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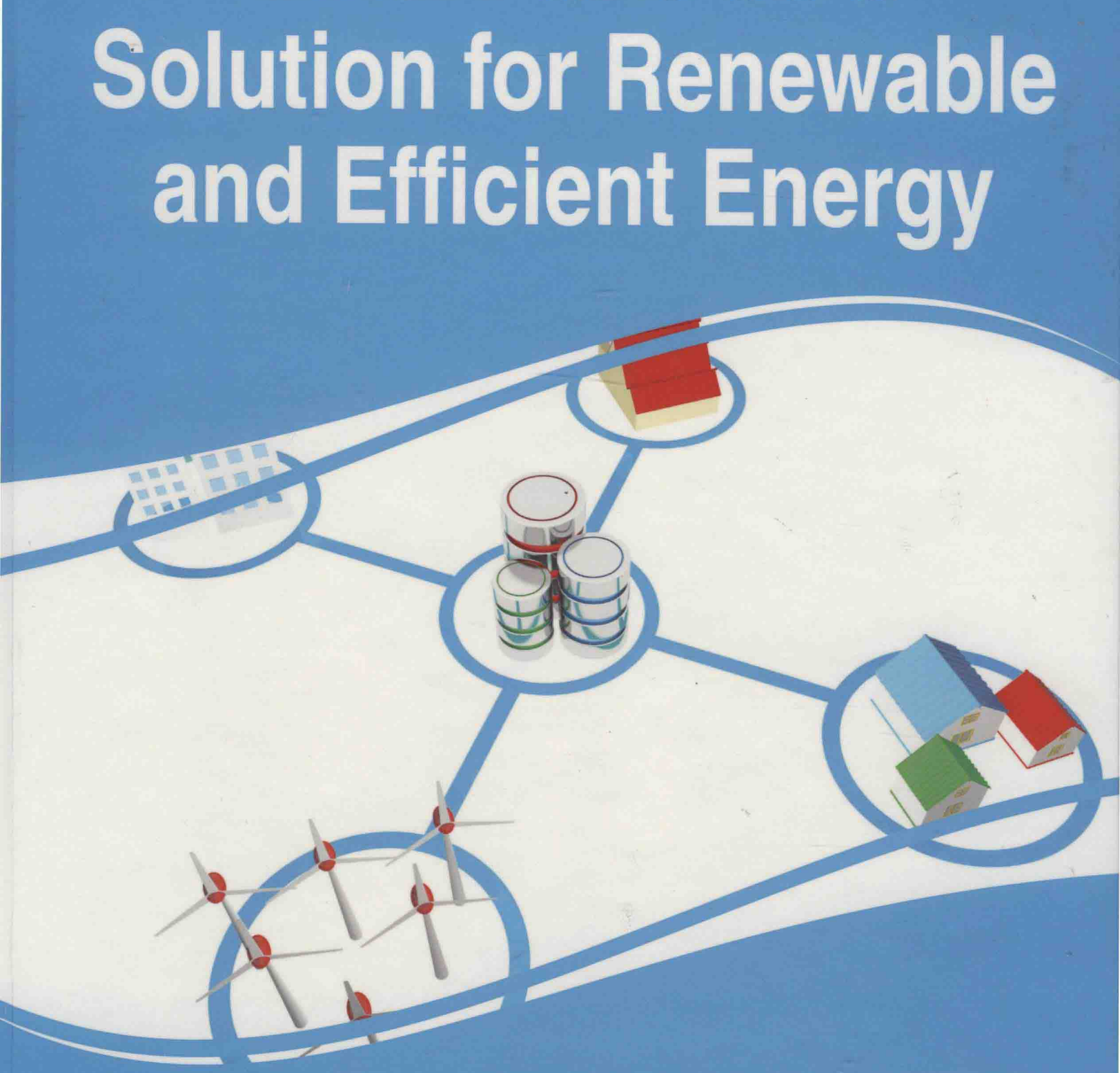
# Smart Grid as a Solution for Renewable and Efficient Energy



Ayaz Ahmad and Naveed Ul Hassan

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# Smart Grid as a Solution for Renewable and Efficient Energy

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A volume in the Advances in Environmental Engineering and Green Technologies (AEEGT) Book Series

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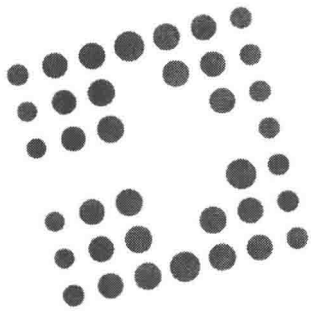

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# Preface

Electricity grid is a complex network of power generation units, transmission lines and distribution networks. Globally, for the last several decades, traditional electrical power systems have reliably provided electricity to several billion electricity consumers. The ever increasing electricity demand fueled by the economic growth and coupled with the need to replace ageing assets is driving the modernization and up-gradation of electrical grid in many parts of the world. By leveraging cost effective information and communication technologies (ICT) and sophisticated power electronic components, the traditional electricity grid can evolve into a smart grid. With the inclusion of sensing and monitoring devices and infrastructure for bi-directional communication and power flow, smart grid evolution provides the means to get rid of some well known weaknesses of a traditional electricity grid, such as, capacity constraints on power generation, inefficiencies of transmission and distribution networks, reliance on fossil fuels, power theft, etc.

In a smart grid, information and power can be efficiently processed that allows large scale integration of renewable and distributed energy sources. On the consumer side, optimization techniques and appropriate algorithms can be designed for demand side management. The role and relationship between the consumers and the grid operator is also evolving as the awareness and uptake of smart grid technologies is gathering pace and momentum. It is however important to understand that owing to the complexity of the power grids, uncertain nature of renewable power plants, strict voltage and frequency control, consumers' age old habits, and tight regulations on electricity markets, the actual implementation of several smart grid concepts is a challenging task. These challenges are driving the research community and power industry to develop new techniques, concepts, algorithms and procedures to realize the smart grid vision.

The objective of this book is to provide a comprehensive and broader coverage of some of the latest research results, trends and developments in smart grids, particularly in the areas of energy management, control and communication techniques. The book also highlights the challenges and open research directions associated to these research areas and can serve as a basis to develop advanced and efficient techniques for smart grids. We have divided the content of the book in two sections:

**Section 1:** Energy Management, Scheduling and Storage
**Section 2:** Measurement, Control, Signal Processing and Communication Techniques

## SECTION 1: ENERGY MANAGEMENT, SCHEDULING, AND STORAGE

In smart grids, the inclusion of ICT infrastructure on the consumer side and in the distribution network allows greater opportunities for energy management and scheduling. The general shape of electricity demand curve is determined by the time of day, while the magnitude of power consumption is largely determined by the time of year and seasonal variations. In traditional grid, to meet a time varying demand curve, a tiered structure of power generation is typically followed in which base-load power plants produce the constant portion of electricity demand, intermediate power plants supply extra energy above the base-load levels, while peaking power plants deliver power only to serve the peak demand. Base-load plants constantly generate electricity; intermediate plants usually run at low capacity and respond to electricity demand variations by rapidly ramping up production whenever required, while the peaking power plants deliver power only for short periods of very high demand. In this tiered structure, cost of electricity obtained from peaking power plants is the highest, followed by electricity cost of intermediate and base-load plants. In smart grids, Advance Metering Infrastructure (AMI), with two-way communication capabilities provides greater opportunities for demand side management and energy saving. Thus, instead of manipulating electricity supply, consumer demand can be managed and power consumption pattern can be controlled to reduce peak load on the grid by using appropriate tools, such as, dynamic pricing and appropriate incentives. Incidents of electricity theft can also be reduced as real time information on electricity consumption in the distribution network becomes available to the grid operator. Consumers can also utilize accurate and frequent information on their energy consumption towards reducing their electricity bills by smart scheduling of their appliances. In smart grids, customer satisfaction also becomes an important consideration, as the deviation from a pre-defined power consumption pattern, either for demand side management or for energy saving, causes inconvenience, particularly to residential customers.

In recent years, there is an increased focus on renewable distributed energy sources e.g., solar panels and wind turbines in order to decrease the consumption of fossil fuels and reduce carbon emissions. A microgrid is an important approach to meet the challenges of integrating distributed renewable energy sources in electrical power systems. Similarly, individual consumers with renewable generation can also become energy producers and often the term 'prosumer' is used to describe this new category of electricity users. The additional energy from renewable sources can be traded with other consumers, microgrids, or gird operator for which new rules for energy trading, pricing, and energy aggregation have to be developed. The energy supplied by the renewable sources is intermittent, e.g., the energy produced by a solar panel fluctuates depending on weather conditions during day time and it is completely unavailable during the night. Similarly, wind speed also varies, which causes some serious problems for the stability of the power systems. Energy storage systems such as batteries can be used to smooth the power produced by renewable energy sources. However, energy storage systems increase the overall cost of the integration of renewable energy systems in smart grids. Intelligent algorithms are therefore required for better management of batteries. Energy storage systems can also be utilized to improve the power quality, power balancing and demand side management.

This section has eight chapters. The first four chapters deal with the research problems related to demand side management, energy efficiency and customer satisfaction, while the remaining chapters in this section discuss microgrids, hybrid energy markets and energy storage systems for better integration of renewable energy sources.

## SECTION 2: MEASUREMENT, CONTROL, SIGNAL PROCESSING, AND COMMUNICATION TECHNIQUES

In traditional grid, power flow, voltage and frequency of the transmission system is regularly monitored and controlled through manned as well as automated controllers. On the other hand, distribution network has limited measurement, control and communication capabilities. This has changed with smart grid evolution and now at the distribution network level, greater automation and control is also becoming available for better integration of renewable distributed energy sources. Faults can occur in any transmission or distribution networks, which can lead to power outages and economic and commercial losses. With an increasing penetration of intermittent renewable generators, interdependencies are also increasing. In such large and complex networks, reliable supply of electrical power becomes challenging and requires sophisticated tools and algorithms to measure cascading failures and reliability critical items. Integration of renewable energy sources in smart grids also requires power electronic components for bi-directional power transactions. For example, solar panels produce DC and their integration on AC grid is not possible without efficient DC-AC converters. Great advances are being made to improve the design and efficiency of various power electronic components such as inverters, converters and active filters as controllable power electronic interfaces are essential for the integration of renewable energy sources in smart grids.

Reliable delivery of power to customers was the main consideration in traditional power grids. In a smart grid, various parameters are measured and lot of data is regularly generated and data delivery is as important as power delivery. Signals, e.g., voltage, current and frequency, acquired by the measurement and monitoring devices have to be efficiently conditioned and processed according to the application requirements. Information security also becomes a challenge in smart grids as the measured data can reveal the load consumption pattern of customers, thereby, raising several privacy concerns. Unauthorized access to data can be dangerous for system operation and the overall security of the power plants. The application of existing encryption and decryption algorithms as well as the development of new algorithms are thus required to ensure information security and integrity in smart grids. In power grids, Geographical Information Systems (GISs) are used to manage and track transmission and distribution network resources, assets and facilities on maps. In smart grids, data collected by various measurement devices can also be displayed on geographical maps for better visualization and planning. Smart grid operators can use GIS for spatial analysis of growth opportunities, situational awareness, customer management, and streamlining metering and billing.

This section consists of seven chapters that detail some of the latest advances in the measurement, control, signal processing and communication techniques in smart grids.

A brief summary of each chapter in this book is given as follows.

- **Chapter 1**: In the first chapter, the background material on Smart Grids (SG) is presented to set the stage for advanced topics in the subsequent chapters. In particular, SG technology is reviewed along with the equipment required to replace the traditional grid. One of the key elements in SGs is the demand side management (DSM) which refers to the management of energy consumption and peak electricity demand. It is carried out by designing appropriate control algorithms which reduce demand and change consumer behavior, benefiting both the utility company and the consumer. From the consumer perspective, the reduced energy consumption decreases the electricity bills and consequently, the individual's expenditures. On the other hand, from the supplier per-

spective, DSM not only minimizes the peak demand but it also cuts down transmission and distribution losses, thereby improving the system efficiency and stability. DSM obtains its objectives in two ways: either by directly reducing the energy consumption by using energy efficient appliances or shifting the high load appliance to the off-peak hours which reduce the Peak-to-Average Load Ratio (PAR). PAR can be reduced by using a Home Energy Controller (HEC) that allows home energy management solutions including demand management, scheduling of the outage, real time pricing algorithms and reduction in peak-to-average power ratio.

- **Chapter 2**: This chapter discusses the energy cost saving strategies in distributed power networks. The need of technology improvement, new models and algorithms for a better integration of renewable energy source in the traditional centralized power network is also emphasized. There are two ways to achieve this integration: the first approach considers a centralized power network and introduces demand response strategies for reducing peak energy demand in the grid. However, the system does not exploit more renewable energy sources and there is a need to reduce greenhouse gas emissions. The second approach is to shift from centralized power to distributed power network. To do this, distributed generation is integrated more efficiently in the power grid to optimize the power grid operation through demand response. For this technique, a prosumer interaction model in a distributed power network is proposed in this chapter. A prosumer (producer-consumer) is a user that not only consumes electricity, but can also produce and store electricity. The prosumer combines both distributed learning and optimization to predict supply/demand in a more efficient way. Therein, prosumers interact in a distributed environment during the purchase or sale of electric power using a double auction with negotiation mechanism. Using two-step combined learning and optimization scheme, each prosumer can learn its optimal bidding strategy and forecast its energy production, consumption and storage.
- **Chapter 3**: This chapter provides an understanding of the use of new and continuously improving algorithms for the optimization and the scheduling of appropriate bodies and devices in a smart grid environment. It also discusses Demand Side Management (DSM) applications to meet the future requirements of energy market and usage. Now these applications can be implemented by using various mathematical methods and algorithms. The overall solution progress includes both deterministic and probabilistic approaches. Due to the success and wide adaptability and the increase in the computational power of computers, two methods of these optimization and planning algorithms are becoming more popular. These methods include the use of artificial intelligence and metaheuristics. For this reason, this chapter presents a review and an analysis of these two techniques and identifies their possible application areas. Main advantages of these methodologies are that, they are mostly dynamic, self-learning and self-improving algorithms so they can provide sustainable solutions for the future based on the current and historical data. In the light of material presented, the chapter concludes with the result that the artificial intelligence is more suitable for modeling and forecasting, whereas metaheuristic methods are better for searching optimum solutions and schedules. Lastly, several future research opportunities are highlighted.
- **Chapter 4**: This chapter presents a flexible framework that allows the Digital Energy Management System (DEMS) operator to minimize the electricity cost according to the required consumer satisfaction level. Furthermore, the concept of low cost power operation is introduced through Hybrid AC/DC Micro-Grid (HMG) to lessen the electricity cost. The customer demands are categorized based on the type of loads, i.e., AC or DC loads and two cost-regimes for both load types are proposed to differentiate the electricity cost of AC and DC buses. An optimal Load Scheduling

and Hybrid Switching (LSHS) algorithm based on Lyapunov optimization framework is also proposed in this chapter, which handles the abrupt switching among AC-DC buses during loads scheduling. The proposed system does not depend on the future performance. Instead, it just requires the information of the electricity price and the conversion cost as its input. It then processes the supply and demand of energy. By placing the user demand in a queue, a buffer for DEMS to entertain user demands can be created when the electricity cost is low. The chapter concludes by presenting simulation results which show that this algorithm can perform well under different system constraints to diminish electricity cost and provide quality of service under specific delay constraints to the consumers.

- **Chapter 5**: This chapter extensively reviews the state of the art in Microgrid (MG) technologies. MGs have a pivotal role in expanding energy access, managing growth in industrializing countries and transforming growth in post-industrial economies. Furthermore, the objectives of Smart Grid that is, a reliable, secure, self-healing power grid, with high Renewable Energy Sources (RES) and Photovoltaic Cells (PV) penetration, controllable loads, and improved generation efficiency can be achieved through an implementation of networks of MGs. A detailed study on the types, benefits and limitations of MG schemes has also been presented. An application of MG technology requires reconsideration of the component and system modeling, along with its operation control and dispatching decision of energy management system due to the varying characteristics of distributed generation systems including, PV and Wind. To integrate PV systems into SG, it is imperative to assess the benefit of investing in emerging PV micro-generation with respect to efficiency and storage requirements. The chapter concludes with a discussion on the issues and challenges of MGs and an outline of several research directions.
- **Chapter 6**: In this chapter, a study on the optimal energy scheduling and trading problem in the hybrid trading market is presented. The hybrid trading market includes an external retail market and the local trading market, the latter of which offers benefits to both the Energy Buyer (EB) and the Energy Seller (ES). Thus, EBs and ESs have the flexibility in trading with the utility companies and the local trading markets. This chapter provides not only a concrete modeling of the energy consumers' and sellers' trading behaviors but also the local trading controller's coordination via pricing. In this context, two different types of local trading controller are considered which include the nonprofit-oriented one that does not expect to gain any reward for coordinating the energy trading between the consumers and sellers; and the profit-oriented one that expects to gain reward from managing the local trading. Concrete optimization problem formulations are also provided for each type of the local trading controller which is then supported by numerical results to validate the advantage of the hybrid trading model. In the end, an extended paradigm that multiple local trading controllers coexist together is presented and the consequent scenario in which the energy consumers and sellers have the freedom to trade with different local trading controllers is modeled.
- **Chapter 7**: In this chapter, the motivation for introducing a predictive energy management based on forecasting strategy is built as the system operation and scheduling depends on forecast of Photovoltaic (PV) energy production and demand. Then formulation for the optimization problem for the grid connected PV battery system is presented. Predictive control strategy is required to shave peak PV and peak load as well as to schedule the battery operation. The approach to solving this optimization problem can be modified for different grid constraints or new objective functions so as to achieve best cost of operation. Generally, the optimization problems for such grid con-



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nected systems are convex but in this case, it is an open loop system. However, for real time operation of such systems, a closed loop control strategy is required, considering the deviation in the prediction and measurement. In order to realize the predictive based energy management, the idea is to implement Model Predictive Control (MPC). The chapter concludes with the future research proposal which states that apart from PV battery system, the control strategy should be designed so as to provide a platform for an integration of other renewable energy sources such as wind.

- **Chapter 8**: This chapter presents a study on the roles and the revolution of the energy storage systems which are essential tools for the development of smart grids. These storage systems have a significant role in energy management of systems having a deployment of renewable energy sources including Photovoltaic cells (PV) and the wind turbine systems. Grid connected energy storage systems have several advantages. They are capable of increasing the grid's reliability and flexibility during power generation and demand fluctuations. By charging during off peak and discharging during peak hours, these systems increase the net revenue of the investors. However, sophisticated control is necessary to optimize the key performance of the energy storage system in the power grid. This chapter also presents a comparison of various energy storage technologies that are available in the market for low-voltage distribution networks. Moreover, an investigation on the future challenges associated with the integration of renewable energy sources on the Malaysian electric networks is also presented. It is emphasized that due to an increase in fossil fuel consumption and global warming, sustainable technologies have emerged. To encourage the utilization of renewable energy sources, various measures are identified in order to create awareness to reduce greenhouse gases.
- **Chapter 9**: This chapter is intended to evaluate and analyze the currently available four topological metrics in order to identify the most suitable and effective approach for the prediction and approximation of the behavior of the cascading failures in smart grid. In fact, the smart grid is the integration of multiple interconnected and interdependent networks that include the power generation network and the communication network where the power generation network is comprised of the conventional generation and distribution, and renewable and distributed energy generation networks. The interconnectivity and interdependency of the networks is the need of smart grid, however, it brings the risks of large scale failure of the whole network, i.e., the risk of cascading failures. That is, the failure of a network or a component of a network can lead to catastrophic malfunctioning of another network which eventually disturbs the smooth functioning of the whole power system. In this chapter, the behavior of the cascading failures in interdependent networks is approximated and described by using two interlinks strategies: the degree-degree correlation interlinks, and the random interlinks. The four topological metrics studied in this chapter include average distance, average betweenness, effective graph resistance, and algebraic connectivity. The chapter provides the analytical study of each of these metrics and compares them with the help of numerical simulations based on sandpile dynamics load distribution.
- **Chapter 10**: Foreseeing the potential benefits of smart grid for future electric railway systems, this chapter focuses on the Railway Electric Smart Grid (RSG) that is envisioned to be the next generation railway power system which will consist of multiple interdependent and integrated networks. More specifically, this chapter is dedicated to the study and identification of the reliability critical item in large and complex rail electrification networks. This chapter discusses the various important aspects of the analysis and modelling of the reliability of the rail electrification systems and provides guidelines on how the reliability assessments of these systems can be improved. To

this end, the chapter presents one example application from the field of rail electrification and applies the Hierarchical Bayesian Networks (HBN) for modelling the reliability of the system. The Bayesian Networks is shown to be helpful in better visualization of the reliability model which can facilitate the decision making process. It is shown that the reliability model developed in this chapter can tackle the dependencies, uncertainties and complexities inherent to the modern railway systems. The chapter also emphasize on the fact that the potential adaptation of the proposed model for reliability quantification of other similar applications needs further studies.

- **Chapter 11:** This chapter presents a comprehensive comparative analysis of two strategies named delta modulator and delta sigma modulator for current controlled DC-AC convertors applications. The comparative study is first performed with the help of MATLAB/SIMULINK environment in terms of various important performance metrics that include the Root Mean Square (RMS) current error, the average switching frequency, the switching frequency power spectral density, and the total harmonic distortion of load current waveforms. The simulation results were then verified on experimental platform by using a TMS320F2812 digital signal processor. The comparative study reveals that Delta Sigma modulator is better than Delta modulator in terms of harmonic content, RMS current error, total harmonic distortion, and average switching frequency. Moreover, it is revealed in this chapter that the Delta Sigma modulator performs well in high frequency modulated invertor and convertors where Delta modulator shows instability. As the renewable energy resources generating energy in DC form are envisioned to be the integral part of the future smart grid, the design and implementation of DC-AC convertors with improved performance is very crucial. This chapter provides insightful information for researchers and practitioners regarding the performance of the DC-AC convertors' control techniques, and the issues, and challenges associated with them and outlines the future research directions.
- **Chapter 12**: This chapter is focused mainly on the importance and potential applications of signal processing techniques in smart grid. In the future smart grid, with the availability of huge amount of measurements (retrieved from different location of the multiple interdependent and interconnected networks in the grid) needed for the development, understanding and diagnosis of various key solutions, signal processing techniques can play a vital role. Different signal processing techniques can be used for different applications. For example, the pattern recognition techniques can potentially be used for consumer profile protection and identification, power quality analysis, fault diagnosis, and spectral estimation or analysis, etc. This chapter, therefore, studies the recent advancements in applications of signal processing techniques in smart grid. It also discusses the limitations and challenges associated to the applications of the existing signal processing techniques in the context of smart grid. The chapter also highlights some future research directions and open problems in this area which need researchers' attention. In summary, this chapter is concluded to provide a base for understating and research in the field of applications of signal processing techniques in smart grid.
- **Chapter 13**: In this chapter, the focus is on routing in smart grid communication networks. The existing routing protocols for smart grid communication are based on the flooding mechanism. However, flooding based routing is very costly in terms of bandwidth usage as well as the energy consumption. In flooding based techniques, the message passes from approximately all nodes in the network to reach to its destination which in addition to bandwidth and energy wastage also results in time delay. Moreover, the duplicate packets generated by the receivers may circulate forever in the network, until and unless certain precautionary measures are taken. Furthermore,

smart grid communication network is a combination of fixed nodes (i.e., control center, smart meter, home appliances, etc.) where due to the switch on/off and fluctuation in the power flow, the nature of communication among the nodes may be dynamic, and the fixed nodes may also disappear from the network topology. Due to these reasons, flooding may not be appropriate for routing in smart grid networks. This chapter first studies the feasibility of flooding free routing in the context of smart grid communication networks and then devises a flooding free routing technique for these networks which does not need routing information, rout request, route request reply, and rout reply acknowledgement.

- **Chapter 14**: This chapter addresses the security issues in Wireless Mesh Networks (WMNs) and the vulnerability of the wireless connections to cyber-attacks in the context of smart grid environment. The chapter introduces a fuzzy logic approach for trust based routing algorithm called Fuzzy-Based Energy-Aware Trust Geo Routing (FEATGR) algorithm for smart grid communication networks that can adapt to dynamic network scenario as well as guarantees the network availability in the presence of malicious attacks. The chapter shows via extensive simulations that the FEATGR algorithm has good performance in terms of packet loss compared to the already available Dynamic Trust Elective Geo Routing (DTEGR) algorithm in conditions of light and medium level of malicious attacks and has equally good performance as GTEGR algorithm has in case of high level of malicious attacks. The chapter also studies the energy consumption of FEATGR algorithm which reveals that without sacrificing the other performance metrics, it has the capability of achieving energy load balance and can thereby extend the battery life time of the nodes. Owing to the overall improved packet loss and energy consumption performance of FEATGR algorithm, the chapter finally suggests that compared to GTEGR, FEATGR is a good candidate for practical implementation.
- **Chapter 15**: This chapter is dedicated to the study of basic concepts and potentials of the geographical information system for the understanding, deployment, monitoring and control of smart grid. The chapter provides a comprehensive introduction of the fundamental concepts of geographical information system in the context of smart grid and enlighten the readers with the benefits of geographical information system for the future smart power system. The chapter highlights the research, advancements, capabilities and usefulness of geographical information system for the transformation of the conventional power grid to a smart grid. The chapter establishes that geographical information system can be helpful in identifying the appropriate locations for timely and economically viable installation of the smart grid components. The chapter also outlines the issues and challenges in the use of geographical information system and discusses the various evolving technologies as the possible solutions such as Internet of Things (IoT), big data analytics, and crowdsourcing, etc. The chapter also identifies a number of research trends in the use of geographical information system in the deployment of smart grid.

The chapters in this book are selected after a rigorous peer review process and they provide necessary information to understand several important aspects of smart grids. We believe that the book provides guidelines for new researchers and it will help the graduate and post-graduate students to better understand various important topics and research trends, such as, demand side management, energy efficiency, energy storage, measurement, control, signal processing and communication techniques in smart grids. Finally, we hope that the book will also stimulate further research and discussions on smart grid.

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Section 1

# Energy Management, Scheduling, and Storage

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