

SECOND EDITION

MODERN POWER SYSTEM ANALYSIS

TURAN GÖNEN



CRC Press
Taylor & Francis Group

SECOND EDITION

**MODERN
POWER
SYSTEM
ANALYSIS**

TURAN GÖNEN



CRC Press

Taylor & Francis Group

Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an *informa* business

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.

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2013 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

Printed in the United States of America by Edwards Brothers Malloy, Lillington, NC 27546
Version Date: 20130111

International Standard Book Number-13: 978-1-4665-7081-8 (Hardback)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Visit the Taylor & Francis Web site at
<http://www.taylorandfrancis.com>

and the CRC Press Web site at
<http://www.crcpress.com>

Contents

Preface.....	xiii
Acknowledgments.....	xv
Author	xvii
Chapter 1 General Considerations	1
1.1 Introduction	1
1.2 Power System Planning	5
References	10
General References.....	11
Chapter 2 Basic Concepts	13
2.1 Introduction	13
2.2 Complex Power in Balanced Transmission Lines	13
2.3 One-Line Diagram	16
2.4 Per-Unit System.....	19
2.4.1 Single-Phase System	20
2.4.2 Converting from Per-Unit Values to Physical Values.....	24
2.4.3 Change of Base.....	24
2.4.4 Three-Phase Systems	25
2.5 Constant Impedance Representation of Loads.....	38
2.6 Three-Winding Transformers.....	40
2.7 Autotransformers.....	41
2.8 Delta–Wye and Wye–Delta Transformations	43
2.9 Short-Circuit MVA and Equivalent Impedance	44
2.9.1 Three-Phase Short-Circuit MVA	45
2.9.1.1 If Three-Phase Short-Circuit MVA Is Already Known	45
2.9.2 Single-Phase-to-Ground Short-Circuit MVA.....	46
2.9.2.1 If Single-Phase Short-Circuit MVA Is Already Known....	46
References	48
General References.....	48
Chapter 3 Steady-State Performance of Transmission Lines	51
3.1 Introduction	51
3.2 Conductor Size	51
3.3 Transmission Line Constants	58
3.4 Resistance	58
3.5 Inductance and Inductive Reactance.....	59
3.5.1 Single-Phase Overhead Lines.....	59
3.5.2 Three-Phase Overhead Lines	60
3.6 Capacitance and Capacitive Reactance	61
3.6.1 Single-Phase Overhead Lines.....	61
3.6.2 Three-Phase Overhead Lines	64

3.7	Tables of Line Constants	65
3.8	Equivalent Circuits for Transmission Lines	68
3.9	Transmission Lines.....	68
3.9.1	Short Transmission Lines (up to 50 mi or 80 km).....	68
3.9.2	Steady-State Power Limit.....	71
3.9.3	Percent Voltage Regulation	73
3.9.4	Representation of Mutual Impedance of Short Lines	79
3.10	Medium-Length Transmission Lines (up to 150 mi or 240 km).....	80
3.11	Long Transmission Lines (above 150 mi or 240 km).....	90
3.11.1	Equivalent Circuit of Long Transmission Line.....	100
3.11.2	Incident and Reflected Voltages of Long Transmission Line.....	103
3.11.3	Surge Impedance Loading of Transmission Line	107
3.12	General Circuit Constants	110
3.12.1	Determination of A, B, C, and D Constants	111
3.12.2	Measurement of ABCD Parameters by Test	112
3.12.3	A, B, C, and D Constants of Transformer.....	116
3.12.4	Asymmetrical π and T Networks	117
3.12.5	Networks Connected in Series	119
3.12.6	Networks Connected in Parallel.....	121
3.12.7	Terminated Transmission Line.....	123
3.12.8	Power Relations Using A, B, C, and D Line Constants	127
3.13	EHV Underground Cable Transmission.....	134
3.14	Gas-Insulated Transmission Lines	142
3.15	Bundled Conductors	147
3.16	Effect of Ground on Capacitance of Three-Phase Lines.....	151
3.17	Environmental Effects of Overhead Transmission Lines.....	152
	References	153
	General References.....	153
Chapter 4	Disturbance of Normal Operating Conditions and Other Problems.....	159
4.1	Introduction	159
4.2	Fault Analysis and Fault Types.....	161
4.3	Balanced Three-Phase Faults at No Load.....	164
4.4	Fault Interruption.....	168
4.5	Balanced Three-Phase Faults at Full Load	175
4.6	Application of Current-Limiting Reactors	181
4.7	Insulators	185
4.7.1	Types of Insulators	185
4.7.2	Testing of Insulators	187
4.7.3	Voltage Distribution over a String of Suspension Insulators	189
4.7.4	Insulator Flashover due to Contamination	194
4.7.5	Insulator Flashover on Overhead High-Voltage DC Lines.....	196
4.8	Grounding.....	197
4.8.1	Electric Shock and Its Effects on Humans.....	197
4.8.2	Reduction of Factor C_g	204
4.8.3	GPR and Ground Resistance.....	206
4.8.4	Ground Resistance	207
4.8.5	Soil Resistivity Measurements	209
4.8.5.1	Wenner Four-Pin Method	209
4.8.5.2	Three-Pin or Driven-Ground Rod Method.....	213

4.9	Substation Grounding.....	214
4.10	Ground Conductor Sizing Factors.....	218
4.11	Mesh Voltage Design Calculations.....	221
4.12	Step Voltage Design Calculations.....	223
4.13	Types of Ground Faults.....	223
4.13.1	Line-to-Line-to-Ground Fault.....	223
4.13.2	Single-Line-to-Ground Fault.....	224
4.14	Ground Potential Rise.....	224
4.15	Transmission Line Grounds.....	233
4.16	Types of Grounding.....	235
	References.....	238
	General References.....	239
Chapter 5	Symmetrical Components and Sequence Impedances.....	245
5.1	Introduction.....	245
5.2	Symmetrical Components.....	245
5.3	Operator a	247
5.4	Resolution of Three-Phase Unbalanced System of Phasors into Its Symmetrical Components.....	248
5.5	Power in Symmetrical Components.....	252
5.6	Sequence Impedances of Transmission Lines.....	255
5.6.1	Sequence Impedances of Untransposed Lines.....	255
5.6.2	Sequence Impedances of Transposed Lines.....	257
5.6.3	Electromagnetic Unbalances due to Untransposed Lines.....	260
5.6.4	Sequence Impedances of Untransposed Line with Overhead Ground Wire.....	267
5.7	Sequence Capacitances of Transmission Line.....	268
5.7.1	Three-Phase Transmission Line without Overhead Ground Wire.....	268
5.7.2	Three-Phase Transmission Line with Overhead Ground Wire.....	271
5.8	Sequence Impedances of Synchronous Machines.....	275
5.9	Zero-Sequence Networks.....	280
5.10	Sequence Impedances of Transformers.....	281
	References.....	288
	General References.....	288
Chapter 6	Analysis of Unbalanced Faults.....	293
6.1	Introduction.....	293
6.2	Shunt Faults.....	293
6.2.1	SLG Fault.....	293
6.2.2	Line-to-Line Fault.....	302
6.2.3	DLG Fault.....	307
6.2.4	Symmetrical Three-Phase Faults.....	312
6.2.5	Unsymmetrical Three-Phase Faults.....	317
6.3	Generalized Fault Diagrams for Shunt Faults.....	323
6.4	Series Faults.....	329
6.4.1	One Line Open.....	330
6.4.2	Two Lines Open.....	330
6.5	Determination of Sequence Network Equivalents for Series Faults.....	332
6.5.1	Brief Review of Two-Port Theory.....	332

6.5.2	Equivalent Zero-Sequence Networks.....	333
6.5.3	Equivalent Positive- and Negative-Sequence Networks	334
6.6	Generalized Fault Diagram for Series Faults	339
6.7	System Grounding	343
6.8	Elimination of SLG Fault Current by Using Peterson Coils	349
6.9	Six-Phase Systems	352
6.9.1	Application of Symmetrical Components.....	353
6.9.2	Transformations.....	353
6.9.3	Electromagnetic Unbalance Factors.....	355
6.9.4	Transposition on the Six-Phase Lines	357
6.9.5	Phase Arrangements.....	358
6.9.6	Overhead Ground Wires	358
6.9.7	Double-Circuit Transmission Lines	358
	References	361
	General References.....	361
Chapter 7	System Protection.....	373
7.1	Introduction	373
7.2	Basic Definitions and Standard Device Numbers	377
7.3	Factors Affecting Protective System Design.....	380
7.4	Design Criteria for Protective Systems	380
7.5	Primary and Backup Protection	382
7.6	Relays.....	385
7.7	Sequence Filters.....	394
7.8	Instrument Transformers	396
7.8.1	Current Transformers	397
7.8.1.1	Method 1. The Formula Method.....	400
7.8.1.2	Method 2. The Saturation Curve Method.....	401
7.8.2	Voltage Transformers	402
7.9	$R-X$ Diagram	403
7.10	Relays as Comparators	409
7.11	Duality between Phase and Amplitude Comparators	409
7.12	Complex Planes	410
7.13	General Equation of Comparators.....	412
7.14	Amplitude Comparator.....	413
7.15	Phase Comparator.....	414
7.16	General Equation of Relays	418
7.17	Distance Relays	419
7.17.1	Impedance Relay	422
7.17.2	Reactance Relay	427
7.17.3	Admittance (Mho) Relay	429
7.17.4	Offset Mho (Modified Impedance) Relay	431
7.17.5	Ohm Relay.....	433
7.18	Overcurrent Relays	439
7.19	Differential Protection.....	450
7.20	Pilot Relaying	459
7.21	Computer Applications in Protective Relaying	462
7.21.1	Computer Applications in Relay Settings and Coordination	462
7.21.2	Computer Relaying.....	462

References	464
General References.....	465
Chapter 8 Power Flow Analysis.....	471
8.1 Introduction	471
8.2 Power Flow Problem.....	473
8.3 Sign of Real and Reactive Powers	475
8.4 Gauss Iterative Method.....	476
8.5 Gauss–Seidel Iterative Method.....	477
8.6 Application of Gauss–Seidel Method: \mathbf{Y}_{bus}	478
8.7 Application of Acceleration Factors	482
8.8 Special Features.....	482
8.8.1 LTC Transformers	483
8.8.2 Phase-Shifting Transformers.....	483
8.8.3 Area Power Interchange Control	484
8.9 Application of Gauss–Seidel Method: \mathbf{Z}_{bus}	488
8.10 Newton–Raphson Method.....	489
8.11 Application of Newton–Raphson Method.....	493
8.11.1 Application of Newton–Raphson Method to Load Flow Equations in Rectangular Coordinates.....	493
8.11.2 Application of Newton–Raphson Method to Load Flow Equations in Polar Coordinates.....	504
8.11.2.1 Method 1. First Type of Formulation of Jacobian Matrix	505
8.11.2.2 Method 2. Second Type of Formulation of Jacobian Matrix	509
8.12 Decoupled Power Flow Method	510
8.13 Fast Decoupled Power Flow Method.....	511
8.14 The DC Power Flow Method.....	513
References	525
General References.....	527
Appendix A: Impedance Tables for Overhead Lines, Transformers, and Underground Cables	533
Appendix B: Standard Device Numbers Used in Protection Systems	621
Appendix C: Unit Conversions from English System to SI System	623
Appendix D: Unit Conversions from SI System to English System	625
Appendix E: Prefixes	627
Appendix F: Greek Alphabet Used for Symbols	629
Appendix G: Additional Solved Examples of Shunt Faults	631
Appendix H: Additional Solved Examples of Shunt Faults Using MATLAB.....	655
Appendix I: Glossary for Modern Power System Analysis Terminology.....	683
Index.....	705