Smart Grid

Fundamentals of Design and Analysis

JAMES MOMOH

WILEY

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IEEE PRESS SERIES ON POWER ENGINEERING
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IEEE Press
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A JOHN WILEY & SONS, INC., PUBLICATION

Library of Congress Cataloging-in-Publication Data:

Momoh, James A., 1950-
Smart grid : fundamentals of design and analysis / James Momoh.
p. cm.
ISBN 978-0-470-88939-8 (hardback)
1. Electric power distribution–Automation. I. Title.
TK3226.M588 2012
333.793'2–dc23
2011024774

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

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PREFACE

The term “smart grid” defines a self-healing network equipped with dynamic optimization techniques that use real-time measurements to minimize network losses, maintain voltage levels, increase reliability, and improve asset management. The operational data collected by the smart grid and its sub-systems will allow system operators to rapidly identify the best strategy to secure against attacks, vulnerability, and so on, caused by various contingencies. However, the smart grid first depends upon identifying and researching key performance measures, designing and testing appropriate tools, and developing the proper education curriculum to equip current and future personnel with the knowledge and skills for deployment of this highly advanced system.

The objective of this book is to equip readers with a working knowledge of fundamentals, design tools, and current research, and the critical issues in the development and deployment of the smart grid. The material presented in its eleven chapters is an outgrowth of numerous lectures, conferences, research efforts, and academic and industry debate on how to modernize the grid both in the United States and worldwide. For example, Chapter 3 discusses the optimization tools suited to managing the randomness, adaptive nature, and predictive concerns of an electric grid. The general purpose Optimal Power Flow, which takes advantage of a learning algorithm and is capable of solving the optimization scheme needed for the generation, transmission, distribution, demand response, reconfiguration, and the automation functions based on real-time measurements, is explained in detail.

I am grateful to several people for their help during the course of writing this book. I acknowledge Keisha D’Arnaud, a dedicated recent graduate student at the Center for Energy Systems and Control, for her perseverance and support in the several iterations needed to design the text for a general audience. I thank David Owens, Senior Executive Vice President of the Edison Electric Institute, and Dr. Paul Werbos, Program Director of the Electrical, Communication and Cyber Systems (ECCS), National Science Foundation (NSF), for encouraging and supporting my interest in unifying my knowledge of systems through computational intelligence to address complex power system problems where traditional techniques have failed. Their support was especially valuable during my stint at NSF as a Program Director in ECCS from 2001 to 2004. I am also grateful for the Small Grant Expository Research award granted by the NSF to develop the first

generation of Dynamic Stochastic Optimal Power flow, a general purpose tool for use in smart grid design and development.

I thank my family for their encouragement and support. I am grateful to my students and colleagues at the Center for Energy Systems and Control, who, as audience and enthusiasts, let me test and refine my ideas in the smart grid, and also for honorary invited presentations to top utility executive management in addressing the emergence of the smart grid across the country. All these exposures rekindled my interest in the design and development of the grid for the future.

James Momoh

1

SMART GRID ARCHITECTURAL DESIGNS

1.1 INTRODUCTION

Today's electric grid was designed to operate as a vertical structure consisting of generation, transmission, and distribution and supported with controls and devices to maintain reliability, stability, and efficiency. However, system operators are now facing new challenges including the penetration of RER in the legacy system, rapid technological change, and different types of market players and end users. The next iteration, the smart grid, will be equipped with communication support schemes and real-time measurement techniques to enhance resiliency and forecasting as well as to protect against internal and external threats. The design framework of the smart grid is based upon unbundling and restructuring the power sector and optimizing its assets. The new grid will be capable of:

- Handling uncertainties in schedules and power transfers across regions
- Accommodating renewables
- Optimizing the transfer capability of the transmission and distribution networks and meeting the demand for increased quality and reliable supply
- Managing and resolving unpredictable events and uncertainties in operations and planning more aggressively.

Smart Grid: Fundamentals of Design and Analysis, First Edition. James Momoh.

TABLE 1.1. Comparison of Today's Grid vs. Smart Grid [4]

Preferred Characteristics	Today's Grid	Smart Grid
Active Consumer Participation	Consumers are uninformed and do not participate	Informed, involved consumers—demand response and distributed energy resources
Accommodation of all generation and storage options	Dominated by central generation—many obstacles exist for distributed energy resources interconnection	Many distributed energy resources with plug-and-play convenience focus on renewables
New products, services, and markets	Limited, poorly integrated wholesale markets; limited opportunities for consumers	Mature, well-integrated wholesale markets; growth of new electricity markets for consumers
Provision of power quality for the digital economy	Focus on outages—slow response to power quality issues	Power quality a priority with a variety of quality/price options—rapid resolution of issues
Optimization of assets and operates efficiently	Little integration of operational data with asset management—business process silos	Greatly expanded data acquisition of grid parameters; focus on prevention, minimizing impact to consumers
Anticipating responses to system disturbances (self-healing)	Responds to prevent further damage; focus on protecting assets following a fault	Automatically detects and responds to problems; focus on prevention, minimizing impact to consumers
Resiliency against cyber attack and natural disasters	Vulnerable to malicious acts of terror and natural disasters; slow response	Resilient to cyber attack and natural disasters; rapid restoration capabilities

1.2 TODAY'S GRID VERSUS THE SMART GRID

As mentioned, several factors contribute to the inability of today's grid to efficiently meet the demand for reliable power supply. Table 1.1 compares the characteristics of today's grid with the preferred characteristics of the smart grid.

1.3 ENERGY INDEPENDENCE AND SECURITY ACT OF 2007: RATIONALE FOR THE SMART GRID

The Energy Independence and Security Act of 2007 (EISA) signed into law by President George W. Bush vividly depicts a smart grid that can predict, adapt, and reconfigure itself efficiently and reliably. The objective of the modernization of the U.S. grid as outlined in the Act is to maintain a reliable and secure electricity [2] infrastructure that

Figure 1.1. Rationale for the smart grid.

will meet future demand growth. Figure 1.1 illustrates the features needed to facilitate the development of an energy-efficient, reliable system.

The Act established a Smart Grid Task Force, whose mission is "to insure awareness, coordination and integration of the diverse activities of the DoE Office and elsewhere in the Federal Government related to smart-grid technologies and practices" [1]. The task force's activities include research and development; development of widely accepted standards and protocols; the relationship of smart grid technologies and practices to electric utility regulation; the relationship of smart grid technologies and practices to infrastructure development, system reliability, and security; and the relationship of smart grid technologies and practices to other facets of electricity supply, demand, transmission, distribution, and policy. In response to the legislation, the U.S. research and education community is actively engaged in:

1. Smart grid research and development program
2. Development of widely accepted smart grid standards and protection
3. Development of infrastructure to enable smart grid deployment
4. Certainty of system reliability and security
5. Policy and motivation to encourage smart grid technology support for generation, transmission and distribution

As Figure 1.2 shows, there are five key aspects of smart grid development and deployment.

1.4 COMPUTATIONAL INTELLIGENCE

Computational intelligence is the term used to describe the advanced analytical tools needed to optimize the bulk power network. The toolbox will include heuristic, evolution programming, decision support tools, and adaptive optimization techniques.

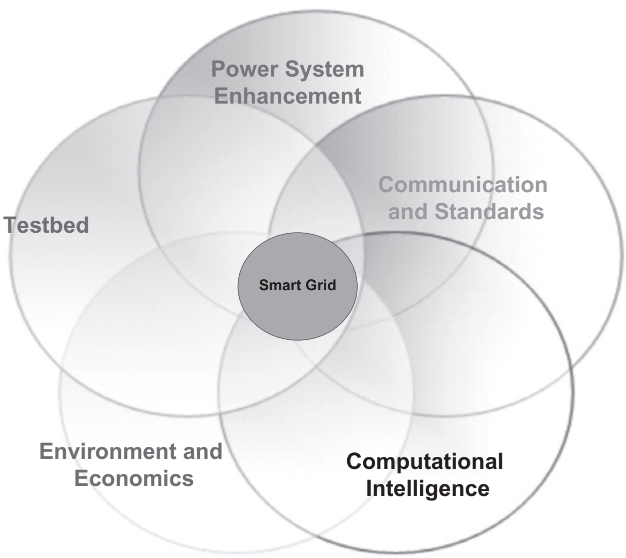

Figure 1.2. Five key aspects of smart grid development.

1.5 POWER SYSTEM ENHANCEMENT

Policy-makers assume that greatly expanded use of renewable energy [4,5] resources in the United States will help to offset the impacts of carbon emissions from thermal and fossil energy, meet demand uncertainty, and to some extent, increase reliability of delivery.

1.6 COMMUNICATION AND STANDARDS

Since planning horizons can be short as an hour ahead, the smart grid's advanced automations will generate vast amounts of operational data in a rapid decision-making environment. New algorithms will help it become adaptive and capable of predicting with foresight. In turn, new rules will be needed for managing, operating, and marketing networks.

1.7 ENVIRONMENT AND ECONOMICS

Based on these desired features, an assessment of the differences in the characteristics of the present power grid and the proposed smart grid is needed to highlight characteristics of the grid and the challenges. When fully developed the smart grid system will allow customer involvement, enhance generation and transmission with tools to allow minimization of system vulnerability, resiliency, reliability, adequacy and power quality. The training tools and capacity development to manage and operate the grids and hence crate new job opportunities is part of the desired goals of the smart grid evolution which will be tested using test-bed. To achieve the rapid deployment of the grids test bed and research centers need to work across disciplines to build the first generation of smart grid.

By focusing on security controls rather than individual vulnerabilities and threats, utility companies and smart-grid technology vendors can remediate the root causes that lead to vulnerabilities. However, security controls are more difficult and sometimes impossible to add to an existing system, and ideally should be integrated from the beginning to minimize implementation issues. The operating effectiveness of the implemented security controls-base will be assessed routinely to protect the smart grid against evolving threats.

1.8 OUTLINE OF THE BOOK

This book is organized into 10 chapters. Following this chapter's introduction, Chapter 2 presents the smart grid concept, fundamentals, working definitions, and system architecture. Chapter 3 describes the tools using load flow concepts, optimal power flows, and contingencies and Chapter 4 describes those using voltage stability, angle stability, and state estimation. Chapter 5 evaluates the computational intelligence approach as a feature of the smart grid. Chapter 6 explains the pathways design of the smart grid using general purpose dynamic stochastic optimization. Chapter 7 reviews renewable supply and the related issues of variability and probability distribution functions, followed by a discussion of storage technologies, capabilities, and configurations. Demand side managemen (DSM) and demand response, climate change, and tax credits are highlighted for the purpose of evaluating the economic and environmental benefit of renewable energy sources. Chapter 8 discusses the importance of developing national standards, followed by a discussion of interoperability such that the new technologies can easily be adapted to the legacy system without violating operational constraints. The chapter also discusses cyber security to protect both RER and communication infrastructure. Chapter 9 explains the significant research and employment training for attaining full performance and economic benefits of the new technology. Chapter 10 discusses case studies on smart grid development and testbeds to aid deployment. The chapter outlines the grand challenges facing researchers and policy-makers before the smart grid can be fully deployed, and calls for investment and multidisciplinary collaboration. Figure 1.3 is a schematic of the chapters.

1.9 GENERAL VIEW OF THE SMART GRID MARKET DRIVERS

To improve efficiency and reliability, several market drivers and new opportunities suggest that the smart grid must:

1. Satisfy the need for increased integration of digital systems for increased efficiency of the power system. In the restructured environment, the deregulated electric utility industry allows a renovation of the market to be based on system constraints and the seasonal and daily fluctuations in demand. Competitive markets increase the shipment of power between regions, which further strains today's aging grid and requires updated, real-time controls.
2. Handle grid congestion, increase customer participation, and reduce uncertainty for investment. This requires the enhancement of the grid's capability to handle demand reliably.
3. Seamlessly integrate renewable energy systems (RES) and distributed generation. The drastic increase in the integration of cost-competitive distributed generation technologies affects the power system.

In addition to system operators and policy-makers, stakeholders are contributing to the development of the smart grid. Their specific contributions and conceptual understanding of the aspects to be undertaken are discussed below.

1.10 STAKEHOLDER ROLES AND FUNCTION

As in the legacy system, critical attention must be paid to the identification of the stakeholders and how they function in the grid's development. Stakeholders range from

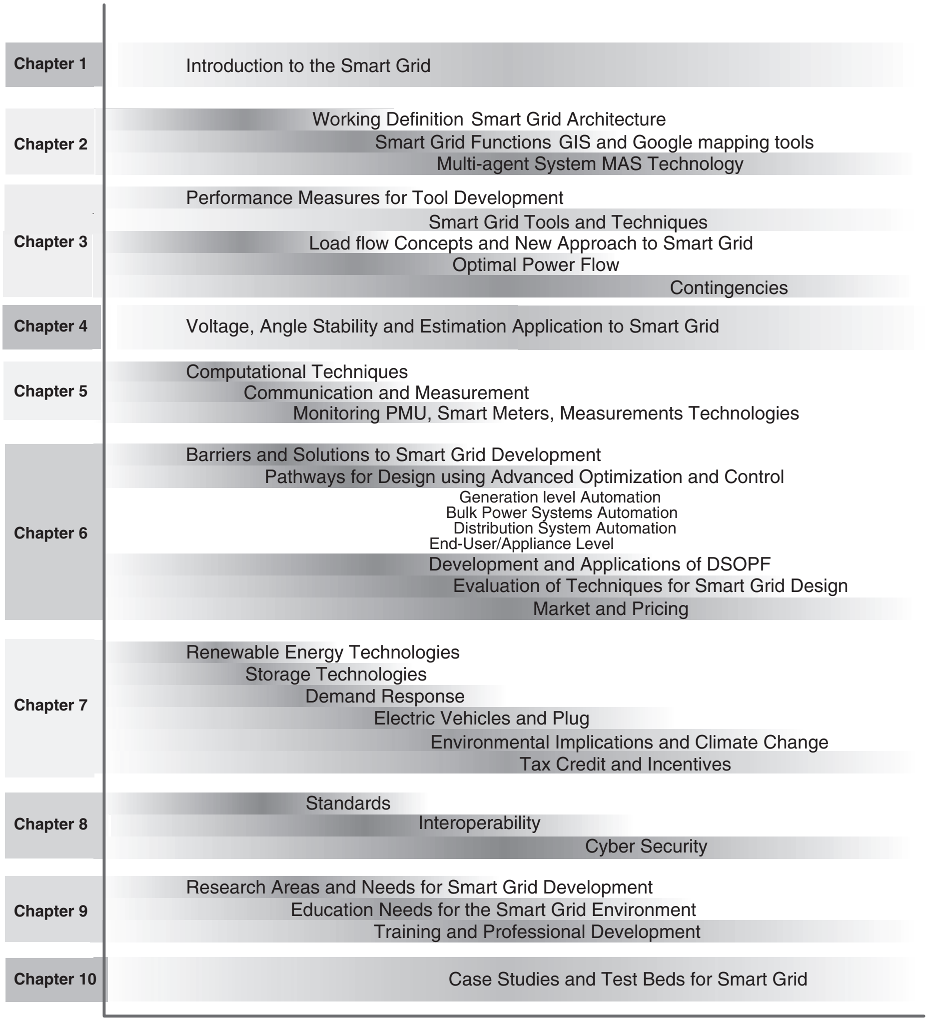

Figure 1.3. Schematic of chapters.

utility and energy producers to consumers, policy-makers, technology providers, and researchers. An important part of the realization of the smart grid is the complete buy-in or involvement of all stakeholders.

Policy-makers are the federal and state regulators responsible for ensuring the cohesiveness of policies for modernization efforts and mediating the needs of all parties. The primary benefit of smart grid development to these stakeholders concerns the mitigation of energy prices, reduced dependence on foreign oil, increased efficiency, and reliability of power supply. Figure 1.4 shows the categories of stakeholders.

Other participants in the development of the smart grid include government agencies, manufacturers, and research institutes. The federal Department of Energy's (DOE)