

Volume 3

SMART GRID HANDBOOK

Chen-Ching Liu
Stephen McArthur
Seung-Jae Lee

WILEY

SMART GRID HANDBOOK

VOLUME 3

Editors-in-Chief

Chen-Ching Liu

Washington State University, USA

Stephen McArthur

University of Strathclyde, UK

Seung-Jae Lee

Myongji University, South Korea

WILEY

This edition first published 2016
© 2016 John Wiley & Sons Ltd

Registered office

John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex,
PO19 8SQ, United Kingdom

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.

The right of the authors to be identified as the authors of this work has been asserted in accordance with the Copyright, Designs and Patents Act 1988.

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 or otherwise, except as permitted by the UK Copyright, Designs and Patents Act 1988, without the prior permission of the publisher.

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.

The Publisher and the Authors make no representations or warranties with respect to the accuracy or completeness of the contents of this work and specifically disclaim all warranties, including without limitation any implied warranties of fitness for a particular purpose. The advice and strategies contained herein may not be suitable for every situation. In view of ongoing research, equipment modifications, changes in governmental regulations, and the constant flow of information relating to the use of experimental reagents, equipment, and devices, the reader is urged to review and evaluate the information provided in the package insert or instructions for each chemical, piece of equipment, reagent, or device for, among other things, any changes in the instructions or indication of usage and for added warnings and precautions. The fact that an organization or Website is referred to in this work as a citation and/or a potential source of further information does not mean that the author or the publisher endorses the information the organization or Website may provide or recommendations it may make. Further, readers should be aware that Internet Websites listed in this work may have changed or disappeared between when this work was written and when it is read. No warranty may be created or extended by any promotional statements for this work. Neither the Publisher nor the Author shall be liable for any damages arising herefrom.

Chapters whose authors are US Government employees are © US Government in North America and © John Wiley & Sons in the rest of the world. The views expressed by those authors who are US Government employees do not necessarily reflect the views of the US Government Agencies they work for.

Library of Congress Cataloging-in-Publication data is available for this book.

978-1-118-75548-8 (hardback)

Cover image: © Daniel Melekhin / Getty Images; © artJazz / Getty Images.

Typeset in 10/12pt Times by SPi Global, Chennai, India

Printed and bound by Markono Print Media Pte Ltd.

This book is printed on acid-free paper responsibly manufactured from sustainable forestry, in which at least two trees are planted for each one used for paper production.

SMART GRID HANDBOOK

EDITORIAL BOARD

Editors-in-Chief

Chen-Ching Liu

Washington State University, USA

Stephen McArthur

University of Strathclyde, UK

Seung-Jae Lee

Myongji University, South Korea

Section Editors

VISION AND DRIVERS

Dan Ton

U.S. Department of Energy, Washington, DC, USA

Xiaoxin Zhou

China Electric Power Research Institute, China

TRANSMISSION

Kevin Tomsovic

University of Tennessee, USA

Vladimir Terzija

University of Manchester, UK

DISTRIBUTION

Kevin Schneider

Pacific Northwest National Laboratory, USA

Seongil Lim

Kyungnam University, Korea

SMART METERS AND CUSTOMERS

Diane Cook

Washington State University, USA

Chen-Ching Liu

Washington State University, USA

INFORMATION AND COMMUNICATIONS TECHNOLOGY

Ron Ambrosio

IBM Thomas J. Watson Research Center, USA

SOCIO-ECONOMIC ISSUES

Michael Pollitt

University of Cambridge, UK

List of Contributors

Ali Abur, Northeastern University, Boston, MA, USA

Pedro M. R. Almeida, Smarter Grid Solutions Ltd., Glasgow, UK

Ronald F. Ambrosio, IBM Thomas J. Watson Research Center, Yorktown Heights, NY, USA

Anestis G. Anastasiadis, National Technical University of Athens, Athens, Greece

Karim L. Anaya, University of Cambridge, Cambridge, UK

Alexander Apostolov, OMICRON Electronics, Los Angeles, CA, USA

Charlie Arteaga, IBM Corp., San Antonio, TX, USA

Graham W. Ault, Smarter Grid Solutions, Glasgow, UK

Zeyar Aung, Masdar Institute of Science and Technology, Abu Dhabi, UAE

Michelle Baddeley, University College London, London, UK

Xiaomin Bai, China Electric Power Research Institute, Beijing, China

Pramod Bangalore, Chalmers University of Technology, Göteborg, Sweden

Pedro N. P. Barbeiro, INESC Technology and Science (INESC TEC), Porto, Portugal

Keith Bell, University of Strathclyde, Glasgow, UK

Ricardo J. Bessa, INESC Technology and Science (INESC TEC), Porto, Portugal

Tianshu Bi, North China Electric Power University, Beijing, China

Saugata Biswas, ALSTOM, Redmond, WA, USA

Mustafa A. Biviji, Energy & Environmental Resources Group, LLC (E2RG), Pittsburgh, PA, USA

Martin Bradley, National Grid, Workingham, UK

Klaus-Peter Brand, ABB Switzerland Ltd., Baden, Switzerland

Graeme Burt, University of Strathclyde, Glasgow, UK

Victoria M. Catterson, Institute for Energy and Environment, University of Strathclyde, Glasgow, UK

Woo-Kyu Chae, KEPCO Research Institute, Daejeon, South Korea

Chao-Shun Chen, I-Shou University, Kaohsiung, Taiwan

- Ziyu Chen**, China Electric Power Research Institute, Beijing, China
- Lin Cheng**, Tsinghua University, Beijing, China
- In-Sun Choi**, Power & Industrial Systems R&D Center of HYOSUNG, Seoul, South Korea
- Young-Jun Choi**, Power & Industrial Systems R&D Center of HYOSUNG, Seoul, South Korea
- Joe H. Chow**, Rensselaer Polytechnic Institute, Troy, NY, USA
- Frances M. Cleveland**, Xanthus Consulting International, Boulder Creek, CA, USA
- Robert A. F. Currie**, Smarter Grid Solutions, Glasgow, UK
- Sarah J. Darby**, University of Oxford, Oxford, UK
- Ali Davoudi**, University of Texas, Arlington, TX, USA
- Francisco de León**, New York University, Brooklyn, NY, USA
- Michele De Nigris**, Ricerca sul Sistema Energetico – RSE S.p.A, Milano, Italy
- Marc Diaz-Aguiló**, New York University, Brooklyn, NY, USA
- Daniel Dotta**, UNICAMP, Campinas, São Paulo, Brazil
- Jethro Dowell**, University of Strathclyde, Glasgow, Scotland
- Janaka B. Ekanayake**, University of Peradeniya, Peradeniya, Sri Lanka
- Istvan Erlich**, University of Duisburg-Essen, Duisburg, Germany
- Joseph H. Eto**, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
- Steve Finney**, University of Strathclyde, Glasgow, UK
- Thomas Frost**, Imperial College London, London, UK
- Jason C. Fuller**, Pacific Northwest National Laboratory, Richland, WA, USA
- Matthias Galus**, Swiss Federal Office of Energy, Zürich, Switzerland
- Clark Gellings**, Electric Power Research Institute, Palo Alto, CA, USA
- Jay Giri**, GE Grid Software Solutions, Redmond, WA, USA
- Margaret Goodrich**, Project Consultants, LLC, Shell Knob, MO, USA
- Richard Green**, Imperial College London, London, UK
- Tim C. Green**, Imperial College London, London, UK
- Thomas Greve**, University of Cambridge, Cambridge, UK
- Efren Guillo-Sansano**, University of Strathclyde, Glasgow, UK
- Erich W. Gunther**, EnerNex LLC, Knoxville, TN, USA
- Jiahui Guo**, The University of Tennessee, Knoxville, TN, USA
- Yonghe Guo**, Michigan Technological University, Houghton, MI, USA

- Ross Guttromson**, Sandia National Laboratories, Albuquerque, NM, USA
- Boknam Ha**, Korea Electric Power Corporation, Daejeon, South Korea
- Samson Y. Hadush**, Vlerick Business School, Brussels, Belgium
- Adam Hahn**, Washington State University, Pullman, WA, USA
- Nikos D. Hatziargyriou**, National Technical University of Athens, Athens, Greece
- Yasuhiro Hayashi**, Waseda University, Tokyo, Japan
- Paul D. H. Hines**, University of Vermont, Burlington, VT, USA
- Wataru Hirohashi**, Waseda University, Tokyo, Japan
- Fred Howell**, Powertech Labs Inc., Surrey, British Columbia, Canada
- Cheng-Ting Hsu**, Southern Taiwan University, Yung-Kang City, Taiwan
- Xuehao Hu**, China Electric Power Research Institute, Qinghe/Beijing, China
- Tatsuya Iizaka**, Fuji Electric Co., Ltd., Tokyo, Japan
- Hideo Ishii**, Waseda University, Tokyo, Japan
- Katrina Jessoe**, University of California, Davis, CA, USA
- Adrià Junyent-Ferré**, Imperial College London, London, UK
- Dong-Joo Kang**, Korea Electro-technology Research Institute (KERI), Ansan, South Korea
- Robert Kavet**, Electric Power Research Institute (EPRI), Palo Alto, CA, USA
- Kiyonori Kawamura**, Kyushu Electric Power Company, Fukuoka, Japan
- Lynne Kiesling**, Northwestern University, Evanston, IL, USA
- Myongsoo Kim**, KEPCO Research Institute, Daejeon, Korea
- Vasilis A. Kleftakis**, National Technical University of Athens, Athens, Greece
- Mark Knight**, GridWise Architecture Council, CGI Utilities, Billerica, MA, USA
- Tatjana Kostic**, ABB Corporate Research, Baden-Daettwil, Switzerland
- Te-Tien Ku**, National Penghu University of Science and Technology, Kaohsiung, Taiwan
- Seongchul Kwon**, Korea Electric Power Corporation (KEPCO), Daejeon, Republic of Korea
- Chun S. Lai**, University of Oxford, Oxfordshire, UK
- Loi L. Lai**, State Grid Energy Research Institute, Beijing, China
- Hak-Ju Lee**, KEPCO Research Institute, Daejeon, South Korea
- Depeng Li**, University of Hawaii at Manoa, Honolulu, HI, USA
- Peng Li**, Tianjin University, Tianjin, China
- Yalong Li**, The University of Tennessee, Knoxville, TN, USA

- Chia-Hung Lin**, National Kaohsiung University of Applied Sciences, Kaohsiung, Taiwan
- Xi Lin**, Powertech Labs Inc., Surrey, British Columbia, Canada
- Chen-Ching Liu**, Washington State University, Pullman, WA, USA
- Yilu Liu**, The University of Tennessee, Knoxville; Oak Ridge National Laboratory, Oak Ridge, TN, USA
- Yong Liu**, The University of Tennessee, Knoxville, TN, USA
- Kithsiri M. Liyanage**, University of Peradeniya, Peradeniya, Sri Lanka
- João Peças Lopes**, Faculdade de Engenharia Universidade do Porto and INESC TEC, Porto, Portugal
- André G. Madureira**, INESC Technology and Science (INESC TEC), Porto, Portugal
- Kenneth E. Martin**, Electric Power Group, Pasadena, CA, USA
- Luciano Martini**, Ricerca sul Sistema Energetico – RSE S.p.A, Milano, Italy
- Manuel A. Matos**, Faculdade de Engenharia Universidade do Porto and INESC TEC, Porto, Portugal
- Giuseppe Mauri**, Ricerca sul Sistema Energetico – RSE S.p.A, Milano, Italy
- Stephen D. J. McArthur**, Institute for Energy and Environment, University of Strathclyde, Glasgow, UK
- Malcolm McCulloch**, University of Oxford, Oxfordshire, UK
- Thomas E. McDermott**, University of Pittsburgh, Pittsburgh, PA, USA
- Alan McMorran**, Open Grid Systems Ltd., Glasgow, UK
- Leonardo Meeus**, Vlerick Business School, Brussels, Belgium; Florence School of Regulation, Robert Schuman Centre for Advanced Studies, European University Institute, Florence, Italy
- George M. Messinis**, National Technical University of Athens, Athens, Greece
- Víctor Miñambres-Marcos**, University of Extremadura, Badajoz, Spain
- Jovica V. Milanović**, The University of Manchester, Manchester, UK
- Paul D. Mitcheson**, Imperial College London, London, UK
- Joydeep Mitra**, Michigan State University, East Lansing, MI, USA
- Masataka Mitsuoka**, Waseda University, Tokyo, Japan
- Hamed Mohsenian-Rad**, University of California, Riverside, CA, USA
- Ilan Momber**, Vlerick Business School, Brussels, Belgium
- Diana Moneta**, Ricerca sul Sistema Energetico – RSE S.p.A, Milano, Italy
- Kip Morison**, BC Hydro, Vancouver, British Columbia, Canada
- Panayiotis Moutis**, National Technical University of Athens, Athens, Greece
- R. Jay Murphy**, Macrodyne, Clifton Park, New York, USA
- Scott Neumann**, UISOL an Alstom Company, Ramsey, MN, USA
- Robert G. Olsen**, Washington State University, Pullman, WA, USA

- Philip N. Overholt**, U.S. Department of Energy, Washington, DC, USA
- Stefan Pantea**, National Grid, Workingham, UK
- Christina N. Papadimitriou**, National Technical University of Athens, Athens, Greece
- Jorge Pereira**, Faculdade de Economia Universidade do Porto and INESC TEC, Porto, Portugal
- Pierre Pinson**, Technical University of Denmark (DTU), Kongens Lyngby, Denmark
- Michael G. Pollitt**, University of Cambridge, Cambridge, UK
- Robert G. Pratt**, U.S. Department of Energy, Pacific Northwest National Laboratory, Richland, WA, USA
- Mohammad Ehsan Raoufat**, University of Tennessee, Knoxville, TN, USA
- David Rapson**, University of California, Davis, CA, USA
- Ashhar Raza**, New York University, Brooklyn, NY, USA
- Pawel Regulski**, The University of Manchester, Manchester, UK
- Pooya Rezaei**, University of Minnesota, Minneapolis, MN, USA
- Marta Rocha**, New University of Lisbon, Lisbon, Portugal
- Sebastian Rohjans**, OFFIS Institute for Information Technology, Oldenburg, Germany
- Enrique Romero-Cadaval**, University of Extremadura, Badajoz, Spain
- Andrew Roscoe**, University of Strathclyde, Glasgow, UK
- Abel Sanchez**, Massachusetts Institute of Technology (MIT), Cambridge, MA, USA
- Rafael Santodomingo**, OFFIS Institute for Information Technology, Oldenburg, Germany; Brunel University, Uxbridge, UK
- Kevin Schneider**, Pacific Northwest National Laboratory, Richland, WA, USA
- Luís Seca**, INESC Technology and Science (INESC TEC), Porto, Portugal
- Marino Sforza**, Terna, Italian TSO, Rome, Italy
- Fekadu Shewarega**, University of Duisburg-Essen, Duisburg, Germany
- Xiaojie Shi**, The University of Tennessee, Knoxville, TN, USA
- Chanan Singh**, Texas A&M University, College Station, TX, USA
- Jeremy B. Smith**, Analysis Group, Boston, MA, USA
- Filipe J. Soares**, INESC Technology and Science (INESC TEC), Porto, Portugal
- Michael Specht**, OFFIS Institute for Information Technology, Oldenburg, Germany
- Anurag Srivastava**, Washington State University, Pullman, WA, USA
- Michael Stanislawski**, GE Energy Management, Cambridge, UK
- Emma M. Stewart**, Lawrence Berkeley National Laboratory, Grid Integration Group, Energy Technologies Area, Berkeley, CA, USA

- Michael Stuber**, Itron Inc., Liberty Lake, WA, USA
- Chih-Che Sun**, Washington State University, Pullman, WA, USA
- Hiroataka Takano**, University of Fukui, Fukui, Japan
- Gareth Taylor**, Brunel University, Uxbridge, UK
- Zach Taylor**, University of California, Riverside, CA, USA
- Richard A. Tell**, Richard Tell Associates, Inc., Mesquite, NV, USA
- Chee-Wooi Ten**, Michigan Technological University, Houghton, MI, USA
- Vladimir Terzija**, The University of Manchester, Manchester, UK
- Lina B. Tjernberg**, KTH Royal Institute of Technology, Stockholm, Sweden
- Kevin Tomsovic**, University of Tennessee, Knoxville, TN, USA
- Dan Ton**, U.S. Department of Energy, Washington, DC, USA
- Mathias Usler**, OFFIS Institute for Information Technology, Oldenburg, Germany
- Athanasios Vassilakis**, National Technical University of Athens, Athens, Greece
- Alexandra von Meier**, California Institute for Energy and Environment, Berkeley, CA, USA
- Chengshan Wang**, Tianjin University, Tianjin, China
- Fred Wang**, The University of Tennessee, Knoxville, TN, USA
- Lei Wang**, Powertech Labs Inc., Surrey, British Columbia, Canada
- Weisheng Wang**, China Electric Power Research Institute, Beijing, China
- Jean-Paul Watson**, Sandia National Laboratories, Albuquerque, NM, USA
- Robert Webb**, Imperial College London, London, UK
- Claire M. Weiller**, University of Cambridge, Cambridge, UK
- Steven E. Widergren**, U.S. Department of Energy, Pacific Northwest National Laboratory, Richland, WA, USA
- John R. Williams**, Massachusetts Institute of Technology (MIT), Cambridge, MA, USA
- Tim Wolf**, Itron Inc., Liberty Lake, WA, USA
- David Wollman**, National Institute of Standards and Technology, Gaithersburg, MD, USA
- Jianzhong Wu**, Cardiff University, Cardiff, UK
- Jinjun Xiong**, IBM Thomas J. Watson Research Center, Yorktown Heights, NY, USA
- Fangyuan Xu**, State Grid Energy Research Institute, Beijing, China
- Lie Xu**, University of Strathclyde, Glasgow, UK
- Kurt Yeager**, Electric Power Research Institute (EPRI); and Galvin and Perfect Power Electricity Initiatives, Palo Alto, CA, USA

Hao Zha, China Electric Power Research Institute, Beijing, China

Ye Zhang, The University of Tennessee, Knoxville, TN, USA

Yichen Zhang, University of Tennessee, Knoxville, TN, USA

Dao Zhou, The University of Tennessee, Knoxville, TN, USA

Qing-Chang Zong, Illinois Institute of Technology, Chicago, IL, USA

Erietta I. Zountouridou, National Technical University of Athens, Athens, Greece

Preface

Over the last several years, the development of smart grids has become a global trend for electric power grids. Although there is not a unique and widely adopted definition of the term, “Smart Grid,” the development is driven by the sea change that is taking place in the power and energy industry. Renewable energy, particularly wind and solar, increases dramatically and represents a significant portion of the power generation capacity. Distributed generation, energy storage, and microgrids are moving power systems towards a de-centralized operational environment. Demand side response is evolving into a market mechanism where customers participate by managing their utilization of electric energy. Smart meters serve as the enabling technology that connects millions of customers with the power grid. The fundamental shift in the paradigm is driven by the international concern over energy and its environmental impact on climate change.

The smart grid concept is also motivated by the need to enhance the reliability of electric power systems. Widespread catastrophic outages caused by cascading events call for new technologies to enhance the monitoring, control, protection, and restoration of the power grids. In the last decade, a large number of Phasor Measurement Units (PMUs) have been installed on the grids in several countries to allow power system dynamics to be sampled much more frequently compared to what was possible with traditional supervisory control and data acquisition systems. The level of automation in the distribution level is greatly improved by the installation of numerous remote-controlled switches and voltage/var controllers. The smart grid depends on the underlying information and communications technology to provide the extensive connectivity among the enormous number of devices and systems on the grid. To a great extent, the “smart” nature of the emerging power grid depends on the massive amount of information brought through this connectivity.

This Handbook is focused on smart grid issues and, as a result, it is not intended to be a comprehensive reference for other related subjects such as renewable energy. Due to the global nature of smart grid development, we have made a great effort to represent a broad range of international perspectives. A total of 83 articles in the three volumes of the Handbook are organized into Sections based on the most relevant subjects on the smart grid: Vision and Drivers, Transmission, Distribution, Smart Meters and Customers, Information and Communications Technology, and Socio-Economic Issues:

- The first section, Vision and Drivers, includes articles that are concerned with the vision, definitions, evolution, and global development of the smart grid as well as new technologies and standards. The roles of renewable energy, demand response, and energy storage are discussed.
- The section on Transmission begins with a set of articles on the deployment of PMUs and their applications; for example, wide area monitoring, monitoring of power system dynamics, testing and standards of PMUs, and future energy management systems. The background of the technology deployment is provided by an article about cascading events causing catastrophic outages in power grids. This section then covers smart grid technologies including remedial control and defense systems, Flexible AC Transmission Systems (FACTS), High Voltage DC (HVDC), dynamic state estimation, dynamic security assessment, power system restoration, load modeling, and reliability evaluation. The coverage is completed through discussions of the industry practice, operational experience, standards, cyber security, and grid codes.

- The Distribution section starts with an introduction to distribution systems and the system configurations in different countries and different load areas served by the grid. Following the introduction are articles describing elements of smart grid in the distribution systems, i.e., control architecture, communications, distributed energy resources, electric vehicles as a distributed resource for energy storage, microgrids, renewable energy devices, power electronics, advanced protection systems, distribution PMUs, cyber security, and distribution/substation automation technologies. A set of articles provides the state-of-the-art in smart grid applications, e.g., feeder automation, Distribution Management System, Voltage/Var control, Conservation Voltage Reduction (CVR), active network management, power quality, condition monitoring and asset management, and reliability evaluation. Similar to the Transmission section, articles also address issues of industry practice, operational experience, and the international perspectives on the topics.
- The section on Smart Meters and Customers is concerned with smart meters and how they enable the customers to interact with the power grid. The industry perspective is provided by articles about drivers for smart meters, their functions, data collection and management and implementations as well as standards and security of smart meters. The section has articles detailing how research and development concerning smart meters has addressed issues around customer choices, customer behaviors, demand response, and home energy management. This section also includes an article that examines the issue of health effects of smart meters based on research.
- On the subject on Information and Communications Technology (ICT), the section includes articles that discuss the elements of ICT required for smart grid development, which includes interoperability and relevant standards, hardware-in-the-loop modeling and simulation, and system level simulation. Other articles are concerned with their application, such as distributed intelligence, transactive energy systems, and data analytics. Industry practice and operational experience are also covered.
- Smart grid development is not simply a matter of technology development and deployment. There are critical Socio-Economic Issues that must be addressed in order to gain public acceptance. The final section deals with these socio-economic issues. The section starts with an introduction to these issues, followed by articles concerning markets, regulation, cost-benefit analysis, organizational models, privacy, and social acceptance.

The development of this Handbook has been a major project that required a large international team of experts representing smart grid R&D, technology deployment, standards, industry practice, and socio-economic aspects. This major outcome cannot be achieved without the tremendous contributions and efforts from the team of Section Editors: Dan Ton, Xiaoxin Zhou, Kevin Tomsovic, Vladimir Terzija, Kevin Schneider, Seongil Lim, Diane Cook, Ron Ambrosio, and Michael Pollitt. They should be proud of the accomplishment of the Handbook and its contribution to the field of smart grid. Needless to say, the authors of all articles deserve special recognition. Smart grid is a dynamic field that is evolving over time and on a global basis. The vast experience of the invited authors brings an authoritative view of the state-of-the art. With Wiley's vision and strong support, we are privileged to have worked with the distinguished team of authors and section editors on this important project as we enter a new era of electric power systems.

Chen-Ching Liu
Washington State University, Pullman, WA, USA
(Formerly University College Dublin, Ireland)

Stephen McArthur
University of Strathclyde, Scotland, UK

Seung-Jae Lee
Myongji University, South Korea