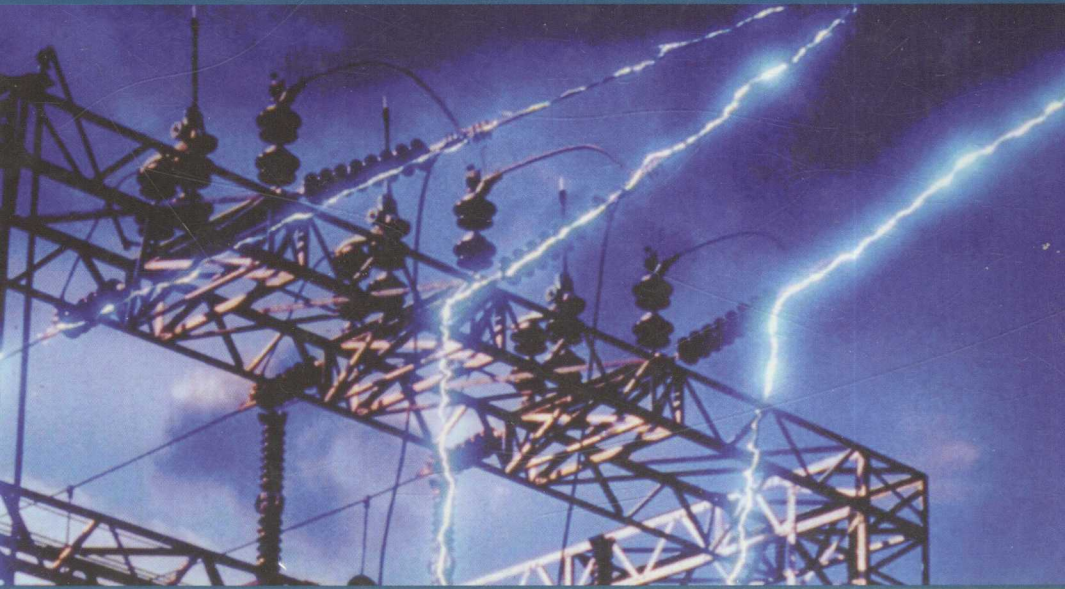


# Electric Power Systems

Edited by Michel Crappe



ISTE

 WILEY

1711  
38

# Electric Power Systems

Edited by  
Michel Crappe



ISTE



E2008001582

 WILEY

First published in France in 2003 by Hermes Science/Lavoisier under the titles "Commande et régulation des réseaux électriques" and "Stabilité et sauvegarde des réseaux électriques"  
First published in Great Britain and the United States in 2008 by ISTE Ltd and John Wiley & Sons, Inc.

Apart from any fair dealing for the purposes of research or private study, or criticism or review, as permitted under the Copyright, Designs and Patents Act 1988, this publication may only be reproduced, stored or transmitted, in any form or by any means, with the prior permission in writing of the publishers, or in the case of reprographic reproduction in accordance with the terms and licenses issued by the CLA. Enquiries concerning reproduction outside these terms should be sent to the publishers at the undermentioned address:

ISTE Ltd  
6 Fitzroy Square  
London W1T 5DX  
UK

John Wiley & Sons, Inc.  
111 River Street  
Hoboken, NJ 07030  
USA

[www.iste.co.uk](http://www.iste.co.uk)

[www.wiley.com](http://www.wiley.com)

© ISTE Ltd, 2008  
© LAVOISIER, 2003

The rights of Michel Crappe to be identified as the author of this work have been asserted by him in accordance with the Copyright, Designs and Patents Act 1988.

---

Library of Congress Cataloging-in-Publication Data

Commande et regulation des reseaux electriques. English.

Electric power systems / edited by Michel Crappe.

p. cm.

Includes bibliographical references and index.

ISBN-13: 978-1-84821-008-0

1. Electric power systems. I. Crappe, Michel. II. Stabilité et sauvegarde des réseaux électriques. English. III. Title.

TK1001.C594 2008

621.319'1--dc22

2007045058

---

British Library Cataloguing-in-Publication Data

A CIP record for this book is available from the British Library

ISBN: 978-1-84821-008-0

---

Printed and bound in Great Britain by Antony Rowe Ltd, Chippenham, Wiltshire.

# Electric Power Systems

# Table of Contents

<b>Preface</b> . . . . .	1
<b>Chapter 1. General Aspects of the Control, Regulation and Security of the Energy Network in Alternating Current</b> . . . . .	5
Noël JANSSENS and Jacques TRECAT	
1.1. Introduction . . . . .	5
1.1.1. History . . . . .	5
1.1.2. Network architecture . . . . .	6
1.2. Power flow calculation and state estimation . . . . .	7
1.2.1. Introduction . . . . .	7
1.2.2. Modeling the components of the network . . . . .	7
1.2.3. Power flow calculation . . . . .	9
1.2.4. State estimation . . . . .	11
1.3. Planning and operation criteria . . . . .	13
1.3.1. Introduction . . . . .	13
1.3.2. Power generation units . . . . .	14
1.3.3. Transmission network . . . . .	15
1.3.4. Electrical power distribution system . . . . .	17
1.4. Frequency and power adjustments . . . . .	18
1.4.1. Objectives and classification of the adjustments . . . . .	18
1.4.2. Primary regulation . . . . .	20
1.4.3. Secondary regulation . . . . .	22
1.4.4. Tertiary regulation . . . . .	23
1.4.5. Generating unit schedule . . . . .	24
1.4.6. Load management . . . . .	25
1.5. Voltage regulation . . . . .	25
1.5.1. Case of short lines . . . . .	26

1.5.2. Case of the line with capacity. . . . . 28  
 1.5.3. Traditional methods of reactive energy compensation  
 and voltage regulation . . . . . 31  
 1.6. Bibliography . . . . . 35

**Chapter 2. Evolution of European Electric Power Systems in the Face  
 of New Constraints: Impact of Decentralized Generation . . . . . 37**

Michel CRAPPE

2.1. Introduction: a new paradigm . . . . . 37  
 2.2. Structure of modern electric transmission and distribution networks . . 38  
     2.2.1. Modern transmission networks. . . . . 38  
     2.2.2. Electrical distribution networks . . . . . 42  
 2.3. Recent development in the European networks and new constraints . . 43  
     2.3.1. Deregulation of the electricity market in accordance  
     with European directives . . . . . 44  
     2.3.2. Reducing greenhouse gas emissions in the generation  
     of electrical energy. . . . . 45  
     2.3.3. Generation of electricity using renewable energy sources . . . . . 46  
     2.3.4. Energy dependency of the European Union . . . . . 46  
 2.4. The specific characteristics of electrical energy . . . . . 47  
     2.4.1. Storage and production/consumption balance . . . . . 48  
     2.4.2. Laws of physics on flow of energy . . . . . 49  
     2.4.3. Strategic role of electrical energy . . . . . 51  
     2.4.4. Voltage regulation in the electrical transmission  
     and distribution networks . . . . . 51  
     2.4.5. Ancillary services. . . . . 52  
 2.5. Decentralized power generation. . . . . 52  
     2.5.1. Definition . . . . . 52  
     2.5.2. Decentralized power generation techniques in Europe,  
     potential and costs . . . . . 54  
     2.5.3. Decentralized power generation and CO<sub>2</sub> emissions,  
     indirect emissions from so-called “zero emission” power plants . . . . . 72  
     2.5.4. Decentralized production and ancillary services. . . . . 74  
 2.6. Specific problems in integrating decentralized production  
 in the networks . . . . . 78  
     2.6.1. Connection conditions . . . . . 78  
     2.6.2. Influence on the design of the HV/MV stations . . . . . 79  
     2.6.3. Influence on the protection of the distribution networks . . . . . 80  
     2.6.4. Stability problems . . . . . 82  
     2.6.5. Influence on the voltage plan . . . . . 83  
     2.6.6. Impacts on transmission networks . . . . . 85

2.6.7. Harmonic disturbances . . . . .	86
2.7. New requirements in research and development . . . . .	86
2.7.1. Technical domain . . . . .	87
2.7.2. Economics . . . . .	91
2.8. Conclusion: a challenge and an opportunity for development for the electrical sector . . . . .	92
2.9. Bibliography . . . . .	92

### **Chapter 3. Planning Methods for Generation and Transmission**

<b>of Electrical Energy</b> . . . . .	95
Jean-Marie DELINCÉ	

3.1. Introduction . . . . .	95
3.1.1. Generation functions . . . . .	96
3.1.2. Functions of a transmission network . . . . .	96
3.2. Planning in integrated systems and in a regulated market . . . . .	97
3.2.1. Generation planning . . . . .	98
3.2.2. Transmission network planning . . . . .	103
3.3. Generation planning in a deregulated market . . . . .	111
3.4. Establishing a development plan of the transmission network . . . . .	114
3.4.1. Reasons for investment . . . . .	114
3.4.2. Constraints and uncertainties . . . . .	115
3.4.3. Planning criteria . . . . .	118
3.4.4. Elaboration of the development plan . . . . .	121
3.5. Final observations . . . . .	125
3.6. Bibliography . . . . .	125

<b>Chapter 4. Power Quality</b> . . . . .	127
---	-----

Alain ROBERT

4.1. Introduction . . . . .	127
4.1.1. Disturbances and power quality . . . . .	127
4.1.2. Quality of electricity supply and electromagnetic compatibility (EMC). . . . .	128
4.2. Degradation of the voltage quality – disturbance phenomena . . . . .	130
4.2.1. Frequency variations . . . . .	130
4.2.2. Slow component of voltage variations . . . . .	131
4.2.3. Voltage fluctuations – flicker . . . . .	131
4.2.4. Voltage dips . . . . .	131
4.2.5. Transients . . . . .	132
4.2.6. Harmonics and interharmonics . . . . .	134
4.2.7. Unbalance . . . . .	135

4.2.8. Overall view of the disturbance phenomena . . . . .	135
4.3. Basic concepts of standardization. . . . .	136
4.4. Quality indices . . . . .	139
4.4.1. Voltage continuity . . . . .	139
4.4.2. Voltage quality . . . . .	143
4.5. Evaluation of quality . . . . .	146
4.5.1. Voltage continuity . . . . .	146
4.5.2. Voltage quality . . . . .	147
4.6. Connection of the disturbance facilities . . . . .	148
4.6.1. Definition of the emission level of a disturbance facility . . . . .	148
4.6.2. Concept of short circuit power . . . . .	149
4.6.3. Determining the emission limits of a disturbance facility . . . . .	151
4.6.4. Verification of the emission limits after commissioning . . . . .	153
4.7. Controlling power quality . . . . .	154
4.7.1. Voltage continuity . . . . .	154
4.7.2. Voltage quality . . . . .	156
4.8. Quality in a competitive market – role of the regulators . . . . .	156
4.9. Bibliography . . . . .	158

**Chapter 5. Applications of Synchronized Phasor Measurements to Large Interconnected Electric Power Systems . . . . .** 161  
 Nouredine HADJSAID, Didier GEORGES and Aaron F. SNYDER

5.1. Introduction. . . . .	161
5.2. Synchronized measurements. . . . .	162
5.3. Applications of synchronized measurements . . . . .	164
5.3.1. State estimation . . . . .	164
5.3.2. Network supervision . . . . .	165
5.3.3. Power system protection. . . . .	166
5.3.4. Power system control . . . . .	166
5.4. Application of synchronized measurements to damp power oscillations. . . . .	167
5.4.1. Power oscillations . . . . .	167
5.4.2. Theory of PSS controllers. . . . .	171
5.4.3. Controller tuning by residue compensation. . . . .	172
5.4.4. Results . . . . .	176
5.5. Conclusion . . . . .	179
5.6. Bibliography . . . . .	179
5.7. Appendices . . . . .	182



<b>Chapter 6. Voltage Instability</b> . . . . .	185
Thierry VAN CUTSEM	
6.1. Introduction . . . . .	185
6.2. Voltage instability phenomena . . . . .	187
6.2.1. Maximum deliverable power for a load . . . . .	187
6.2.2. PV and QV curves . . . . .	188
6.2.3. Long-term voltage instability illustrated through a simple example . . . . .	189
6.2.4. Load restoration . . . . .	194
6.2.5. Classification of instabilities . . . . .	196
6.3. Countermeasures for voltage instability . . . . .	199
6.3.1. Compensation . . . . .	199
6.3.2. Automatic devices and regulators . . . . .	199
6.3.3. Operation planning . . . . .	201
6.3.4. Real time . . . . .	201
6.3.5. System protection schemes . . . . .	201
6.4. Analysis methods of voltage stability and security . . . . .	204
6.4.1. Contingency analysis . . . . .	204
6.4.2. Determination of loadability limits . . . . .	208
6.4.3. Determination of secure operation limits . . . . .	210
6.4.4. Preventive control . . . . .	213
6.5. Conclusion . . . . .	214
6.6. Bibliography . . . . .	215
<b>Chapter 7. Transient Stability: Assessment and Control</b> . . . . .	219
Daniel RUIZ-VEGA and Mania PAVELLA	
7.1. Introduction . . . . .	219
7.2. Transient stability . . . . .	220
7.2.1. Problem statement . . . . .	220
7.2.2. Operating procedures . . . . .	221
7.2.3. Deregulation of the electricity sector . . . . .	223
7.3. Transient stability assessment methods: brief history . . . . .	224
7.3.1. Conventional time domain approach: strengths and weaknesses . . . . .	224
7.3.2. Direct approaches: a brief history . . . . .	226
7.3.3. Note on automatic learning approaches . . . . .	228
7.4. The SIME method . . . . .	229
7.4.1. Origins . . . . .	229
7.4.2. Formulation . . . . .	230
7.4.3. Preventive SIME vs emergency SIME . . . . .	235
7.5. Different descriptions of transient stability phenomena . . . . .	236
7.6. The preventive SIME method . . . . .	240

7.6.1. Stability limits . . . . .	241
7.6.2. FILTRA: generic software for contingency filtering . . . . .	243
7.6.3. Stabilization of contingencies (“control”) . . . . .	245
7.6.4. Transient stability assessment and control: integrated software and example of application . . . . .	247
7.6.5. Current status of the preventive SIME . . . . .	252
7.7. Emergency SIME method . . . . .	252
7.7.1. Aims . . . . .	252
7.7.2. Origins . . . . .	253
7.7.3. Estimation of time taken by the different tasks . . . . .	256
7.7.4. Illustration . . . . .	256
7.7.5. Note on corrective control in open loop. . . . .	258
7.7.6. Conclusion . . . . .	259
7.8. Bibliography . . . . .	260

**Chapter 8. Security of Large Electric Power Systems – Defense Plans –  
Numerical Simulation of Electromechanical Transients . . . . .** 263  
 Marc STUBBE and Jacques DEUSE

8.1. Introduction. . . . .	263
8.2. Degradation mechanisms of network operation . . . . .	264
8.2.1. The system. . . . .	264
8.2.2. Continuity of supply . . . . .	267
8.2.3. Degradation mechanisms . . . . .	270
8.2.4. Unfavorable factors causing spread of the incident . . . . .	275
8.3. Defense action and the notion of a defense plan . . . . .	277
8.3.1. Frequency instability . . . . .	277
8.3.2. Voltage instability . . . . .	280
8.3.3. Loss of synchronism . . . . .	281
8.3.4. Cascade tripping . . . . .	281
8.3.5. Notion of defense plan. . . . .	282
8.4. The extended electromechanical model . . . . .	282
8.4.1. Definition, validity domain . . . . .	282
8.4.2. Numerical simulation . . . . .	284
8.4.3. Mathematic properties . . . . .	285
8.4.4. Algorithmic properties . . . . .	285
8.5. Examples of defense action study. . . . .	292
8.5.1. Methodological considerations . . . . .	292
8.5.2. Load shedding due to voltage criteria [DEU 97] . . . . .	293
8.5.3. Islanding plan in case of loss of synchronism . . . . .	304
8.5.4. Industrial networks . . . . .	306
8.6. Future prospects . . . . .	310

8.6.1. Evolution of simulation tools . . . . .	313
8.6.2. Real-time curative action . . . . .	313
8.6.3. Load actions . . . . .	314
8.6.4. Decentralized production . . . . .	315
8.7. Bibliography . . . . .	315

**Chapter 9. System Control by Power Electronics or Flexible Alternating Current Transmission Systems . . . . .** 317  
 Michel CRAPPE and Stéphanie DUPUIS

9.1. Introduction: direct current links and FACTS . . . . .	317
9.2. General concepts of power transfer control . . . . .	319
9.2.1. Introduction . . . . .	319
9.2.2. Power transmission through reactance . . . . .	320
9.2.3. Modification of reactance in link X . . . . .	322
9.2.4. Modification of voltage and the segmentation method . . . . .	324
9.2.5. Modification of the transmission angle . . . . .	325
9.2.6. Comparison of three methods in a simple case . . . . .	325
9.3. Control of power transits in the networks . . . . .	326
9.3.1. Circulation of power in a meshed network: power loop concept . . . . .	326
9.3.2. Modification of transits on parallel lines of a corridor . . . . .	329
9.4. Classification of control systems according to the connection mode in the network . . . . .	330
9.4.1. Series type controller . . . . .	330
9.4.2. Parallel or shunt type controller . . . . .	331
9.4.3. Compensators of series-series and series-shunt types . . . . .	332
9.5. Improvement of alternator transient stability . . . . .	333
9.5.1. Introduction to transient stability . . . . .	333
9.5.2. Simplified study of transient stability by area criterion . . . . .	334
9.5.3. Study of an application case . . . . .	337
9.5.4. Improvement of transient stability by ideal shunt compensation . . . . .	339
9.5.5. SVC type shunt compensator . . . . .	341
9.5.6. Shunt compensation with SVG (static var generator) compensator . . . . .	343
9.5.7. Series type compensation by modification of link reactance . . . . .	344
9.5.8. Series type compensation by modification of the transmission angle . . . . .	345
9.6. Damping of oscillations . . . . .	346
9.7. Maintaining the voltage plan . . . . .	346
9.8. Classification and existing applications of FACTS . . . . .	347
9.8.1. Classic systems with thyristors . . . . .	347
9.8.2. Systems with fully controllable elements . . . . .	353
9.8.3. Glossary . . . . .	359

9.9. Control and protection of FACTS . . . . .	360
9.10. Modeling and numerical simulation. . . . .	362
9.10.1. UPFC modeled by two voltage sources . . . . .	362
9.10.2. UPFC modeled by a series voltage source and a shunt current source . . . . .	363
9.10.3. UPFC modeled by two current sources . . . . .	364
9.10.4. UPFC modeled by two power injections . . . . .	365
9.10.5. Internal models of the UPFC . . . . .	366
9.11. Future prospects . . . . .	367
9.12. Bibliography . . . . .	368
<b>List of authors . . . . .</b>	<b>371</b>
<b>Index . . . . .</b>	<b>373</b>

## Preface

This book, which deals with electric transmission systems, is the English translation of two books written in French and published in 2003 by Hermes Science Publications (*Commande et Régulation des Réseaux Electriques, Stabilité et Sauvegarde des Réseaux Electriques*) in the electrical engineering series of the *Traité EGEM* (series in electronics and electric engineering and micro-electronics). It consists of two parts, corresponding to the two books in question. The first deals with the control, regulation and security of large scale electric power networks and the second with the stability and safety of the systems. The two parts include 5 and 4 chapters respectively, written by renowned experts from the industrial world or from universities. Its aim is to present the state of the art in the concerned domains as well as future prospects, especially in the fields of research and development. It is aimed at specialists, scientists and people involved in research in the electricity sector; it presupposes thorough knowledge of the basic concepts of electrical engineering. It has not been possible to cover all the problems related to the subject in an exhaustive manner in a single book. The subjects discussed in this collective work are the result of a choice made by the editor and based on his experience in research and teaching.

If some repetitions have occurred, they show the different approaches and attitudes towards essential phenomena and have been deliberately maintained with a pedagogical aim in mind and to reinforce the perception of sensitive issues. Moreover, it also makes it possible for each chapter to be read independently of the others. Different solutions are sometimes suggested to resolve some problems, which proves that the field is wide open and a lot of research and development remains to be carried out.

Electricity is an energy carrier that is indispensable to human activities in developed countries, and is an essential factor in development for poorer countries. Electric transmission systems are key elements in ensuring a reliable supply of good

quality electric power. The introduction of new generation systems or management methods of electric power must, as a result, be the subject of in-depth study to ensure compatibility with sure and reliable functioning of transmission networks. The recent changes in electric transmission systems and new constraints in the electric power sector in Europe have particularly complicated matters. The new paradigm in the field of development and management of the electric power sector, due to the recent restructuring of the latter on the application of European Directives to organize the electricity market in Europe, appears if not explicitly then at least in a subtle manner in most of the chapters. At present, the setting up of the European market for electric power, concomitant with environmental constraints, is proving to be much more difficult than expected by its protagonists and is presenting numerous challenges, which can only be removed at the cost of significant efforts in research and development. Moreover, recent major blackouts that have occurred in Europe in a number of countries (Sweden, Denmark, Switzerland, Italy and Greece) and the blackout of 4 November 2006 have reminded us that the stability and the collapse of electric systems are problems that are very real and not purely academic. The blackout of 4 November is particular affected several millions of Europeans for several minutes to an hour, and moreover led 200 million people to be at risk of being deprived of electricity for several hours, even several days. The current situation therefore considerably reinforces the value of books on electric power transmission networks, such as this one.

In the first part, the book focuses on fundamental aspects of electric power systems, the evolution of European transmission networks in the face of new regulations, the impact of decentralized production, generation and transmission planning, quality of the electric power supply and finally advanced control methods.

The second part deals with voltage stability, transient stability, the defense plan, electromechanical aspects of digital simulation and finally power electronics to enhance controllability, stability and power transfer capability of large transmission networks. It naturally completes the first part.

If this book could guide the reader towards research and development in the field of electric power systems, it would amply fulfill its aim.

Sincere gratitude once again to the different authors and all the people who have contributed from near or far to the publication of these two books in French, especially Olivier Deblecker of the Faculté Polytechnique de Mons (Faculty of Engineering, Mons) for his help in the formatting of the different contributions. I especially thank the editor of ISTE/Hermes Science for having decided on the publication of the two books in English and for having ensured its translation.

Michel CRAPPE  
Professor Emeritus of the Faculté Polytechnique de Mons  
(Faculty of Engineering, Mons)





## Chapter 1

# General Aspects of the Control, Regulation and Security of the Energy Network in Alternating Current

### 1.1. Introduction

#### 1.1.1. *History*

Though Edison managed to distribute electricity through direct current (at 110 V) for lighting for the first time in 1882 and the first long distance transmission was achieved in 1882 between Miesbach and Munich (57 km, 2,000 V), it soon became clear that long distance transmission needed a higher voltage if the volume of copper was to be kept low (Deprez in 1881) and thus should use alternating current and a transformer, whose principle was patented by Gaulard and Gibbs in 1881. Three phase generators have a simpler design concept and easier current breaking facility than that of direct current machines. In 1891, a power plant on the Neckar in Lauffen was linked to Frankfurt (a distance of 176 km) through a 15 kV alternating current line. Around 1920, with Europe standardizing its frequency at 50 Hz and suspended insulators coming into the picture, the voltage was raised to 132 kV. In the beginning, the distance between the hydroelectric power plants and the cities was the main reason for this long distance transmission. With the development of thermal power plants it became obvious that there existed a complementarity between these different modes of production giving rise to a better use of resources through interconnections within a country as well as between neighboring countries. As a result international connections