# HANDBOOK OF ELECTRICAL POWER SYSTEM DYNAMICS

**IEEE Press**
445 Hoes Lane
Piscataway, NJ 08854

# HANDBOOK OF ELECTRICAL POWER SYSTEM DYNAMICS

## Modeling, Stability, and Control

Edited by

Mircea Eremia
Electrical Power Systems Department
University "Politehnica" of Bucharest

Mohammad Shahidehpour
Illinois Institute of Technology

IEEE PRESS

IEEE PRESS SERIES ON POWER ENGINEERING

Mohamed E. El-Hawary, *Series Editor*

WILEY

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

Handbook of electrical power system dynamics : modeling, stability, and control / edited by Mircea Eremia, Mohammad Shahidehpour.
pages cm
Includes bibliographical references.
ISBN 978-1-118-49717-3 (cloth)
1. Electric power system stability–Mathematical models–Handbooks, manuals, etc. 2. Electric power systems–Control–Handbooks, manuals, etc. 3. Electric machinery–Dynamics–Handbooks, manuals, etc. I. Eremia, Mircea. II. Shahidehpour, M., 1955-
TK1001.H35 2012
621.31—dc23

2012032673

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

# CONTENTS

# FOREWORD

Electricity is the driving factor of the modern world. Humanity is demanding more and more energy as the demand for better life quality, and industry development is increasing. The history of modern civilization begun more than one century ago when electricity generators and infrastructure for electricity transmission were invented. As the demand for electrical power has increased, the electrical power systems have been expanded over large distances and become more complex. There has been, thus, a continuous need for innovation to create more efficient and reliable components.

Recently, the electrical power systems have gone through a deregulation process, and electricity market has been created aiming to stimulate competition, achieve fair electrical energy price, encourage the investments for modernization and commissioning new power plants, etc. However, the immediate effects of the electricity market were additional problems in power system operation.

The limited conventional energy resources and the need for environment protection, on one hand, and the advantages of actual robust simulation hardware and software tools, on the other hand, encouraged the humanity to successfully exploit the Aeolian, solar, and other nonconventional resources. The share of electricity generation from renewable energy sources has significantly increased in the last years, and the targets are very ambitious for the future. Large wind farms are developed onshore and offshore, resulting in significant change in the generation pattern and thus changes in the power flow. Moreover, under the increasing share of generation from renewables, changes in power flows may sometimes occur quite often during one hour. This problem, in effect, requires strengthening the transmission grid.

The power system operators are, thus, facing bigger challenges than that in the past, such as limitations in scheduling and handling generation resources due to the electricity market, operation of the transmission networks close to their technical limits due to difficulties in constructing new transmission facilities, and generation uncertainties due to the intermittency and less inaccurate forecasts of the renewable energy sources, or even due to natural forces like earthquakes and storms.

The major grid blackouts experienced in the last years prove that investments and innovation are always required in the power system infrastructure, management, and education. The operational manual of the ENTSO-E network has been updated in order to prevent major incidents that occurred in the past due to permissive rules. In a strongly interconnected continental power system, as it is the ENTSO-E network, collaboration between power system operators based on clear rules is critical.

As a reaction to the technical issues of power systems, new concepts are under development. It is expected that the new ideas for more intelligent electrical networks (Smart Grids) and creation of continental supergrids may improve the power system security while satisfying the customers' needs as regards the quantity and quality. This may be seen as a new era of electricity.

This book is a successful collection of theories and applications, from modeling for dynamic analysis, methods for stability assessment and control strategies that finally help the reader to understand the causes and effects of power system blackouts and, on one hand, to understand why some preventive actions are required in order to ensure appropriate security levels and avoid the blackouts. The authors of this book, both from academia and industry, are active specialists in CIGRE and IEEE-PES activities.

*Education has been a critical ingredient for creating a sustainable electricity industry. Investment in education is the minimum condition to create professionals.*

André Merlin
President of CIGRE

# ACKNOWLEDGMENTS

The authors wish to take this opportunity to acknowledge all persons and institutions that contributed directly or indirectly in carrying out this book, either by technical or by editorial support.

Special acknowledgments are addressed to Prof. Prabha Kundur, president of Kundur Power System Solutions Inc., for his support and inspiring recommendations. His book on power system dynamics, a reference work in the field, has been also inspiring for several theories presented in this book.

For some chapters the authors benefited by the kindness of some institutions or companies, which permitted reprinting or adapting figures, equations, or excerpts. Special thanks are thus addressed to Institute of Electrical and Electronics Engineers (IEEE), International Electrotechnical Committee (IEC), Conseil International des Grands Réseaux Électriques – International Council on Large Electric Systems (CIGRE), as well as John Wiley & Sons, Inc. for their reprinting permission and support. Acknowledgments are also addressed to Schneider Electric for the implicit permission to reprint some excerpts.

The authors express their gratitude to Prof. Ronald Harley (GeorgiaTech) for his permission to reprint some excerpts in Chapter 2. A stamp on the theory presented in Chapter 2 is also due to Prof. Eugeniu Potolea (University "Politehnica" of Bucharest) to whom the authors would like to address special thanks. Acknowledgments are extended to Prof. Mihaela Morega for recommendations at Chapter 2 and Prof. Florin Alexe for the recommendations at Chapter 3 (both are from University "Politehnica" of Bucharest).

Acknowledgments are addressed also to Prof. Daniel Roye and Prof. Seddik Bacha (INP Grenoble) for granting reprinting permission of some figures in Chapter 4 and for providing valuable recommendations.

In carrying out Chapter 5, Prof. Nicolae Golovanov (University "Politehnica" of Bucharest) has offered his expertise for which the authors would like to address thanks. Valuable ideas have been used in Chapter 5 following the collaboration with Dr. Jay C. Das, a consultant of AMEC Inc.

The authors would like to express their gratitude to Prof. Wilson Xu (University of Alberta) for granting the permission to reprint some excerpts in Chapter 11. Acknowledgments are extended to Dr. Mrinal K. Pal (an independent consultant of MKPalConsulting) for granting the use of some ideas in Chapter 11. Some theories presented in Chapter 11 are the result also following the collaboration with Prof. Thierry Van Cutsem (Université de Liège) and emeritus professor Jacques Trecat (Faculté Polytechnique de Mons).

The authors of Chapter 13 would like to address thanks to Dmitry N. Efimov (Energy Systems Institute of the Russian Academy of Science, Irkutsk) and Dr. Lu Wei, a PhD of INP Grenoble, for their valuable contribution.

Writing a book is a complex work. The authors would like to extend their gratitude to Dr. Mircea Scutariu (Mott McDonald, Glasgow), Dr. Constantin Surdu (EdF France),

Dr. Valentin Ilea, Dr. Ioana Pisică, Dr. Petre Răzuşi, Dr. Florin Cătălin Ionescu and PhD students Cristian Virgil Cristea, Alexandru Mandiş, and Valeriu Iulian Presadă (University "Politehnica" of Bucharest) for their help in drawing figures and editing text and equations.

The authors gratefully acknowledge the excellent collaboration with the IEEE Press and John Wiley & Sons, and address many thanks to Taisuke Soda, Mary Hatcher, Sanchari Sil, and Danielle LaCourciere for their patience and professionalism in carrying out the printed book.

Mircea Eremia
Mohammad Shahidehpour

# CONTRIBUTORS

**Alberto Berizzi**, Dipartimento di Elettrotecnica, Politecnico di Milano, Piazza Leonardo da Vinci, 32, 20133 Milano, Italy

**Yvon Besanger**, INP Grenoble, LEG, 961 rue de la Houille Blanche, 38402 Saint Martin d'Heres, Cedex, France

**Alberto Borghetti**, Department of Electrical Engineering, University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy

**Klaus-Peter Brand**, Power Systems, ABB Switzerland Ltd., 72 Bruggerstrasse, CH-5400 Baden, Switzerland

**Constantin Bulac**, Department of Electrical Power Systems, University "Politehnica" of Bucharest, 313, Spl. Independenţei, 060042 Bucharest, Romania

**Sandro Corsi**, CESI, Via Rubattino 54, 20134 Milano, Italy

**Mircea Eremia**, Department of Electrical Power Systems, University "Politehnica" of Bucharest, 313, Spl. Independenţei, 060042 Bucharest, Romania

**Feng Gao**, Technische Universität Berlin, Einsteinnufer 11 (EMH-1), D-10587 Berlin, Germany

**Nouredine Hadjsaid**, INP Grenoble, LEG, 961 rue de la Houille Blanche, 38402 Saint Martin d'Heres, Cedex, France

**Roberto Marconato**, Dipartimento di Elettrotecnica, Politecnico di Milano, Piazza Leonardo da Vinci, 32, 20133 Milano, Italy

**Ivan De Mesmaeker**, Power Systems, ABB Switzerland Ltd., 72 Bruggerstrasse, CH-5400 Baden, Switzerland

**Carlo Alberto Nucci**, Department of Electrical Engineering, University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy

**Mario Paolone**, Department of Electrical Engineering, University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy

**Les Pereira**, Northern California Power Agency, 180 Cirby Way, Roseville, CA 95678, USA

**Mohammad Shahidehpour**, Electrical and Computer Engineering Department, Illinois Institute of Technology, 3301 South Dearborn Street, Chicago, IL 60616-3793, USA

**Kai Strunz**, Technische Universität Berlin, Einsteinnufer 11 (EMH-1), D-10587 Berlin, Germany

**Lucian Toma**, Department of Electrical Power Systems, University "Politehnica" of Bucharest, 313, Spl. Independenţei, 060042 Bucharest, Romania

**Ion Triştiu**, Department of Electrical Power Systems, University "Politehnica" of Bucharest, 313, Spl. Independenţei, 060042 Bucharest, Romania

**S.S. (Mani) Venkata**, Alstom Grid, 10865 Willows Road, NE, Redmond, WA 98052-2502, USA

**Nikolai Voropai**, Siberian Branch of the Russian Academy of Sciences, Energy Systems Institute, 130 Lermontov Street, Irkutsk 664033, Russia