SMART MICROGRIDS

Lessons from Campus Microgrid Design and Implementation

edited by

Hassan Farhangi

BCIT™ BRITISH COLUMBIA INSTITUTE OF TECHNOLOGY

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Vancouver, Canada

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Yesterday I was young, so I wanted to change the world.
Today I am wise, so I am changing myself.

Rumi

Dedicated to all those who strive to better the life of others by being better human beings themselves and who have the wisdom to strike a balance between progress and keeping this lonely planet habitable for the future generations.

… and to Sara and Aras

Contents

Foreword

This book discusses an applied research initiative conducted at British Columbia Institute of Technology (BCIT) to design and realize a campus-wide smart microgrid as a living laboratory in its Burnaby campus in Vancouver, Canada. BCIT is an institute of higher education, publicly funded to serve the citizens of British Columbia and its partners around the world and to educate and train graduates who are career-ready, are immediately productive in their chosen workplace, and are ongoing assets for their employers.

BCIT was established in 1964 in Burnaby (Greater Vancouver), British Columbia, Canada, as a professional school to train technicians, technologists, and practitioners needed to serve the industry. Since its inception, BCIT has grown substantially to become one of the largest postsecondary academic institutes in Canada. BCIT has five large campuses around Greater Vancouver with many schools and departments, including the School of Business, School of Computing and Academic Studies, School of Construction and the Environment, School of Energy, School of Health Sciences, and School of Transportation. Approximately 18,000 full-time students and 28,000 part-time students enroll and enter BCIT every year. It has more than 1700 full-time and about 500 part-time faculty and staff.

BCIT's technical education currency is assured through applied research. It conducts grant-funded and industry-sponsored applied research and development focused on solving industry's challenges. Bringing together multidisciplinary teams from a range of research areas and technical expertise, BCIT researchers create practical applied research solutions that can be transformed immediately into commercially relevant products, services, and applications. These activities often result in licensing opportunities, spin-off companies, and new start-ups and are primarily motivated by the creation of direct and indirect benefits for students and the public. Applied research provides students with practical learning opportunities and produces outcomes that further enhance the economic success of and employment opportunities for British Columbia.

The Smart Microgrid Applied Research Team (SMART) is a department within the Technology Centre of BCIT. It converges the information technology, communication engineering, electrical engineering, and computing fields to develop technologies and solutions for complex applied research problems in the energy sector. SMART focuses on smart grid and cybersecurity research in collaboration with industry stakeholders.

In 2007, SMART, BC Hydro (British Columbia electric power authority), the government of British Columbia, and the government of Canada began a joint research and development program for designing, constructing, and implementing Canada's first campus-based smart microgrid at BCIT's Burnaby campus to deliver a "path from laboratory to field" through cost-effective solutions for emerging smart grids. As a result of this program, BCIT has amassed a unique technical expertise in delivering cost-effective solutions for smart grid living laboratory design and realization. Capitalizing on its successful track record in developing smart grid technologies and solutions, BCIT strives to share its knowledge and expertise in this area with industry and academic stakeholders in Canada and the world. The present book is an attempt to disseminate and share that unique experience with the world.

Dr. Kim Dotto
Dean, Applied Research
British Columbia Institute of Technology
Burnaby, British Columbia, Canada

Preface

This book is designed as a narrative on how a complex system, such as a microgrid, is designed, implemented, tested, and used. It captures the essence of experiences that our team at British Columbia Institute of Technology (BCIT) has accumulated through eight years of intensive research in this area. As such, the book is meant to reflect our team's thought processes in spec design, technology selection, integration methodology, and realization of various components of the microgrid and its larger system as a whole.

Discussions between BCIT and its partners about the need for a microgrid started in 2007. At the time, the void was felt for an environment with sufficient scale and similar topology to a utility grid to enable our strategic partners to experiment with and qualify technologies, products, and solutions that targeted the utility environment. In that regard, one of the main drivers for the utility's push to set up a microgrid was its initial application as a sandbox where competing technologies and solutions for a smart grid could be evaluated, qualified, and tested.

Nevertheless, the partners soon realized that such an environment could also be used as a platform to develop new technologies and solutions, as well as help with the education of the new generation of workforce, which utilities require to help them realize their smart grid development and rollout plans.

Those early requirements convinced the design team of the merits to spend ample time in the early stages of the initiative to put together a microgrid strategic road map that captured the needs and objectives of partners and stakeholders. The road map enabled the design team to ensure that each component, subsystem, or capability that was implemented in the microgrid enabled and facilitated the emergence of the next set of capabilities and features of the system.

Chapter 1, entitled "Microgrid as the Building Block of Smart Grid," authored by Hassan Farhangi, attempts to introduce the concept of microgrid and its role in the evolution of the legacy grid toward a future smart grid and covers introductory topics such as definitions, architectures, and types of microgrids.

Chapter 2, entitled "Smart Grid System Integration," authored by Hassan Farhangi, introduces models for a smart grid and what it takes to map such models, or parts thereof, within the existing utility grid. The approach in this chapter is to enable the reader to start from an abstract model of a smart grid and quickly move toward what is feasible within the confines of the present legacy grid.

Chapter 3, entitled "Campus Microgrid," authored by Hassan Farhangi, discusses the background of the BCIT microgrid initiative, the drivers behind its development, and the interests and requirements of its stakeholders. An important section in this chapter covers the thought process behind the microgrid road map, the document that drove and oversaw the microgrid initiative from its start to present day.

Chapter 4, entitled "Cogeneration Plants," authored by Minoo Shariat-Zadeh, covers technology fundamentals in the design and implementation of a microgrid's cogeneration plants. The role and the importance of applicable standards are also briefly covered.

Chapter 5, entitled "Electrical Storage System," authored by Eric Hawthorne, provides an extensive overview of electrical storage fundamentals, technology choices. and its integration issues within microgrids. Given the specific nature of experiences the design team has accumulated in storage design and integration, a dedicated section in this chapter is devoted to lessons learned by the design team in developing the BCIT microgrid's electrical storage system.

Chapter 6, entitled "Energy Management System," authored by Janet So, covers one of the most important technologies in microgrid design of the same name. Often regarded as the lynchpin of smart microgrids, the energy management system is the central planning and control system that enables the microgrid to achieve its operational objectives and targets.

Chapter 7, entitled “Microgrid Communication and Control,” coauthored by Hassan Farhangi and Kelly Carmichael, provides an overview of a microgrid’s communication and data processing requirements, technologies, and networks. The chapter also covers different network domains implemented within the BCIT smart microgrid and their interactions with operational applications of the microgrid.

Chapter 8, entitled “Interconnection,” authored by Ali Palizban, covers the critical topic of a microgrid’s interconnection with the main grid and the processes involved in ensuring that grid-tied microgrids could safely interconnect with the larger grid.

Chapter 9, entitled “Microgrid Economic, Environmental, and Social Studies,” authored by Joey Dabell, covers the very first question that microgrid planners need to answer, which is the economic justification of a microgrid. The chapter also covers the important topic of environmental assessments, which in turn is one of the first major reviews that the microgrid design has to pass before it could be investable. And last but not least, the chapter deals with the need for community outreach and consumer behavior.

Chapter 10, entitled “Microgrid Use Cases, Testing, and Validation,” authored by Clay Howey, provides an overview of industry standard use cases, developed by the Electric Power Research Institute, and explains BCIT’s preferences for use cases implemented in our test plans and lessons learned in the process.

Chapter 11, entitled “Campus Microgrid Lessons Learned,” coauthored by Joey Dabell and Clay Howey, covers a wide variety of experiences and lessons that the BCIT’s design team has accumulated in their eight years of design and implementation of the microgrid.

In addition to BCIT’s design team, who have authored this book, BCIT’s smart microgrid could have not been realized without the generous help, support, and contributions of many executives and researchers, both in industry and in academia, who provided their knowledge, expertise, and guidance to help us move forward. As a research team, we are thankful for their support and contributions and would like to dedicate this book to their generosity and selfless support.

Among these, our sincere thanks go to Dr. Kim Dotto, BCIT's dean for applied research, Dr. Don Wright, past BCIT president Paul Dangerfield, past BCIT vice president for education, and Kathy Kinloch, current BCIT president, who supported our efforts every step of the way, helping us to navigate the organizational complexities at BCIT.

Moreover, many departments and individuals within BCIT supported our work and collaborated extensively with the design team in the process of design and construction of our microgrid. Among these, our special thanks go to Joe Newton and his manager, Nancy Paris.

Furthermore, we would like to offer our sincere appreciations and gratitude to our industry partners, who helped us with guidance, advice, and technology. Among these, our warmest thanks are reserved for Kip Morison, Helen Whittaker, and Giuseppe Stanciulescu of BC Hydro; John Gorjup and Dr. Felix Kwamena of Natural Resources Canada; Dr. Lisa Dignard of CanmetENERGY; Dr. Andrew Vallerand and Rodney Howes of Defence Research and Development Canada; and Jean Lassard of Hydro-Québec.

Last but not least, we have benefited tremendously from our discussions with power system experts, including Dr. Geza Joos of McGill University, Dr. Reza Iravani of the University of Toronto, Dr. Chris Marnay of the Lawrence Berkeley National Laboratory, and Dr. Ali Palizban of BCIT's School of Energy.

Dr. Hassan Farhangi
Editor

Acknowledgments

Over the years, countless individuals, organizations, and entities have provided the Smart Microgrid Applied Research Team at British Columbia Institute of Technology (BCIT) with generous support, funding, and contributions in our quest to establish Canada's very first smart microgrid on the BCIT campus in Burnaby. It may not be possible to list each and every person, and their contributions, in empowering us to achieve our goals. Nevertheless, here is an incomplete list of our partners:

Utilities

- BC Hydro
- Hydro One
- Hydro-Québec
- New Brunswick Power
- Manitoba Hydro

Government

- British Columbia Ministry of Energy and Mines (Innovative Clean Energy Fund)
- Government of Canada (Western Diversification Fund, Natural Resources Canada, Natural Sciences and Engineering Research Council, Defence Research and Development Canada)

Research centers

- CanmetENERGY
- Powertech Labs
- Institut de recherche d'Hydro-Québec

Private sector

- Siemens
- Panasonic
- Tantalus Systems Corporation
- Corinex Communications Corporation
- Schneider Electric
- IBM
- General Electric
- ABB
- Car2Go

Academia

- Simon Fraser University
- McGill University
- University of Toronto
- University of New Brunswick
- University of Alberta
- University of Waterloo
- Ryerson University
- University of Manitoba
- University of British Columbia
- University of Aachen (Germany)

Editor

Hassan Farhangi, PhD, senior member IEEE, PEng, is the director of smart grid research at British Columbia Institute of Technology (BCIT) in Burnaby, British Columbia, Canada, and adjunct professor at Simon Fraser University in Vancouver, Canada. Dr. Farhangi has held adjunct professor appointments at the National University of Singapore, Royal Road University in Victoria, Canada, and at the University of British Colombia in Vancouver, Canada. Dr. Farhangi is currently the chief system architect and the principal investigator of BCIT's smart microgrid initiative at its Burnaby campus in Vancouver, British Columbia, and the scientific director and principal investigator of Natural Sciences and Engineering Research Council's (NSERC) pan-Canadian smart microgrid network (NSERC Smart Microgrid Network or NSMG-Net). He is well published with numerous contributions in scientific journals and conferences on smart grids and has served on various international standardization committees, such as International Electrotechnical Commission (IEC) Canadian Subcommittee (CSC) Technical Committee 57 (TC 57) Working Group 17 (WG 57) (IEC 61850), Conseil International des Grands Réseaux Électriques (CIGRÉ) WG C6.21 (Smart Metering), CIGRÉ WG C6.22 (Microgrids Evolution), and CIGRÉ WG C6.28 (Hybrid Systems for Off-Grid Power Supply). A frequent keynote speaker at various international smart grid conferences, Dr. Farhangi has more than 30 years of experience in academic and applied research in Europe, Asia, the United States, and Canada. Before joining BCIT, he served as the chief technical officer of a number of companies involved in the design and development of systems, components, and solutions for the smart grid. Dr. Farhangi obtained his PhD degree from the University of Manchester Institute of Science and Technology in the United Kingdom in 1982; his MSc degree from the University of Bradford in the United Kingdom in 1978; and his BSc degree from the University of Tabriz in Iran in 1976, all in electrical and electronic engineering. Dr. Farhangi is a founding member of SmartGrid Canada, an academic member of CIGRÉ, a member of the Association of Professional Engineers and Geoscientists of British Columbia, and a senior member of the Institute of Electrical and Electronic Engineers.

Contributors

Kelly Carmichael has 22 years of experience working in the information technology industry. He holds a diploma in computer science from Thompson Rivers University, Kamloops, British Columbia. His information technology work experience ranges from employment in an embryonic entrepreneurial start-up firm all the way up to the large multinational giant IBM. Carmichael has been involved in development projects spanning complex distributed systems all the way to low-level operating system services. He has an interest in the theory and practice of delivering quality, reliable, and maintainable information systems.

Joey Dabell is a project leader at the British Columbia Institute of Technology (BCIT). As a faculty researcher, she functions as a project manager for smart microgrid research, development, and demonstration projects where she coordinates the research, development, and demonstration activities of the multidiscipline Smart Microgrid Applied Research Team. In this role she facilitates collaborations between academic, industry, and community partners; coordinates microgrid-related training and outreach efforts; and participates in business development. Dabell's research interests and activities are at the intersection of microgrid and renewable energy technologies with policy, community outreach, and energy behavior change, particularly as these relate to the socioeconomic and environmental issues leading to 100% renewable energy. She is an active member of BCIT's Sustainability Committee. Dabell received her MET from the University of British Columbia, Vancouver, Canada, in 2009, and her BTech in computer graphics and artificial intelligence programming from BCIT in 1995.

Eric Hawthorne received his MSc degree in computing and information science from Queen's University, Kingston, Ontario, Canada, in 1988. He is a research associate at the Smart Microgrid Applied Research Team within the Centre for Applied Research and Innovation of British Columbia Institute of Technology in Vancouver, Canada. His work focuses on software and systems architecture and renewable energy microgrid energy management systems. He has extensive experience in smart grid applications, systems engineering, and software engineering. He is a coauthor of *97 Things Every Software Architect Should Know: Collective Wisdom from the Experts*. His main research interests are smart grid control systems for renewable energy integration and demand response.

Clay Howey has over 25 years' experience in project management, software development, distributed systems, and data communications. Currently, he is the technical lead on the smart microgrid research initiative at British Columbia Institute of Technology and coordinates the activities of researchers in the areas of energy management, renewable generation integration, substation automation, smart metering, electric vehicles and charging stations, and demand response. Howey also has experience in mobile wireless application development and has expertise in artificial intelligence applications, employing technologies such as expert systems, fuzzy logic, and neural networks.

Ali Palizban received his PhD in electrical engineering from the University of New South Wales, Sydney, Australia. He is currently the program head of the electrical power and industrial control options of the Department of Electrical and Computer Engineering at the British Columbia Institute of Technology's School of Energy. He has worked in the electric power industry consulting engineering firms, academic, and research and development institutions for over 27 years. He is involved in applied research on microgrid design and implementation, substation automation, and voltage/volt-ampere reactive optimization projects. He has published several peer-reviewed papers in electrical power and control systems. He is a member of the Association of Professional Engineers and Geoscientists of British Columbia and a senior member of Institute of Electrical and Electronic Engineers. He is interested in teaching and research in power system analysis and design, control, automation systems, and smart microgrids. He has been directly involved in the design of British Columbia Institute of Technology's microgrid from the early stage of feasibility study, simulation analysis, installation, testing, and final phases of commissioning and operation.

Minoo Shariat-Zadeh received her BSc degree in electrical engineering from the Azad University of Tehran, Iran, in 1995. She is a research associate at the Smart Microgrid Applied Research Team within the Centre for Applied Research and Innovation of British Columbia Institute of Technology in Vancouver, Canada. She functions as a team leader and participant and designs, plans, and conducts smart microgrid projects, renewable energy resource integration, power automation systems, and substation automation systems. She has worked in manufacturing, consulting engineering firms, and research and development for over 19 years. She is a member of the Association of Professional Engineers and Geoscientists of British Columbia. Her main research interests are smart grids, smart microgrids, renewable energies, and control and automation systems.

Janet So is a research analyst in the Smart Microgrid Applied Research Team at British Columbia Institute of Technology. As part of the software team in the smart microgrid research initiative, she has developed applications in areas of energy management system, meter and sensor data acquisition, and demand response algorithms. Her research interests are in smart grid software control systems and demand response. So is an experienced software developer, particularly in web applications. She has worked on a variety of small and large software projects ranging from an e-commerce fashion website to a business intelligent software suite. So holds a BSoftEng from the University of Waterloo, Ontario, Canada.

List of Abbreviations

AC	alternating current
AEPS	area electric power system
AMI	advanced metering infrastructure
AMR	automated meter reading
APS	area power system
a-Si	amorphous silicon
BCIT	British Columbia Institute of Technology
BESS	battery energy storage system
BMU	battery management unit
BOS	balance of system
CAES	compressed air energy storage
CB	circuit breaker
CIGS	copper indium gallium deselenide
CIS	copper indium selenide
CSA	Canadian Standards Association
CSA C22.2 No. 107.1	Standard for General Use Power Supplies
c-Si	monocrystalline silicon
CSV	comma-separated values
CVR	conservation voltage reduction
DAU	data aggregator unit
DC	direct current
DEMS	decentralized energy management system

DER	distributed energy resource
DFIG	doubly fed induction generator
DG	distributed generation
DGTIR	Distributed Generation Technical Interconnection Requirements
DOE	U.S. Department of Energy
DR	demand response
EMS	energy management system
Energy OASIS	Open Access to Sustainable Intermittent Sources
EPRI	Electric Power Research Institute
EV	electric vehicle
FAT	factory acceptance test
FIT	factory integration test
FTP	file transfer protocol
GHG	greenhouse gas
GIS	geographical information system
GOOSE	generic object oriented substation event
GPS	global positioning system
GW	gigawatts (unit of power)
HAWT	horizontal axis wind turbine
HMI	human–machine interface
IEC	International Electrotechnical Commission
IEC 61850	International Electrotechnical Commission standard 61850: Communication Networks and Systems in Substations
IEEE	Institute of Electrical and Electronics Engineers
IEEE 1547	IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems
IEEE 519	IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems
IT	information technology
kW	kilowatts (unit of power)
kWh	kilowatt-hour (unit of energy)

LAN	local area network
LNG	liquid natural gas
LV	low-voltage
MC	microgrid controller
MCC	microgrid control center
mc-Si	polycrystalline silicon
MDMS	metering data management system
MEM	microgrid energy manager
MEMS	microgrid energy management system
MO	market operator
MS	microgrid switch
MV	medium-voltage
MW	megawatts
NIST	National Institute of Standards and Technology
NOCT	normal operating cell temperature
PCC	point of common coupling
PCS	power conversion system
PIR	project interconnection requirements
PLC	programmable logic controller; power-line communication
PTP	precision time protocol
PV	photovoltaic
R&D	research and development
RD&D	research, development, and demonstration
RESTful	representative state transfer; a web services communication protocol guideline
SAT	site acceptance test
SCADA	supervisory control and data acquisition
SLD	single-line diagram
SOC	battery state of charge (usually as a percentage of capacity)
STCs	standard test conditions
ToU	time of use
UI	user interface
UL	Underwriters Laboratories Inc.

UL 1741	UL Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources
V2G	vehicle to grid
VAR	volt-ampere reactive optimization
VAWT	vertical axis wind turbine
VVO	voltage/volt-ampere reactive optimization
W/kg	watts per kilogram (unit of specific power)
Wh/kg	watt-hours per kilogram (unit of specific energy)
Wh/L	watt-hours per liter
Wi-Fi	wireless local area network
WiMAX	Worldwide Interoperability for Microwave Access

1

Microgrid as the Building Block of Smart Grid

HASSAN FARHANGI

Contents

Environmental, economic, and political issues in the latter half of the last century have made it challenging for the electric utility industry to continue with the status quo. The rising cost of primary fuels is increasingly challenging the sustainability of generating power out of fossil-based sources in the long run. And given the role that fossil fuels play in electricity generation across the world, the utility industry's baseline costs and carbon footprints are on the rise. At the same time and since tariffs for the sale of electricity to consumers, set by utility commissions across most jurisdictions in the developed world, have not changed, utility companies face reduced revenues and therefore tighter operating budgets.

This means that utilities are unable to invest in the upgrade and modernization of their aging infrastructure, which has well passed its useful life span. An aging infrastructure reduces system reliability and efficiency, which in turn translates into higher technical losses and even lesser revenues for the utilities. And while the supply is under pressure, the demand for electricity increases unabated due to mass electrification of life and economy. It is in this context that the reliability of the largest-ever human-made machine, and the marvel of engineering progress in the last century, i.e., the electrical grid, diminishes to a degree that errors and anomalies in one part of the system cause mass domino failures in the entire network. Blackouts experienced in eastern United States and Canada in 2003, and parts of Europe in the same year, affecting millions of people and costing billions of dollars, are but examples of how critical it is to address the reliability issues of the system sooner rather than later.

Considering the operational and economic challenges that the utilities are facing, the industry has begun looking beyond current technologies toward a future in which such issues would be resolved. That future is called intelligent grid or smart grid. In the smart grid of the future, generation will not follow consumption (as is the case today). In other words, when demand rises, the preferred solution would not be more generation. Rather, the utility will look at gaining more efficiency with their existing assets (i.e., minimizing losses), managing end-user demand (i.e., load control), and partnering with consumers to roll back the load (i.e., conservation). All of these approaches will ensure that consumption follows generation. That is a fundamental change of paradigm. The smart grid of the future will be able to optimize the use of its assets, reduce losses, curtail unnecessary load, and ensure sustainable rationality between what could be economically generated and the load that has to be serviced. And all of that has to be done with proactive commitment to environmental stewardship. The latter requires the industry to invest in renewable sources of energy and facilitate green cogeneration.

The problem, however, is that transition will not be smooth by any stretch of the imagination. In the absence of mature technologies, interoperable standards, and exhaustively qualified solutions, cash-strapped utility companies cannot afford taking the risks involved in upgrading their electricity grid overnight. These companies provide a critical service to society, which cannot be put into jeopardy by rushing through the transition from the legacy grid to a smart grid. Instead, the industry in the developed world is taking steps to modernize the grid through strategic and gradual implantation of fully validated smart grid functions and features into the legacy system.

It goes without saying that these solutions have to be part and parcel of a well-thought-out strategic smart grid road map, which identifies what functions are needed when and how these should be integrated with the larger system at hand. In other words, given the financial resources available to utility companies, the industry in the developed world has already begun adopting technologies for generation diversification, optimal deployment of expensive assets, demand response, energy conservation, reduction of the industry's overall carbon footprint, etc. It is apparent that in this particular case, utilities in the less developed world have a clear advantage compared with their counterparts in the developed world. They do not have a legacy system to worry about. In other words, they could start their smart grid implementation as greenfield projects. Removing the requirement for backward compatibility with the existing grid provides such utilities with a straightforward and a less costly path to a smart grid.

1.1 Introduction to Smart Grid

The existing electricity grid is unidirectional in nature. It is practically built as the required plumbing to transport and distribute power from where it is generated (mainly far from load centers) to where it is needed by consumers (load centers). In other words, the existing grid is essentially a large pipe that connects electricity generators with electrical loads.

This large pipe assumes different forms and uses a variety of complex technologies to ensure highest efficiency in the process of converting the power contained in the primary sources of energy into electricity and subsequently minimal losses in the process of transporting and distributing that energy to the consumers. Nevertheless, the existing electricity system at best converts only one-third of primary fuel energy into electricity without recovering the waste heat, which is mainly a by-product of the combustion process. Almost 8% of its output is lost along its transmission lines, while 20% of its generation capacity exists merely to meet peak demand only (i.e., 5% of the time). In addition to that, due to the hierarchical topology of its assets, the existing electricity grid suffers from domino effect failures.

The next-generation electricity grid, known as smart grid (or intelligent grid), is expected to address the major shortcoming of the existing grid. In essence, a smart grid needs to provide the utility companies with full visibility and pervasive control over their assets and services. A smart grid is required to be self-healing and resilient to system anomalies. And last but not least, a smart grid needs to empower its stakeholders to define and realize new ways of engagement with each other and be proactive in various forms of energy transactions across the system.

To allow pervasive control and monitoring, the smart grid is emerging as a convergence of information technology (IT) and communication technology with power system engineering.

Figure 1.1 depicts the salient features of a smart grid in comparison with those of the existing grid [1]. This side-by-side comparison of the existing grid with a smart grid reveals that these entities use different hierarchies, technologies, and command/control strategies, which are in particular the following:

- The existing grid traditionally uses electromechanical switchgear, while a smart grid will see the replacement of such components with equivalent digital components.
- For the most part, the existing grid relies on limited communication with its field components, capturing few sensory data, status, and alarms from the field and applying limited remote control over some of its gear. A smart grid, on the

Existing grid	Intelligent grid
Electromechanical	Digital
One-way communication	Two-way communication
Centralized generation	Distribution generation
Hierarchical	Network
Few sensors	Sensors throughout
Blind	Self-monitoring
Manual restoration	Self-healing
Failures and blackouts	Adaptive and islanding
Manual check/test	Remote check/test
Limited control	Pervasive control
Few customer choices	Many customer choices

Figure 1.1 Comparison of a legacy grid and a smart grid. (From Farhangi, H., *IEEE Power & Energy Magazine*, 8, 18–28, 2010. © 2010 IEEE. With permission.)