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Robust Power System Frequency Control

Second Edition

Springer

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ISSN 2196-3185 ISSN 2196-3193 (electronic)
ISBN 978-3-319-07277-7 ISBN 978-3-319-07278-4 (eBook)
DOI 10.1007/978-3-319-07278-4
Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014939936

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Dedicated to my parents and Halimeh

Foreword

The evolution of the Power Grid over the past two decades, influenced by the deregulation of the power Industry and the emergence of the smart grid has posed several challenges to the Power industry. An important one is maintaining the frequency at the nominal value under widely operating system conditions. The presence of renewable sources such as Wind power, Solar power as well as the Micro grid and Battery storage technologies has made frequency control a challenging task. The Wide Area Measurement System (WAMS) has opened up new possibilities for monitoring and control.

In this context, this new edition of Prof. Bevrani's earlier Springer 2009 book is a welcome addition in addressing these important issues. Professor Bevrani's extensive familiarity with this problem has made the book a rich source of information both to the industry and the academia. It emphasizes real-time simulations, design, and optimization under varying operating conditions. It brings out clearly the inadequacy of damping due to renewable sources and proposes new solutions.

Professor Bevrani has interacted with researchers from all over the world and hence the book will have a wide appeal.

April 2014 M. A. Pai

Preface

Frequency control is an important control problem in electric power system design and operation, and is becoming more significant today due to the increasing size, changing structure, emerging new distributed renewable power sources and uncertainties, environmental constraints, and the complexity of power systems.

In the last two decades, many studies have focused on damping control and voltage stability and related issues, but there has been much less work on the power system frequency control analysis and synthesis. While some aspects of frequency control have been illustrated along with individual chapters, many conferences, and technical papers, a comprehensive and sensible practical explanation of robust frequency control in a book form encouraged author to provide the first edition of *Robust Power System Frequency Control* in 2009. Following numerous kind notes and valuable feedback from readers worldwide and the publisher; as well as considering recent relevant challenges and developments, the author is pleased to present the second revised edition.

This updated edition of the industry standard reference on power system frequency control offers new solutions to the technical challenges introduced by the escalating role of distributed generation and renewable energy sources (RESs) in modern electric grids. The role of frequency control loops (primary, secondary, tertiary and emergency) in modern power systems is explained. The impacts of low inertia and damping effect on system frequency in the presence of increased distributed and renewable power penetration are given particular consideration, as the bulk synchronous machines-based conventional frequency control are rendered ineffective in emerging grid environments where distributed/variable units with little or no rotating mass become dominant. Frequency stability and control issues relevant to the exciting new field of microgrids are also undertaken in this new edition.

Robust Power System Frequency Control means the control must provide adequate minimization on a system's frequency and tie-line power deviation, and expend the security margin to cover all operating conditions and possible system configurations. The main goal of robust frequency control designs in the present monograph is to develop new frequency control synthesis methodologies for multi-area power systems based on the fundamental frequency regulation concepts, together with powerful robust control theory and tools. The proposed control techniques meet all or a combination of the following specifications:

- *Robustness*: guarantee robust stability and robust performance for a wide range of operating conditions. For this purpose, robust control techniques are to be used in synthesis and analysis procedures.
- *Decentralized property*: in a new power system environment, centralized design is difficult to numerically/practically implement for a large-scale multi-area frequency control synthesis. Because of the practical advantages it provides, the decentralized frequency control design is emphasized in the proposed design procedures for real-world power system applications.
- *Simplicity of structure*: in order to meet the practical merits, in many proposed control schemes the robust decentralized frequency control design problem is reduced to a synthesis of low-order or a proportional integral control problem, which is usually used in a real frequency control system.
- *Formulation of uncertainties and constraints*: the frequency control synthesis procedure must be flexible enough to include generation rate constraints, time delays, and uncertainties, in the power system model and control synthesis procedure. The proposed approaches advocate the use of a physical understanding of the system for robust frequency control synthesis.

This book provides a thorough understanding of the basic principles of power system frequency behavior in a wide range of operating conditions. It uses simple frequency response models, control structures, and mathematical algorithms to adapt modern robust control theorems with frequency control issue and conceptual explanations. Most developed control strategies are examined by real-time simulations. Practical methods for computer analysis and design are emphasized.

This book emphasizes the physical and engineering aspects of the power system frequency control design problem, providing a conceptual understanding of frequency regulation and application of robust control techniques. The main aim is to develop an appropriate intuition relative to the robust load frequency regulation problem in real-world power systems, rather than to describe sophisticated mathematical analytical methods.

This book could be useful for engineers and operators in power system planning and operation, as well as academic researchers. It could be useful as a supplementary text for university students in electrical engineering at both undergraduate and postgraduate levels in standard courses of power system dynamics, power system analysis, and power system stability and control.

The presented techniques and algorithms in this monograph address systematic, fast, and flexible design methodologies for robust power system frequency regulation. The developed control strategies attempt to invoke the well-known strict conditions and bridge the gap between the power of robust/optimal control theory, and practical power system frequency control synthesis.

Outlines

This revised edition is divided into 12 chapters and four appendices. Chapter 1 provides an introduction to the general aspects of power system controls. Fundamental concepts and definitions of stability and existing controls are emphasized. The timescales and characteristics of various power system controls are described and the importance of frequency stability and control is explained.

Chapter 2 introduces the subject of real power and frequency control, providing definitions and basic concepts. Overall view of frequency control loops including primary, secondary, tertiary, and emergency controls is given. Then the primary and secondary control loops are discussed in detail. The secondary control mechanism which is known as load-frequency control (LFC) is first described for a single control area and then extended to a multi-area control system. Tie-line bias control and its application to a multi-area frequency control system are presented. Past achievements in the frequency control literature are briefly reviewed.

Chapter 3 describes frequency control characteristics and dynamic performance of a power system with primary and secondary control loops. An overview of frequency response model for primary, secondary, tertiary, and emergency controls is presented. Static and dynamic performances are explained, and the effects of physical constraints (generation rate, dead band, time delays, and uncertainties) on power system frequency control performance are emphasized.

Chapter 4 provides a new decentralized method to design robust proportional-integral (PI)-based LFC using a developed iterative linear matrix inequalities (ILMI) algorithm. For this purpose the H_∞ static output feedback control (SOF) is applied. Then the chapter is focused on robust PI-based LFC problem with communication delays in a multi-area power system. The proposed methods are applied to multi-area power system examples with different LFC schemes, and the closed-loop system is tested under serious load change scenarios.

Chapter 5 formulates the PI-based frequency control problem with communication delays as a robust SOF optimization control problem. The H_2/H_∞ control is used via an ILMI algorithm to approach a suboptimal solution for the assumed design objectives. The proposed method was applied to a control area power system through a laboratory real-time experiment. Finally, the genetic algorithm (GA), as a well-known optimization technique, is successfully used for tuning of PI-based frequency control loop by tracking the robust performance indices obtained by mixed H_2/H_∞ control design.

Chapter 6 presents the application of structured singular value theory (μ) for robust decentralized load frequency control design. System uncertainties and practical constraints are properly considered during a synthesis procedure. The robust performance is formulated in terms of the structured singular value for the measuring of control performance within a systematic approach. In this chapter, a decentralized robust model predictive control (MPC)-based frequency control design is introduced. The MPC controller uses a feedforward control strategy to reject the impact of load change. The proposed controller is applied to a three control area power system and the obtained results are compared with the application of ILMI-based robust PI controller.

Chapter 7 addresses the frequency control issue in the restructured power systems. A brief description of frequency regulation markets is given. The impacts of power system restructuring on frequency regulation are simulated, and a dynamical model to adapt a classical frequency response model to the changing environment of power system operation is introduced. An agent-based LFC in a deregulated environment is proposed, and real-time laboratory tests have been performed. Furthermore, two frequency control synthesis approaches using a real values-based learning classifier system and a bisection search method are addressed; and finally, a design framework for economic frequency control is explained.

Chapter 8 describes a generalized frequency response model suitable for the analysis of a power system in the presence of significant disturbances and emergency conditions. The effects of emergency control/protection dynamics are properly considered. Under frequency load shedding (UFLS) strategies are reviewed and decentralized area based load shedding design is emphasized. The potential benefits of targeted load shedding compared to more conventional shared load shedding approaches are examined using simulation of a three control area power system. Finally, the necessity of using both voltage and frequency data, specifically in the presence of high penetration of RES, to develop an effective load shedding scheme is emphasized.

Chapter 9 presents an overview of the key issues concerning the integration of RESs into the power system frequency regulation that are of most interest today. The most important issues with the recent achievements in this literature are briefly reviewed. The impact of RESs on frequency control problem is described. An updated frequency response model is introduced. Power system frequency response in the presence of RESs and associated issues is analyzed, the need for the revising of frequency performance standards is emphasized and an overall framework for contribution of RESs in frequency control is addressed.

Chapter 10 presents some important issues regarding the wind power and frequency regulation problem. The most recent achievements in the relevant area are reviewed. The impact of power fluctuation due to high penetration of wind power on the system frequency response is emphasized, and to address this issue, advanced control synthesis methodologies are presented. The capability of wind turbines to support power system frequency control is discussed, and for this purpose, some frequency response models are explained. The potential of robust control techniques such as H_∞ control and MPC for effective contribution of wind turbines in the frequency regulation through the inertial, primary, and secondary control loops are highlighted.

Chapter 11 reviews the main control concepts in a Microgrid (MG), as basic elements of future smart grids, which have an important role to increase the grid efficiency, reliability, and to satisfy the environmental issues. The MG control loops are classified into local, secondary, global, and central/emergency controls. Then, the MG frequency response model is analyzed using the root locus method and the impact on each distributed generator on the frequency regulation is discussed. A generalized droop control for control of frequency (and voltage) in an MG is introduced and finally, several intelligent/robust control methodologies are explained.

Chapter 12 addresses the most important issues on the virtual synchronous generator (VSG) concept with the relevant past achievements. The most important VSG design frameworks and topologies are described. An overview of the key issues in the integration of VSGs in the MGs and power grids, and their application areas that are of most interest today is presented. Then the chapter is focused on the potential role of VSGs in the grid frequency control task. Finally, the need for further research on the more flexible and effective VSGs, and some other related areas is emphasized.

Acknowledgments

Much of the information, outcomes, and insight presented in this book were achieved through a long-term research conducted by the author and his research groups on robust control and power system frequency regulation over the last 20 years in Iran (1993–2002, 2006–2007, 2010–2014: K. N. Toosi University of Technology, West Regional Electric Company, and University of Kurdistan), Japan (2002–2006, 2009, 2011–2013: Osaka University, Kumamoto University, Research laboratory of Kyushu Electric Power Company, and Kyushu Institute of Technology), Australia (2007–2008: Queensland University of Technology) and France (2014: Ecole Centrale de Lille).

It is a pleasure to acknowledge the scholarships, awards, and support the author received from various sources: The Ministry of Education, Culture, Sports, Science and Technology, Government of Japan (Monbukagakusho), Japan Society for the Promotion of Science (JSPS), Mitani-Watanabe and Ise laboratories in Japan, West Regional Electric Company (WREC), Research Office at University of Kurdistan (UOK), the Australian Research Council (ARC), and French Ministry of Education, Research and Technology.

The author would like to thank Prof. Y. Mitani and Prof. M. Watanabe (Kyushu Institute of Technology), Prof. T. Hiyama (Kumamoto University), Prof. T. Ise (Osaka University), Prof. G. Ledwich, and Prof. A. Ghosh (Queensland University of Technology), and Prof. B. Francois (Ecole Centrale de Lille) for their continuous support and valuable comments.

Special thanks go to my colleagues and postgraduate students S. Shokoohi, H. Golpira, A. G. Tikdari, P. R. Daneshmand, F. Daneshfar, F. Habibi, P. Babahajyani, B. Badmasti, M. Aryan Nezhad, A. Morattab, J. Morel, Q. Shafiee, and T. H. Mohamed for their active role to provide this book. Finally, the author offers his deepest personal gratitude to his family for their support and patience during working on the book.

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