

QI HUANG
SHI JING
JIANB
WEI Z

INNOVATIVE TESTING AND MEASUREMENT SOLUTIONS FOR SMART GRID

 **IEEE**
IEEE PRESS

WILEY

INNOVATIVE TESTING AND MEASUREMENT SOLUTIONS FOR SMART GRID

Qi Huang, Shi Jing, and Jianbo Yi

University of Electronic Science and Technology of China, China

Wei Zhen

Sichuan Electric Power Research Institute, State Grid of China Company, China



WILEY

This edition first published 2015

© 2015 John Wiley & Sons Singapore Pte. Ltd.

Registered office

John Wiley & Sons Singapore Pte. Ltd., 1 Fusionopolis Walk, #07-01 Solaris South Tower, Singapore 138628.

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

All Rights Reserved. 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 expressly permitted by law, without either the prior written permission of the Publisher, or authorization through payment of the appropriate photocopy fee to the Copyright Clearance Center. Requests for permission should be addressed to the Publisher, John Wiley & Sons Singapore Pte. Ltd., 1 Fusionopolis Walk, #07-01 Solaris South Tower, Singapore 138628, tel: 65-66438000, fax: 65-66438008, email: enquiry@wiley.com.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The Publisher is not associated with any product or vendor mentioned in this book. This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the Publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

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. It is sold on the understanding that the publisher is not engaged in rendering professional services and neither the publisher nor the author shall be liable for damages arising herefrom. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

MATLAB® is a trademark of The MathWorks, Inc. and is used with permission. The MathWorks does not warrant the accuracy of the text or exercises in this book. This book's use or discussion of MATLAB® software or related products does not constitute endorsement or sponsorship by The MathWorks of a particular pedagogical approach or particular use of the MATLAB® software.

Library of Congress Cataloging-in-Publication Data

Huang, Qi (Electrical engineer)

Innovative testing and measurement solutions for smart grid / Qi Huang, Shi Jing, Jianbo Yi,
University of Electronic Science and Technology of China, Wei Zhen, Sichuan Electric Power Research
Institute.

pages cm

Includes bibliographical references and index.

ISBN 978-1-118-88992-3 (hardback)

1. Smart power grids—Testing. I. Title.

TK3105.H83 2015

621.31028'7 — dc23

2015005390

Typeset in 9/11pt TimesLTStd by Laserwords Private Limited, Chennai, India
Printed and bound in Singapore by Markono Print Media Pte Ltd

INNOVATIVE TESTING AND MEASUREMENT SOLUTIONS FOR SMART GRID

To our families

About the Authors

Qi Huang was born in Guizhou Province, China. He received a BSc degree in electrical engineering from Fuzhou University, Fuzhou, Fujian, China, in 1996, an MSc degree in electrical engineering from Tsinghua University, Beijing, China, in 1999, and a Ph.D degree in electrical engineering from Arizona State University, Tempe, in 2003.

Currently, he is a professor at the University of Electronic Science and Technology of China (UESTC), Chengdu, Sichuan, China; executive dean of School of Energy Science and Engineering, UESTC; and the director of Sichuan State Provincial Lab of Power System Wide-area Measurement and Control.

His current research and academic interests include power system high-performance computing, power system instrumentation, power system monitoring and control, and integration of distributed generation into the existing power system infrastructure.

Shi Jing was born in Jiangsu Province, China, in 1980. He received a BSc degree in electrical engineering from South West University for Nationality, Chengdu, Sichuan, China, in 2003, an MSc degree in automation engineering in 2006, and Ph.D degree in electrical engineering in 2013, both from UESTC, Chengdu, Sichuan, China.

He is currently an assistant professor at School of Energy Science and Engineering, UESTC. His current research fields include distributed measurement and control as well as smart grid and time synchronization technology for power systems.

Jianbo Yi was born in Gansu Province, China, in 1981. He received a BSc degree in measurement techniques and instruments in 2003, an MSc degree in automation engineering in 2007, and Ph.D degree in electrical engineering in 2013, from UESTC, Chengdu, Sichuan, China.

He is currently a lecturer at School of Energy Science and Engineering, UESTC. His current research fields include power system fault diagnosis and stability analysis of wide area power systems.

Wei Zhen was born in Hebei Province, China. He received a BSc degree in power system automation from Xian Jiaotong University (XJTU), Xi'an, Shanxi, China, in 1982. He then served as a senior engineer, and director of the Power System Engineering Research Center, Sichuan Electric Power Test and Research Institute, Chengdu, Sichuan, China.

His research fields include power system relay protection, power system analysis, and state-of-the-art technology development.

Foreword

The lead author of this book, Professor Qi Huang, also my former Ph.D student, invited me to write a foreword for this book. I am honored and proud to express my opinion on this work.

In recent years, cascading outages have led to the need for a well-developed electrical system characterized by efficient computer controls and reliable communication. The development of real time phasor measurements that digitize the voltage and current for each phase, and the use of a phase-lock oscillator along with a Global Positioning System (GPS) to obtain high-speed synchronized time tagged phasors transmitted to a local or remote receiver, therefore, present an excellent opportunity for modernizing the electric system, often referred to as the “smart grid.”

Today’s smart grid requires technological advancements in areas such as sensors, measurement, communications, and information processing. In addition, any new building block of a smart grid must be tested to ensure its functionality and performance requirements.

Professor Qi Huang and his team have been conducting research in smart grid measurement and testing for many years. They have pioneered the application of novel sensing methods for the smart grid, e.g., use of fiber optic sensors for icing monitoring of overhead transmission lines, and highly-sensitive magnetoresistive sensors for transient magnetic field detection, as well as noncontact fault location or operation state monitoring of high voltage overhead transmission lines. They have also been leaders in the testing area, proposing a holistic testing approach and implementing a test system that is currently widely used by utilities in China.

This book deals with two rather neglected areas of the smart grid technology: First, it explores the use of novel sensors, signal detection methods, and analysis techniques. Second, it presents utility-proven solutions for testing the smart grid with a range of novel components.

The smart grid is both revolutionary and evolutionary in nature. I believe that the publishing of this book will be beneficial to the entire smart grid community by accelerating the deployment of the smart grid, and by assisting the readership in understanding the characteristics of smart grid technologies and their relationship to “smart substations” of the future.

The impact is particularly important in China, which probably has the largest market for the smart grid in the world. It is my pleasure and honor to recommend this book for professionals and stakeholders in the electricity generation and distribution industry.

Dr George G. Karady
Power System Chair Professor
Arizona State University
School of Electrical, Computer and Energy Engineering
Arizona, USA

Preface

A revolution in power industries, including generation, transmission and distribution, driven by environmental and economic considerations, is taking place all over the world. The smart grid allows for integration of diverse generation and storage options, reduced losses, improved efficiencies, increased grid flexibility, reduced power outages, allowing for competitive electricity pricing and integration of electric vehicles and overall becoming more responsive to market, consumer and societal needs. It is bringing profound changes to both power systems and many related industries.

The smart grid has enormous potential to transform our energy infrastructure to become a self-healing electricity grid that will reduce energy consumption, which is exciting and deserves our engineering attention. The concept of smart grid has become more consolidated and has gained more and more attention since 2009 after many countries and economic unions announced their plans for the smart grid. Utilities around the world are investing plenty of money to deploy and implement smart grid technologies to modernize their operational and information systems, with the aim to transform the power grid, enabling utilities to monitor, analyze, and synchronize their networks to improve reliability, availability, and efficiency. The smart grid is generally envisioned as the platform for implementation of strategic development of power grids and optimized allocations of energy and resources. It is not only a revolution of the electric power industry but also the catalyst to create or breed new industries.

Under the driving force of smart grid development, the power grids of the future come into reality by enabling intelligent communication across sensing, measurement, and control layers of the existing power systems. Sensors and measurements become a core part of the grid and new, challenging problems have to be dealt with and solved. Also, to fully enjoy the potential benefits of the smart grid, advanced testing solutions would have to be developed to verify the functionalities as well as performance. Improving the reliability and distribution of electricity through the use of testing and measurement equipment is critical for the growth of the smart grid.

This book presents the most up-to-date technological developments in measurement and testing solutions of power systems under the smart grid environment. Although the authors try to include more aspects in the book, the research conducted in the authors' research labs are our focus. The book is divided into two parts: Sensor, Measurement and Data Management and Advanced Test Technologies for Smart Grid.

Chapter 1 starts with the world-wide state-of-art of the smart grid. The demand and requirements of sensors, measurement and testing in the future smart grid are identified. Measurements and testing become a core part of the grid and new challenging problems have to be dealt with and solved.

Sensors and sensor networks have an important impact on meeting environmental challenges. In order to route the power in more optimal ways to respond to a very wide range of conditions in a "smart" manner, it is necessary to deploy more (new types of) sensors in the existing power system infrastructure to obtain more information. In Chapter 2, the use of fiber optic sensors (FBG: fiber-optic Bragg grating) for building smart transmission network, and the use of magnetic sensors to build noncontact measurement of current to realize specific purposes, are presented.

Modern electric power protection, monitoring, and control systems rely on the availability of high-accuracy time. The time synchronization techniques are reviewed in Chapter 3. With the wide-area synchronized measurement system, it is possible to detect low-frequency oscillations in the power network on-line. Together with dynamic visualization techniques, wide area situational awareness, which is recognized as a key functionality in smart grids, is possible. These two topics are also discussed in the book.

During the deployment of the smart grid, the measurement technologies for energy balance, efficiency and power quality are evolving. Smart meter, as well as advanced metering infrastructure (AMI), are the fundamental characteristics that differentiate the smart grid from the traditional power grid. They are cost-effective and maximize energy efficiency. Chapter 4 presents the smart meter and AMI for the smart grid, and reviews the measurement progress of power quality. Also, one of the aims of the smart grid is to integrate the clean energy power generation source. Due to the intermittency of the power sources such as wind power and solar power, it is important to measure and predict the output of such a power generation system. The prediction of solar power output by cloud measurement and wind measurement as well as prediction in a wind farm are presented.

The smart grid is an information revolution for utilities. Plenty of data produced by the smart grid requires efficient data management tools. In Chapter 5, data and data processing in the smart grid are reviewed. An efficient integration tool, power system sensor network, is introduced and a vision of data cloud for the smart grid is presented. Big data and its potential in smart grid data analytics are also discussed.

The second part of the book is about testing. Since smart substations are developing quickly in China, the book focuses on the testing of a smart substation.

In a smart substation, a highly complex networked secondary system is required to perform information sharing and exchanging. This presents a novel challenge for the verification of function and interoperability of the secondary systems. In Chapter 6, a novel whole-view test of a secondary system in a smart substation is presented.

In order to build a highly reliable smart substation, the video monitoring system and many environmental monitoring systems are integrated to support the operation of a smart substation. These systems are expected to act in a correlated manner, to enhance security and effectively prevent any accidents. The testing of a video surveillance system and testing of a video linkage system based on simulation are presented in Chapter 7.

Electronic instrument transformers (EIT) are the key elements to implement smart substations. However, many problems are present in the fast deployment of EITs in a smart substation. It is imperative to develop an efficient testing tool to verify the performance of EITs. The test for the dynamic performance of EITs, especially using the Rogowski coil based current instrument transformer, is described in detail in Chapter 8.

Chapter 9 summarizes the results of the book and presents the future vision about sensors, measurement and testing solutions in the smart grid.

Acknowledgments

The authors are grateful to many people who have made the book possible.

Special thanks go to Mr Mingxin Hou and Clarissa Lim from Wiley. Without their encouragement and help, it would have been impossible to finish the writing of the book. Also, the authors would like to appreciate the efforts of all graduate students who ever worked in the authors' research lab. Most of the contents are from the research projects in our research lab.

Special thanks go to Dr Jian Li, Mr Dongsheng Cai, Mr Xiaohua Wang, Mr Yun Chen, and Mr Xiaoning Wang, for their direct contribution to editing, drawing, literature collection and collation during the writing of the book. During the editing, Dr Jian Li solved many of the Latex problems, which greatly speeded up the writing process. Also, the authors would like to appreciate the contribution and effort of our colleagues Dr Weidong He, and Dr Changhua Zhang.

It is our honor that Dr George Karady agreed to write the foreword and the authors would like to express our sincere gratitude to him.

Qi Huang, Shi Jing, and Jianbo Yi and Wei Zhen

Contents

About the Authors	xi
Foreword	xiii
Preface	xv
Acknowledgments	xvii
1 Introduction	1
1.1 The Concept and Worldwide Development of Smart Grid	1
1.1.1 <i>Concept of Smart Grid</i>	1
1.1.2 <i>Worldwide Development of Smart Grid</i>	3
1.2 Importance and Necessity of Measurement and Test in Smart Grid	4
1.3 State of Art in Measurement and Test of Smart Grid	6
1.3.1 <i>Sensor and Measurement</i>	6
1.3.2 <i>Test</i>	7
1.4 Outline of the Book	8
References	9
 Part I SENSOR, MEASUREMENT AND DATA MANAGEMENT	
2 New Types of Sensors for Smart Grid	13
2.1 Introduction	13
2.2 Application of Advanced Magnetic Sensor in Smart Grid	13
2.2.1 <i>Introduction</i>	13
2.2.2 <i>Point Measurement of Transient Magnetic Field in Substation with Magnetoresistive Sensor</i>	16
2.2.3 <i>Noncontact Fault Location of High Voltage Transmission Line with Magnetic Sensor</i>	25
2.2.4 <i>Operation-state Monitoring of High Voltage Transmission Line with Magnetoresistive Sensor</i>	44
2.2.5 <i>Electronic Current Transformer Based on Magnetoresistive Sensor</i>	49
2.3 Application of Fiber Optic Sensor in Smart Grid	59
2.3.1 <i>Introduction</i>	59
2.3.2 <i>Detection of Icing on High Voltage Transmission Line with Fiber Optic Sensor</i>	61

2.3.3	<i>Application Fiber Optic Sensor in Power System Surveillance</i>	73
	References	77
3	Synchronized Wide Area Measurement for Smart Grid	81
3.1	Introduction	81
3.2	Time Synchronization in Substation	82
3.2.1	<i>Introduction</i>	82
3.2.2	<i>Time Synchronization Based on NTP Protocol</i>	83
3.2.3	<i>Time Synchronization Based on IEEE 1588 Protocol</i>	84
3.2.4	<i>Time Synchronization Based on GPS and IEEE1588 protocol</i>	86
3.2.5	<i>Wireless Time Synchronization Technology</i>	89
3.2.6	<i>Programmable Step-delay Time Clock for Substation Test</i>	92
3.2.7	<i>Test of a Time Synchronization System in a Hydro Plant Management System</i>	95
3.3	Dynamic Visualization of Power System Synchronphasor	97
3.3.1	<i>Introduction</i>	97
3.3.2	<i>State-of-art Dynamic Visualization Technologies</i>	99
3.3.3	<i>Implementation of a Dynamic Visualization System for Real-time Power Data</i>	100
3.4	On-line Measurement of Low Frequency Oscillation Based on WAMS	101
3.4.1	<i>System Architecture</i>	102
3.4.2	<i>Measurement of Oscillation Mode with Improved HHT</i>	104
3.4.3	<i>Disturbance Location</i>	124
3.5	Wide Area Situational Awareness	131
3.5.1	<i>Introduction</i>	131
3.5.2	<i>Framework of WASA</i>	133
3.5.3	<i>Advanced Visual Analytics</i>	135
3.5.4	<i>Time-space Analysis of Dynamic Frequency in Large Scale Power Network</i>	139
	References	144
4	Measurement of Energy, Power Quality and Efficiency in Smart Grid	147
4.1	Smart Meter and AMI for Smart Grid	148
4.1.1	<i>Transition from AMR to AMI</i>	148
4.1.2	<i>Smart Meters and Architecture of AMI</i>	152
4.1.3	<i>An AMI for a Small Hydroplant</i>	155
4.1.4	<i>AMI in Future</i>	157
4.2	Measurement for Power Quality in Smart Grid	159
4.2.1	<i>Power Quality Issues in Smart Grid</i>	160
4.2.2	<i>Development of Measurement for Power Quality</i>	161
4.3	Measurement for Integration of Distributed Generation	165
4.3.1	<i>Integration of Renewable Resources with Smart Grid</i>	165
4.3.2	<i>Short-term Forecasting of Solar Generation by Cloud Motion Measurement</i>	167
4.3.3	<i>Measuring Wind for Optimal Wind Power Generation</i>	175
	References	181
5	Data Management in Smart Grid	183
5.1	Introduction	183
5.2	Data and Data Processing in Smart Grid	184
5.2.1	<i>Smart Grid Data</i>	184
5.2.2	<i>Concept of Big Data</i>	185
5.2.3	<i>Smart Grid Big Data and Data Analytics Tool</i>	186
5.2.4	<i>Decentralized Data Processing in Smart Grid</i>	193