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Control and Optimization Methods for Electric Smart Grids

Springer

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To Joe,
A true pioneer in rethinking sensing, communications and control of electric power systems

Preface

In the 21st century, electric power engineering is going green and smart. Triggered by several recent catastrophes such as the major blackout in the Northeastern USA in 2003 and Hurricane Katrina in New Orleans in 2005 together with the Energy Act of 2007, the term *smart grid* has become almost ubiquitous across the world not only as a political concept but also as an entirely new technology requiring a tremendous amount of inter-disciplinary research. The initiatives taken by the smart grid research community in the United States have so far been successful in bringing researchers from power system engineering, signal processing, computer science, communications, business, and finance as well as chemical and wind engineering among other disciplines under the same roof in order to cater to the diverse research needs of this technology. As a part of this enterprise power engineers, for example, are investigating efficient and intelligent ways of energy distribution and load management, computer scientists are researching cyber security issues for reliable sharing of information across the grid, the signals community is looking into advancing instrumentation facilities for detailed grid monitoring, wind engineers are studying renewable energy integration, while business administrators are reframing power system market policies to adapt to these new changes in the system.

Concomitant with these advances, researchers have also come to recognize the urgent need for new systems-level knowledge of power and energy systems for sustaining the advancement of this emerging field. This, in turn, has led to a natural demand for the two lifelines of system theory in smart grid research, namely – control and optimization. Almost every facet of making a power system *smart* or self-regulated boils down to using control theory in some form or other. Relevant examples include modeling, identification, estimation, robustness, optimal control, and decision-making over networks. Over the past two years, for instance, several research workshops, conference tutorial sessions, and national meetings have been organized to discuss the strong potential of control and optimization in smart grid applications starting from small residential-level energy management, smart metering, and power markets to much broader-scale problems such as wide-area monitoring and control. The editors of this book have been involved in the organization of many of these workshops. Several of the contributing authors too have given invited presentations in these gatherings, three of the most notable ones being a special session in the IEEE Conference on Decision and Control (Atlanta, GA, 2010), a tutorial session in the American Control Conference (San Francisco, CA, 2011) and a Workshop on Cyber-Physical Applications in Smart Power Systems (North Carolina State University, Raleigh, NC, 2011). The initial idea for publishing this book arose from these meetings with the objective of consolidating some of the most promising and transformative recent research in smart grid control in hopes of laying the foundation for future advances in this critical field of study.

The book contains eighteen chapters written by leading researchers in power, control, and communication systems. The essays are organized into three broad sections, namely Architectures and Integration, Modeling and Analysis, and Communication and Control. As is apparent from their titles, the main perspective of these sections is to capture in a holistic way how tomorrow's grid will need to be an enormously complex system in order to solve the problems that we are facing today. Literally, with every passing day, our national grid is becoming integrated with new generation in the form of renewable energy resources, new loads in the form of smart vehicles, new sensors such as smart meters and Phasor Measurement Units, and newer mechanisms of decision-making guided by complex power market dynamics. Our goal is to capture the spectrum of this exponential transformation, and at the same time present the plethora of open problems that this transformation poses for our control theory colleagues. Many of these problems may sound like routine questions in control and optimization, but they often lead to challenging, interesting, and ultimately highly rewarding directions for theoretical research. To the best of our knowledge, this is the first comprehensive book on this topic.

The Architectures and Integration section opens the book with visionary ideas on sustainable architectures for power system operation and control under significant penetration of highly variable renewable energy resources presented in Chap. 1. This is followed by a discussion on the economics of electricity markets and their impacts on demand response in Chap. 2. Chapter 3 furthers the demand response concept for enabling random energy integration. Chapter 4 illustrates several practical constraints in smart grid sensing and communications that may destabilize real-time power market operations and proposes new communication topologies that can bypass such problems. Chapter 5 presents a fresh control perspective to demand-side energy management in residential and commercial units using convex optimization-based model predictive control. Chapter 6 highlights the architectural challenges needed for integration of plug-in-hybrid vehicles into the grid focusing on problems related to demand response and communications necessary to accomplish the smart features of these smart vehicles.

The Modeling and Analysis section presents the upcoming research directions on mathematical modeling, data analysis, and information processing in power systems. Chapter 7 opens this section with a modeling framework that can be highly useful for analyzing the impacts of wind power penetration on the dynamics of the conventional grid. Chapter 8 delves into novel data analysis techniques for wide-area oscillation tracking in large-scale power systems and highlights the importance of signal processing as a major tool for wide-area monitoring research. Chapter 9 models the dynamic mechanisms of cascading failures in geographically dispersed grids, while Chap. 10 presents a reliability modeling framework for tomorrow's phasor-integrated power system using ideas of real-time fault diagnosis and Markovian models of measurement networks. The discussion switches gears towards the computational aspects of the smart grid in Chap. 11, which presents a modeling and control strategy for data centers that are becoming essential parts of today's grid operations. Chapter 12 closes this section with a discussion on how various geometrical properties of power system topologies can influence disturbance propagation in the system, thereby highlighting the importance of combinatorics in smart grid research.

The Communication and Control section unites some of the most critical control design challenges for tomorrow's grid with a focus on how communications and security will play integral roles in the execution of such controllers. The section opens with Chap. 13, which presents game-theoretic optimization problems for charging coordination of plug-in electric vehicles, and, thereby addresses the intersection of two emerging trends in the modernization of power systems, namely vehicle electrification and flexible loading. Chapter 14 addresses the seminal problem of cyber-security of smart grids and presents a vulnerability assessment framework to quantify risk due to intelligent coordinated attacks on grid assets. Chapter 15 discusses the applications of wide-area phasor measurement technology in distribution-level power systems, initiating a new line of thinking on monitoring and control. Chapter 16 fuses different ideas of cooperative control theory to develop *distributed* algorithms for economic dispatch, thereby enabling the future grid to be independent of centralized decision-making strategies. Chapters 17 and 18 address wide-area control problems for oscillation damping in power transmission systems. The former presents a new adaptive control approach for delay compensation in Synchrophasor-based feedback, while the latter using model reference control and clustering methods for adding damping to inter-area oscillations.

As can be seen, the chapters in each section maintain their own thematic continuity and at the same time have significant overlaps with chapters in other sections as well. Therefore, one may read the book in its entirety or focus on individual chapters. Due to its broad scope, this will be an ideal resource for students in advanced graduate-level courses and special topics in both power and control systems. It will also interest utility engineers who seek an intuitive understanding of the emerging applications of control and optimization methods in smart grids. Until now there has been very little literature concerning the formulation of a comprehensive control problem for the smart grid enterprise, and on relating different models and approaches to its overall solution methodology. The chapters in this book represent work in progress by the community on the way towards such solutions.

We would like to express our gratitude to all the contributing authors for providing their valuable input toward the development of this book. We also thank our colleagues Murat Arcak, John Wen, Tariq Samad, Ning Lu, Steven Elliot, M. A. Pai, Massoud Amin, Manu Parashar, Sumit Roy, and Yufeng Xin for many

interesting discussions that have motivated us to undertake the idea of publishing this book. Sincere thanks also go to Merry Stuber from Springer for proofreading different versions of the manuscript and guiding the editorial work.

Last but not least, this book is dedicated to Joe Chow on the occasion of his 60th birthday. Dr. Chow is one of the most distinguished researchers and educators in the field of power systems and control theory. His research career spans nearly 40 years, and includes pioneering contributions to singular perturbation theory in the late 1970s, multivariable control of power systems in the 1980s, FACTS controller designs in the 1990s, and Wide-area Phasor Measurements over the past two decades. His ground-breaking work has earned him the highest acclaim from both power and control research communities all around the world. We take great pleasure in offering this book as a small token of appreciation in honor of Joe on this very special occasion.

Raleigh, NC, USA — Aranya Chakrabortty
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