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Concepts, Technologies and Evolution

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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.

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, derivers, 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 the by 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.

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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