 227
 - environmental challenges 224
 - future STG 228
 - basic components of 230
 - characteristics of 228–30
 - smart control centers 237–43
 - smart transmission network 231–2
 - smart transmission substations 232–7
 - infrastructure challenges 224
 - integration of synchrophasor
 - measurements technology into transmission system operation and control 225–7
 - market/customer requirements 224
 - operational and coordination issues 227–8
 - research activities 243
 - in China 253–6
 - in Europe 243–8
 - in USA 248–53
 - vision of 229
- smart transmission network 231–2
- sodium nickel chloride battery 198–9
- sodium sulfur battery 197–8
- sorption (adsorption, absorption)
 - storage systems 207–8
- special protection schemes (SPSs) 83–4
- standardized communication services 104
- standards management boards (SMBs) 66
- standards models and protocols 58
- State Grid Corporation of China (SGCC) 19, 254–5
- state-of-charge (SOC) 178
- state-of-health (SOH) estimation 178
- station bus 117, 234–5
- storage of sensible heat, storage (SHS) 205–6
- strategic deployment document (SDD) 17
- Strategic Research Agenda (SRA) 16
- substation automation (SA) 87, 103
- substation configuration description (SCD) 115
- substation configuration language (SCL) 107, 115
- supercapacitors: *see* double-layer capacitors (DLCs)
- superconducting magnetic energy storage (SMES) 204–5
- supervisory control and data acquisition (SCADA) system 3, 82, 90–2, 103, 225, 241, 249–50
- supply and demand matching (SDM) 146
- switched Ethernet 104
- synchronized measurement technology (SMT) 225
- synchronized phasor measurement 85, 248
- synchrophasor measurements
 - technology
 - integration of, into transmission system operation and control 225–7
- synthetic natural gas (SNG) 202–3
- system specification description (SSD) 115
- TCP/IP 104
- technical benefits, of Smart Grid 9–10
- technical councils (TCs) 66

- ul style="list-style-type: none;">
- technical virtual power plant (TVPP) 150–1
- thermal energy storage systems (TES) 205–8
- “time-of-use (TOU)” tariffs 175
- transmission system 25
- transmission system operators (TSOs) 146, 148, 151, 228
- transmission system projects 254–6
- transportation electrifications
 - benefits of 165
 - driving factors toward 165
 - energy independence and security 165
 - environmental benefits 166
 - volatility and high prices of oil 165
- Transport Layer Security (TLS) protocol 97
- Ultra High Voltage (UHV) Power Transmission 18
- uniform pricing scheme 239
- unit commitment (UC) programs 238
- USA
 - Smart Grid concept in 1
 - smart transmission grid research in 248–53
- use cases 54–6
- US Energy Independence and Security Act 1
- US Smart Grid efforts 13
 - GridWise vision 14
 - IntelliGridSM 14
- Utilities Communication Architecture (UCA) International Users Group (UCAIug) 71–2
- Utility Standards Board (USB) 66, 76–7
- vanadium redox flow battery (VRFB) 200–1
- vehicle to grid (V2G) 165
- vendor collaborations 74–5
- virtual local area network (VLAN) 117
- virtual model 112
- virtual power plant (VPP) 119, 148
 - concept of 148–9
- virtual private network (VPN) 96
- vision, of Smart Grid 10
 - China’s Smart Grid efforts 18–20
 - definition of 10–11
 - European Smart Grid efforts 15–18
 - IEEE Computer Society Smart Grid Vision Project (CS-SGVP) 11
 - architectural concepts layer 1 12
 - functional concepts layer 2 12–13
 - technological concepts layer 3 13
 - US Smart Grid efforts 13
 - GridWise vision 14
 - IntelliGridSM 14
- Web2Energy 118
- web services for application-to-application communications 70
- West-East Electricity Transfer Project 18
- wide-area information integration (WAI) 128
- wide-area measurement and control systems (WAMACS) 127
- wide-area measurement system (WAMS) 19, 122
- wide-area monitoring, protection, and control (WAMPAC) system 96, 225
- wide-area networks (WAN) 50, 146
- wide-area protection 128
- WiMAX 39
- wind farm supervisory controller (WFSC) 215
- wind power-based plants, integration of 211
 - improvement in LVRT capability 216–18
 - mitigation of power fluctuation 211–16
- wind turbine generator (WTG) system 211, 215

wired communication technologies
 38–9
 cellular communication 39
 fiber optic communications 38
 900 MHz band 40
 power line carrier (PLC) 38
 WLAN 39–40
 ZigBee 39
Wireless Local Area Network
 (WLAN) 39–40

working groups (WGs) 66
World Wide Web Consortium (W3C)
 70–1
ZEBRA (Zero Emission
 Battery Research) battery:
 see sodium nickel chloride
 battery
ZigBee 39, 88–9, 124
ZigBee Alliance (ZA) 74

Introduction to the Smart Grid:

Concepts, Technologies and Evolution

Introduction to the Smart Grid: Concepts, Technologies and Evolution is essential reading for researchers, engineers and advanced students working in energy engineering.

In recent years it became increasingly apparent that conventional electrical networks cannot meet the requirements of the 21st century. These include reliability, efficiency, liberalisation of electricity markets, as well as effective and seamless integration of various types of renewable energy sources, electric vehicles, and customers as players. The emergence of new technologies such as distributed control, monitoring devices, and tremendous advances in information and communication technology have paved the way to realize the Smart Grid concept.

The book identifies and discusses the tools required to ensure the interoperability among the various digitally-based components of the Smart Grid. Topics covered include an introduction to the smart grid concept; smart grid versus conventional electric networks; smart grid infrastructure; interoperability standards; communication system and its cyber security; international standard IEC 61850 and its application to smart grids; power system protection under smart grid environment; application of smart grid concept to distribution networks; integration of electric vehicles; energy storage systems; smart transmission grid.

Essential reading for professional engineers and researchers, and advanced students.

About the Author

Salman K Salman is Professor Emeritus at The Robert Gordon University-Aberdeen, Scotland, where he led the Renewable Energy & Power Systems Group. His research interest includes integration of renewable energy sources into electrical distribution networks, modelling of wind turbines, protection of distribution networks with integrated distributed generation, substation automation. He worked closely with industry including ALSTOM, ScottishPower, Cruickshank Partners and National Grid. He is the co-author of "*Digital Protection for Power Systems*" (IET, 1997) and the author of more than 120 papers.

ISBN 978-1-78561-119-3



9 781785 611193 >



Energy Engineering

The Institution of Engineering and Technology • www.theiet.org
978-1-78561-119-3