



**University of Kurdistan**

Dept. of Electrical and Computer Engineering

*Smart/Micro Grid Research Center*

[smgrc.uok.ac.ir](http://smgrc.uok.ac.ir)

## **Power System Monitoring and Control**

Bevrani H, Watanabe M, Mitani Y

Published (to be published) in: **IEEE-Wiley Press**

publication date: **2014**

### **Citation format for published version:**

Bevrani H, Watanabe M, Mitani Y (July 2014) Power System Monitoring and Control, IEEE-Wiley Press, New York, USA.

### **Copyright policies:**

- Download and print one copy of this material for the purpose of private study or research is permitted.
- Permission to further distributing the material for advertising or promotional purposes or use it for any profit-making activity or commercial gain, must be obtained from the main publisher.
- If you believe that this document breaches copyright please contact us at [smgrc@uok.ac.ir](mailto:smgrc@uok.ac.ir) providing details, and we will remove access to the work immediately and investigate your claim.

---

# POWER SYSTEM MONITORING AND CONTROL

---

Hassan Bevrani, Masayuki Watanabe & Yasunori Mitani



# POWER SYSTEM MONITORING AND CONTROL





---

# POWER SYSTEM MONITORING AND CONTROL

---

**Hassan Bevrani**

University of Kurdistan, Iran  
Kyushu Institute of Technology (Visiting Professor), Japan

**Masayuki Watanabe**

Kyushu Institute of Technology, Japan

**Yasunori Mitani**

Kyushu Institute of Technology, Japan



**WILEY**

Cover Image: iStockphoto © OJO\_Images

Copyright © 2014 by John Wiley & Sons, Inc. All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.  
Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at [www.copyright.com](http://www.copyright.com). Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at <http://www.wiley.com/go/permission>.

**Limit of Liability/Disclaimer of Warranty:** While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at [www.wiley.com](http://www.wiley.com).

***Library of Congress Cataloging-in-Publication Data:***

Bevrani, Hassan.

Power system monitoring and control / Hassan Bevrani, Masayuki Watanabe, Yasunori Mitani.  
pages cm

Includes bibliographical references and index.

ISBN 978-1-118-45069-7 (hardback)

I. Electric power systems—Control. I. Watanabe, Masayuki (Electrical engineer) II. Mitani, Yasunori.  
III. Title.

TK1007.B483 2014

621.317—dc23

2013041134

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

*Dedicated to our families and our students*





---

# CONTENTS

---

<b>Preface</b>	<b>xiii</b>
<b>Acknowledgments</b>	<b>xvii</b>
<b>1 AN INTRODUCTION ON POWER SYSTEM MONITORING</b>	<b>1</b>
1.1 Synchronized Phasor Measurement	2
1.2 Power System Monitoring and Control with Wide-Area Measurements	2
1.3 ICT Architecture Used in Wide-Area Power System Monitoring and Control	4
1.4 Summary	5
References	5
<b>2 OSCILLATION DYNAMICS ANALYSIS BASED ON PHASOR MEASUREMENTS</b>	<b>7</b>
2.1 Oscillation Characteristics in Power Systems	8
2.1.1 Eigenvalue Analysis and Participation Factor	8
2.1.2 Oscillation Characteristics in an Interconnected Power System	9
2.2 An Overview of Oscillation Monitoring Using Phasor Measurements	12
2.2.1 Monitoring of the Japan Power Network	12
2.2.2 Monitoring of the Southeast Asia Power Network	14
2.3 WAMS-Based Interarea Mode Identification	15
2.4 Low-Frequency Oscillation Dynamics	16
2.4.1 Electromechanical Modes Characteristics	16
2.4.2 Oscillation Characteristics Analyses in Southeast Asia Power Network	18
2.5 Summary	24
References	24

<b>3</b>	<b>SMALL-SIGNAL STABILITY ASSESSMENT</b>	<b>26</b>
3.1	Power System Small-Signal Stability	27
3.2	Oscillation Model Identification Using Phasor Measurements	29
3.2.1	Oscillation Model of the Electromechanical Mode	29
3.2.2	Dominant Mode Identification with Signal Filtering	30
3.3	Small-Signal Stability Assessment of Wide-Area Power System	32
3.3.1	Simulation Study	32
3.3.2	Stability Assessment Based on Phasor Measurements	33
3.3.3	Stability Assessment Based on Frequency Monitoring	38
3.4	Summary	41
	References	41
<b>4</b>	<b>GRAPHICAL TOOLS FOR STABILITY AND SECURITY ASSESSMENT</b>	<b>43</b>
4.1	Importance of Graphical Tools in WAMS	43
4.2	Angle–Voltage Deviation Graph	45
4.3	Simulation Results	48
4.3.1	Disturbance in Generation Side	49
4.3.2	Disturbance in Demand Side	50
4.4	Voltage–Frequency Deviation Graph	52
4.4.1	$\Delta V$ – $\Delta F$ Graph for Contingency Assessment	53
4.4.2	$\Delta V$ – $\Delta F$ Graph for Load Shedding Synthesis	56
4.5	Frequency–Angle Deviation Graph	58
4.6	Electromechanical Wave Propagation Graph	60
4.6.1	Wave Propagation	62
4.6.2	Angle Wave and System Configuration	64
4.7	Summary	68
	References	68
<b>5</b>	<b>POWER SYSTEM CONTROL: FUNDAMENTALS AND NEW PERSPECTIVES</b>	<b>70</b>
5.1	Power System Stability and Control	71
5.2	Angle and Voltage Control	73
5.3	Frequency Control	75
5.3.1	Frequency Control Dynamic	77
5.3.2	Operating States and Power Reserves	81
5.4	Supervisory Control and Data Acquisition	83
5.5	Challenges, Opportunities, and New Perspectives	88
5.5.1	Application of Advanced Control Methods and Technologies	88

5.5.2	Standards Updating	90
5.5.3	Impacts of Renewable Energy Options	90
5.5.4	RESs Contribution to Regulation Services	92
5.6	Summary	94
	References	95
<b>6</b>	<b>WIDE-AREA MEASUREMENT-BASED POWER SYSTEM CONTROL DESIGN</b>	<b>96</b>
6.1	Measurement-Based Controller Design	97
6.2	Controller Tuning Using a Vibration Model	98
6.2.1	A Vibration Model Including the Effect of Damping Controllers	98
6.2.2	Tuning Mechanism	101
6.2.3	Simulation Results	102
6.3	Wide-Area Measurement-Based Controller Design	107
6.3.1	Wide-Area Power System Identification	107
6.3.2	Design Procedure	110
6.3.3	Simulation Results	110
6.4	Summary	118
	References	118
<b>7</b>	<b>COORDINATED DYNAMIC STABILITY AND VOLTAGE REGULATION</b>	<b>119</b>
7.1	Need for AVR–PSS Coordination	120
7.2	A Survey on Recent Achievements	123
7.3	A Robust Simultaneous AVR–PSS Synthesis Approach	126
7.3.1	Control Framework	126
7.3.2	Developed Algorithm	128
7.3.3	Real-Time Implementation	131
7.3.4	Experiment Results	132
7.4	A Wide-Area Measurement-Based Coordination Approach	135
7.4.1	High Penetration of Wind Power	136
7.4.2	Developed Algorithm	138
7.4.3	An Application Example	141
7.4.4	Simulation Results	141
7.5	Intelligent AVR and PSS Coordination Design	149
7.5.1	Fuzzy Logic-Based Coordination System	149
7.5.2	Simulation Results	151
7.6	Summary	155
	References	155

<b>8</b>	<b>WIDE-AREA MEASUREMENT-BASED EMERGENCY CONTROL</b>	<b>158</b>
8.1	Conventional Load Shedding and New Challenges	159
8.1.1	Load Shedding: Concept and Review	159
8.1.2	Some Key Issues	161
8.2	Need for Monitoring Both Voltage and Frequency	162
8.3	Simultaneous Voltage and Frequency-Based LS	165
8.3.1	Proposed LS Scheme	165
8.3.2	Implementation	167
8.3.3	Case Studies and Simulation Results	168
8.3.4	An Approach for Optimal UFVLS	176
8.3.5	Discussion	177
8.4	Wave Propagation-Based Emergency Control	178
8.4.1	Proposed Control Scheme	178
8.4.2	Simulation Results	180
8.5	Summary	183
	References	183
<b>9</b>	<b>MICROGRID CONTROL: CONCEPTS AND CLASSIFICATION</b>	<b>186</b>
9.1	Microgrids	187
9.2	Microgrid Control	192
9.3	Local Controls	195
9.4	Secondary Controls	198
9.5	Global Controls	202
9.6	Central/Emergency Controls	204
9.7	Summary	206
	References	207
<b>10</b>	<b>MICROGRID CONTROL: SYNTHESIS EXAMPLES</b>	<b>209</b>
10.1	Local Control Synthesis	209
10.1.1	Robust Voltage Control Design	209
10.1.2	Intelligent Droop-Based Voltage and Frequency Control	215
10.2	Secondary Control Synthesis	221
10.2.1	Intelligent Frequency Control	221
10.2.2	ANN-Based Self-Tuning Frequency Control	228
10.3	Global Control Synthesis	235
10.3.1	Adaptive Energy Consumption Scheduling	235
10.3.2	Power Dispatching in Interconnected MGs	240
10.4	Emergency Control Synthesis	242

10.4.1	Developed LS Algorithm	243
10.4.2	Case Study and Simulation	243
10.5	Summary	246
	References	246
<b>Appendix A</b>	<b>New York/New England 16-Machine 68-Bus System Case Study</b>	<b>249</b>
<b>Appendix B</b>	<b>Nine-Bus Power System Case Study</b>	<b>254</b>
<b>Appendix C</b>	<b>Four-Order Dynamical Power System Model and Parameters of the Four-Machine Infinite-Bus System</b>	<b>256</b>
<b>Index</b>		<b>261</b>



---

# PREFACE

---

Power system monitoring and control (PSMC) is an important issue in modern electric power system design and operation. It is becoming more significant today due to the increasing size, changing structure, introduction of renewable energy sources, distributed smart/microgrids, environmental constraints, and complexity of power systems.

The wide-area measurement system (WAMS) with phasor measurement units (PMUs) provides key technologies for monitoring, state estimation, system protection, and control of widely spread power systems. A direct, more precise, and accurate monitoring can be achieved by the technique of phasor measurements and global positioning system (GPS) time signal. A proper grasp of the present state with flexible wide-area control and smart operation addresses significant elements to maintain wide-area stability in the complicated grid, with the growing penetration of distributed generation and renewable energy sources.

In response to the existing challenge of integrating advanced metering, computation, communication, and control into appropriate levels of PSMC, this book provides a comprehensive coverage of PSMC understanding, analysis, and realization. The physical constraints and engineering aspects of the PSMC have been fully considered, and developed PSMC strategies are explained using recorded real data from practical WAMS via distributed PMUs and GPS receivers in Japan and Southeast Asia (Singapore, Malaysia, and Thailand). In addition to the power system monitoring, protection, and control, the application of WAMS in emergency control schemes, as well as the control of distributed microgrids, is also emphasized.

This book will be useful for engineers and operators in power system planning and operation, as well as for academic researchers. It describes both monitoring and control issues in power systems, from introductory to advanced steps. This book can also 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. This book is organized into 10 chapters.

*Chapter 1* introduces power system monitoring and control, especially with wide-area phasor measurement applying PMUs. Some applications of WAMS globally, as well as information and communication technology (ICT) architecture used in the phasor measurement system are outlined as an introduction.

*Chapter 2* describes the oscillatory dynamics in the wide-area power system by using acquired monitoring data with phasor measurement units. Particularly, interarea low-frequency oscillations in Japan and Southeast Asia power systems have been investigated

by adopting band-pass filtering based on the fast Fourier transform (FFT) technique. Since both systems have the longitudinal configuration, the low-frequency mode oscillates in the opposite phase between both ends of the power network. The oscillatory dynamics can be captured successfully by wide-area phasor measurements.

*Chapter 3* emphasizes the small-signal stability assessment with phasor measurements. Particularly, the stability of the interarea low-frequency oscillation mode has been investigated by adopting the method to identify the oscillation dynamics with a simple oscillation model. The filtering approach improves the accuracy of the estimated eigenvalues. The stability can be evaluated successfully by the presented approach.

*Chapter 4* introduces graphical tools for power system stability and security assessment, such as angle–voltage deviation, voltage–frequency deviation, frequency–angle deviation, and electromechanical wave propagation graphs. The necessity of using the graphical tools rather than pure analytical and mathematical approaches in wide-area power system stability and security issues is explained. Applications for designing of wide-area controllers/coordinators as well as emergency control plans are discussed.

*Chapter 5* introduces the general aspects of power system stability and control. Fundamental concepts and definitions of angle, voltage, frequency stability, and existing controls are emphasized. The timescales and characteristics of various power system controls are described. The supervisory control and data acquisition (SCADA) and energy management system (EMS) architectures in modern power grids are explained. Finally, various challenges and new research directions are presented.

*Chapter 6* describes a method for tuning power system stabilizers (PSSs) based on wide-area phasor measurements. The low-order system model, which holds the characteristics of the interarea oscillation mode and control unit, is identified by monitoring data from wide area phasor measurements. The effectiveness of the proposed method has been demonstrated through the power system simulation. The results show that the appropriate controller can be designed by using the identified low-order model.

*Chapter 7* addresses two control strategies to achieve stability and voltage regulation, simultaneously. The first control strategy is developed using the  $H_\infty$  static output feedback control technique via an iterative linear matrix inequalities algorithm. The proposed method was applied to a four-machine infinite bus power system through a laboratory real-time experiment, and the results are compared with a conventional automatic voltage regulator–PSS design. The second control strategy uses a criterion in the normalized phase difference versus voltage deviation plane. Based on the introduced criterion, an adaptive angle-based switching strategy and negative feedback are combined to obtain a robust control methodology against load/generation disturbances.

*Chapter 8* emphasizes the necessity of using both voltage and frequency data, specifically in the presence of high wind power penetration, to develop an effective load shedding scheme. First, it is shown that the voltage and frequency responses may behave in opposite directions, following contingencies, and concerning this issue, a new load shedding scheme is proposed. Then, an overview on the electromechanical waves in power systems is presented, and the amplification of a propagated wave due to reflections or in combination with waves initiated from other disturbances is studied. Finally, based on a given descriptive study of electrical measurements and electromechanical wave



propagation in large electric power systems, an emergency control scheme is introduced to detect the possible plans.

*Chapter 9* proposes a comprehensive review on various microgrid control loops, and relevant standards are given with a discussion on the challenges of microgrid controls. In addition to the main MG concepts, the required control loops in the microgrids are classified into primary control, secondary control, global control, and central/emergency control levels.

*Chapter 10* addresses several synthesis methodology examples based on robust, intelligent, and optimal/adaptive control strategies for controller design in the microgrids. These examples cover all control levels; that is, primary, secondary, global, and central/emergency controls.



---

# ACKNOWLEDGMENTS

---

Most of the contributions, outcomes, and insight presented in this book were achieved through long-term teaching and research conducted by the authors and their research groups on power system monitoring and control issues over the years. Since 2000, the authors have intensively worked on various projects in the area of power system monitoring, dynamic stability analysis, and advanced control issues.

Some previous research and project topics are power system stabilization using superconducting magnetic energy storage (Osaka University, Japan); Campus WAMS project (for the sake of monitoring of power system dynamics, stability, and power flow status using installed PMUs in several university campuses in Japan, Thailand, Malaysia, and Singapore); high-tech green campus project (Kyushu Institute of Technology and Kyushu Electric Co., Japan); intelligent/robust automatic generation control (Frontier Technology for Electrical Energy, Japan and West Regional Electric Co., Iran); power system emergency control (Queensland University of Technology, and Australian Research Council, Australia); and sophisticated smart grid controls (Kyushu Institute of Technology, Japan; and University of Kurdistan, Iran). It is a pleasure to acknowledge the support and awards the authors received from all the mentioned sources.

The authors would also like to thank their colleagues and postgraduate students Dr. M. Fathi, H. Golpira, A. G. Tikdari, S. Shokoohi, F. Habibi, N. Hajimohammadi, and R. Khezri for their active role and continuous support. Finally, the authors offer their deepest personal gratitude to their families for their patience during the preparation of this book.