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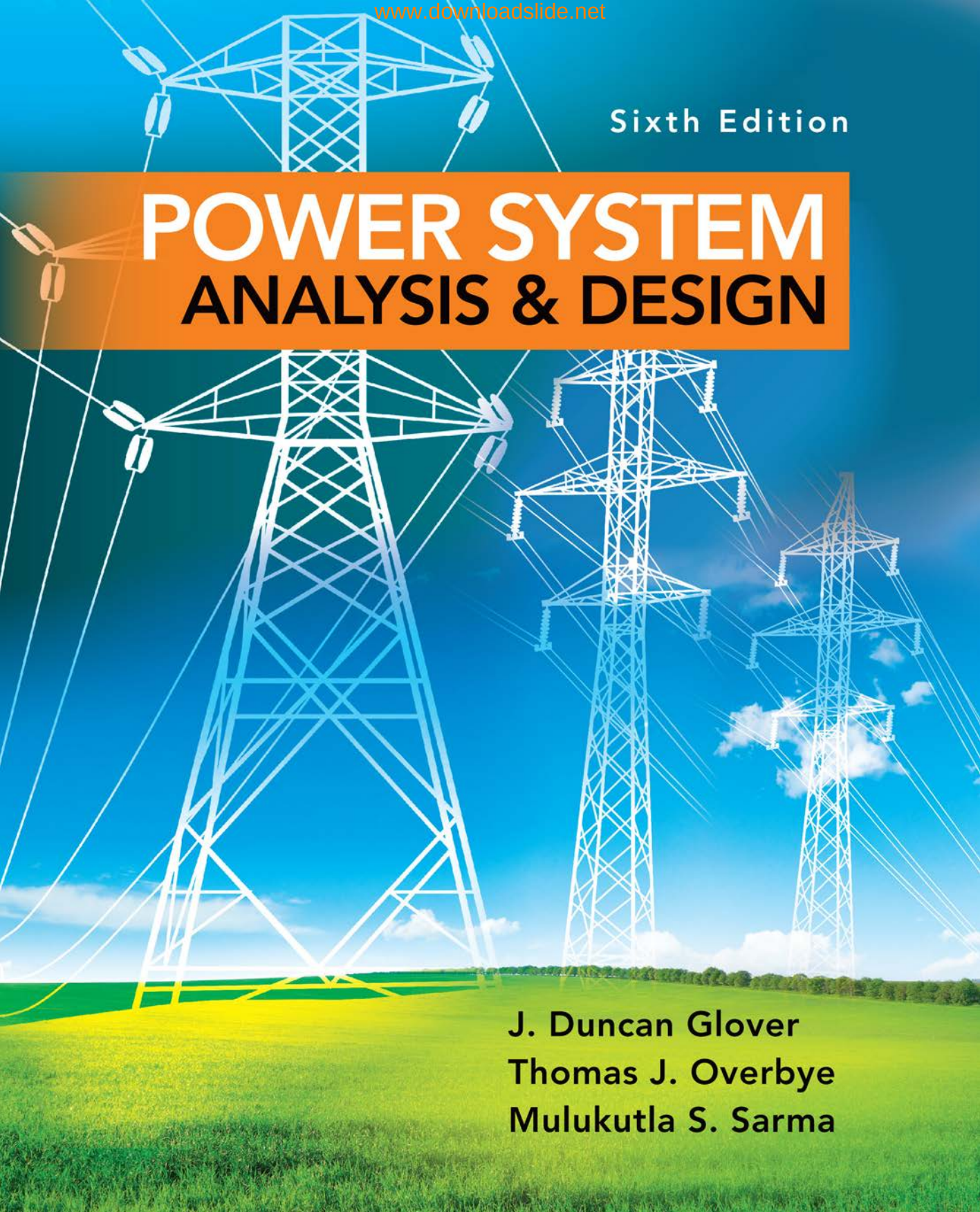

Sixth Edition

POWER SYSTEM ANALYSIS & DESIGN

J. Duncan Glover
Thomas J. Overbye
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POWER SYSTEM ANALYSIS & DESIGN

SIXTH EDITION

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In loving memory of my mentors Professor Fred C. Schweppe [1933–1988] and Dr. Alexander Kusko [1921–2013]. You taught me, you guided me, you set the bar for which I continue to strive. You shall not be forgotten.

My Guardian Poet[s]

A guardian poet you have been to me
Much like an angel, there protecting me
When I was silent, lost in dark of night
You read my words and brought me back to light

You told me that my words were ever true
That in my writes were thoughts profound and new
You would not let me simply drift away
A word of hope you'd send to greet each day

Your name is there below each thing I write
To tear dimmed eyes you brought a vision bright
"The Queen of Passion," how I love the name
You gave to me and life is not the same

To you, my Guardian Poet, thanks I bring
You fool me not; I see your angel wing

Eileen Manassian Ghali

To Jo, Tim, Hannah, and Amanda

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Contents

Preface xi
List of Symbols, Units, and Notation xvii

CHAPTER 1 Introduction 1

Case Study: How the Free Market Rocked the Grid 2
1.1 History of Electric Power Systems 10
1.2 Present and Future Trends 17
1.3 Electric Utility Industry Structure 20
1.4 Computers in Power System Engineering 21
1.5 PowerWorld Simulator 22

CHAPTER 2 Fundamentals 31

Case Study: Key Connections 32
2.1 Phasors 40
2.2 Instantaneous Power in Single-Phase AC Circuits 42
2.3 Complex Power 47
2.4 Network Equations 52
2.5 Balanced Three-Phase Circuits 55
2.6 Power in Balanced Three-Phase Circuits 63
2.7 Advantages of Balanced Three-Phase versus Single-Phase Systems 68

CHAPTER 3 Power Transformers 87

Case Study: Power Transformers—Life Management and Extension 88
3.1 The Ideal Transformer 95
3.2 Equivalent Circuits for Practical Transformers 101

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3.3 The Per-Unit System 107
3.4 Three-Phase Transformer Connections and Phase Shift 115
3.5 Per-Unit Equivalent Circuits of Balanced Three-Phase Two-Winding Transformers 120
3.6 Three-Winding Transformers 125
3.7 Autotransformers 129
3.8 Transformers with Off-Nominal Turns Ratios 131

CHAPTER 4 Transmission Line Parameters 161

Case Study: Integrating North America's Power Grid 162
Case Study: Grid Congestion - Unclogging the Arteries of North America's Power Grid 167
4.1 Transmission Line Design Considerations 173
4.2 Resistance 178
4.3 Conductance 181
4.4 Inductance: Solid Cylindrical Conductor 181
4.5 Inductance: Single-Phase Two-Wire Line and Three-Phase Three-Wire Line with Equal Phase Spacing 186
4.6 Inductance: Composite Conductors, Unequal Phase Spacing, Bundled Conductors 188
4.7 Series Impedances: Three-Phase Line with Neutral Conductors and Earth Return 196
4.8 Electric Field and Voltage: Solid Cylindrical Conductor 201
4.9 Capacitance: Single-Phase Two-Wire Line and Three-Phase Three-Wire Line with Equal Phase Spacing 204
4.10 Capacitance: Stranded Conductors, Unequal Phase Spacing, Bundled Conductors 206
4.11 Shunt Admittances: Lines with Neutral Conductors and Earth Return 210
4.12 Electric Field Strength at Conductor Surfaces and at Ground Level 215
4.13 Parallel Circuit Three-Phase Lines 218

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CHAPTER 5 Transmission Lines: Steady-State Operation 237

Case Study: The ABCs of HVDC Transmission Technologies: An Overview of High Voltage Direct Current Systems and Applications 238

5.1 Medium and Short Line Approximations 258

5.2 Transmission-Line Differential Equations 265

5.3 Equivalent π Circuit 271

5.4 Lossless Lines 274

5.5 Maximum Power Flow 282

5.6 Line Loadability 284

5.7 Reactive Compensation Techniques 289

CHAPTER 6 Power Flows 309

Case Study: Finding Flexibility—Cycling the Conventional Fleet 310

6.1 Direct Solutions to Linear Algebraic Equations: Gauss Elimination 330

6.2 Iterative Solutions to Linear Algebraic Equations: Jacobi and Gauss-Seidel 334

6.3 Iterative Solutions to Nonlinear Algebraic Equations: Newton-Raphson 340

6.4 The Power Flow Problem 345

6.5 Power Flow Solution by Gauss-Seidel 351

6.6 Power Flow Solution by Newton-Raphson 353

6.7 Control of Power Flow 363

6.8 Sparsity Techniques 369

6.9 Fast Decoupled Power Flow 372

6.10 The "DC" Power Flow 372

6.11 Power Flow Modeling of Wind Generation 374

6.12 Economic Dispatch 376

6.13 Optimal Power Flow 389

Design Projects 1–3 404–412

CHAPTER 7 Symmetrical Faults 415

Case Study: Short-Circuit Modeling of a Wind Power Plant 416

7.1 Series R–L Circuit Transients 435

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7.2 Three-Phase Short Circuit—Unloaded Synchronous Machine 438
7.3 Power System Three-Phase Short Circuits 442
7.4 Bus Impedance Matrix 445
7.5 Circuit Breaker and Fuse Selection 455
Design Project 3 (*continued*) 472

CHAPTER 8 Symmetrical Components 475

Case Study: Technological Progress in High-Voltage Gas-Insulated Substations 476
8.1 Definition of Symmetrical Components 493
8.2 Sequence Networks of Impedance Loads 499
8.3 Sequence Networks of Series Impedances 506
8.4 Sequence Networks of Three-Phase Lines 508
8.5 Sequence Networks of Rotating Machines 510
8.6 Per-Unit Sequence Models of Three-Phase Two-Winding Transformers 516
8.7 Per-Unit Sequence Models of Three-Phase Three-Winding Transformers 522
8.8 Power in Sequence Networks 524

CHAPTER 9 Unsymmetrical Faults 539

Case Study: Innovative Medium Voltage Switchgear for Today's Applications 540
9.1 System Representation 547
9.2 Single Line-to-Ground Fault 553
9.3 Line-to-Line Fault 557
9.4 Double Line-to-Ground Fault 560
9.5 Sequence Bus Impedance Matrices 567
Design Project 3 (*continued*) 588
Design Project 4 589

CHAPTER 10 System Protection 593

Case Study: Upgrading Relay Protection Be Prepared for the Next Replacement or Upgrade Project 594
10.1 System Protection Components 612

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10.2 Instrument Transformers 614
10.3 Overcurrent Relays 620
10.4 Radial System Protection 625
10.5 Reclosers and Fuses 629
10.6 Directional Relays 633
10.7 Protection of a Two-Source System with Directional Relays 634
10.8 Zones of Protection 635
10.9 Line Protection with Impedance (Distance) Relays 639
10.10 Differential Relays 645
10.11 Bus Protection with Differential Relays 647
10.12 Transformer Protection with Differential Relays 648
10.13 Pilot Relaying 653
10.14 Numeric Relaying 654

CHAPTER 11 Transient Stability 669

Case Study: Down, but Not Out 671
11.1 The Swing Equation 689
11.2 Simplified Synchronous Machine Model and System Equivalents 695
11.3 The Equal-Area Criterion 697
11.4 Numerical Integration of the Swing Equation 707
11.5 Multimachine Stability 711
11.6 A Two-Axis Synchronous Machine Model 719
11.7 Wind Turbine Machine Models 724
11.8 Design Methods for Improving Transient Stability 730

CHAPTER 12 Power System Controls 739

Case Study: No Light in August: Power System Restoration Following the 2003 North American Blackout 742
12.1 Generator-Voltage Control 757
12.2 Turbine-Governor Control 761
12.3 Load-Frequency Control 767

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CHAPTER 13 Transmission Lines: Transient Operation 779

Case Study: Surge Arresters 780
Case Study: Emergency Response 794
13.1 Traveling Waves on Single-Phase Lossless Lines 809
13.2 Boundary Conditions for Single-Phase Lossless Lines 813
13.3 Bewley Lattice Diagram 822
13.4 Discrete-Time Models of Single-Phase Lossless Lines and Lumped RLC Elements 828
13.5 Lossy Lines 834
13.6 Multiconductor Lines 838
13.7 Power System Overvoltages 841
13.8 Insulation Coordination 847

CHAPTER 14 Power Distribution 859

Case Study: It's All in the Plans 860
14.1 Introduction to Distribution 875
14.2 Primary Distribution 878
14.3 Secondary Distribution 885
14.4 Transformers in Distribution Systems 890
14.5 Shunt Capacitors in Distribution Systems 900
14.6 Distribution Software 905
14.7 Distribution Reliability 906
14.8 Distribution Automation 910
14.9 Smart Grids 913

Appendix 921
Index 925

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Preface

The objective of this book is to present methods of power system analysis and design, particularly with the aid of a personal computer, in sufficient depth to give the student the basic theory at the undergraduate level. The approach is designed to develop students' thinking processes, enabling them to reach a sound understanding of a broad range of topics related to power system engineering, while motivating their interest in the electrical power industry. Because we believe that fundamental physical concepts underlie creative engineering and form the most valuable and permanent part of an engineering education, we highlight physical concepts while giving due attention to mathematical techniques. Both theory and modeling are developed from simple beginnings so that they can be readily extended to new and complex situations.

NEW TO THIS EDITION

New chapter-opening case studies bring principles to life for students by providing practical, real-world engineering applications for the material discussed in each chapter.

Comprehensively revised problem sets ensure students have the practice they need to master critical skills.

Updated Instructor Resources

These resources include

- Instructor's Solutions Manual with solutions to all problems
- Comprehensive Test Bank offering additional problems
- Annotated Lecture Note PowerPoint Slides
- Lesson Plans that detail how to most effectively use this edition
- Updated PowerWorld Simulator Software
- Student PowerPoint Notes

New design projects in this edition meet Accreditation Board for Engineering and Technology (ABET) requirements to provide valuable hands-on experience and to help ensure students are receiving an education that meets globally recognized accreditation standards.

The latest version of the valuable PowerWorld Simulator (version 19) is included and integrated throughout the text.

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KEY FEATURES

The text presents present-day, practical applications and new technologies along with ample coverage of the ongoing restructuring of the electric utility industry. It is supported by an ample number of worked examples, including illustrations, covering most of the theoretical points raised. It also includes PowerWorld Simulator version 19 to extend fully worked examples into computer implementations of the solutions. Version 19 includes power flow, optimal power flow, contingency analysis, short circuit, and transient stability.

The text includes a chapter on Power Distribution with content on Smart Grids.

It also includes discussions on modeling of wind turbines in power flow and transient stability.

Four design projects are included, all of which meet ABET requirements.

POWERWORLD SIMULATOR

One of the most challenging aspects of engineering education is giving students an intuitive feel for the systems they are studying. Engineering systems are, for the most part, complex. While paper-and-pencil exercises can be quite useful for highlighting the fundamentals, they often fall short in imparting the desired intuitive insight. To help provide this insight, the book uses PowerWorld Simulator version 19 to integrate computer-based examples, problems, and design projects throughout the text.

PowerWorld Simulator was originally developed at the University of Illinois at Urbana-Champaign to teach the basics of power systems to nontechnical people involved in the electricity industry, with version 1.0 introduced in June 1994. The program's interactive and graphical design made it an immediate hit as an educational tool, but a funny thing happened—its interactive and graphical design also appealed to engineers doing analysis of real power systems. To meet the needs of a growing group of users, PowerWorld Simulator was commercialized in 1996 by the formation of PowerWorld Corporation. Thus while retaining its appeal for education, over the years PowerWorld Simulator has evolved into a top-notch analysis package, able to handle power systems of any size. PowerWorld Simulator is now used throughout the power industry, with a range of users encompassing universities, utilities of all sizes, government regulators, power marketers, and consulting firms.

In integrating PowerWorld Simulator with the text, our design philosophy has been to use the software to extend, rather than replace, the fully worked examples provided in previous editions. Therefore, except when the problem size makes it impractical, each PowerWorld Simulator example includes a fully worked hand solution of the problem along with a PowerWorld Simulator case. This format allows students to simultaneously see the details of how a problem is solved and a computer implementation of the solution. The added benefit from PowerWorld Simulator is its ability to easily extend the example. Through its interactive design, students can quickly vary example parameters and immediately see the impact such changes have on the solution. By reworking the examples with the new parameters, students get immediate feedback on whether they understand the solution process.

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The interactive and visual design of PowerWorld Simulator also makes it an excellent tool for instructors to use for in-class demonstrations. With numerous examples utilizing PowerWorld Simulator instructors can easily demonstrate many of the text topics. Additional PowerWorld Simulator functionality is introduced in the text problems and design projects.

PREREQUISITES

As background for this course, it is assumed that students have had courses in electric network theory (including transient analysis) and ordinary differential equations and have been exposed to linear systems, matrix algebra, and computer programming. In addition, it would be helpful, but not necessary, to have had an electric machines course.

ORGANIZATION

The text is intended to be fully covered in a two-semester or three-quarter course offered to seniors and first-year graduate students. The organization of chapters and individual sections is flexible enough to give the instructor sufficient latitude in choosing topics to cover, especially in a one-semester course. The text is supported by an ample number of worked examples covering most of the theoretical points raised. The many problems to be worked with a calculator as well as problems to be worked using a personal computer have been revised in this edition.

After an introduction to the history of electric power systems along with present and future trends, *Chapter 2* orients the students to the terminology and serves as a brief review of fundamentals. The chapter reviews phasor concepts, power, and single-phase as well as three-phase circuits.

Chapters 3 through 5 examine power transformers including the per-unit system, transmission-line parameters, and steady-state operation of transmission lines. *Chapter 6* examines power flows including the Newton-Raphson method, power-flow modeling of wind generation, economic dispatch, and optimal power flow. These chapters provide a basic understanding of power systems under balanced three-phase, steady-state, normal operating conditions.

Chapters 7 through 10, which cover symmetrical faults, symmetrical components, unsymmetrical faults, and system protection, come under the general heading of power system short-circuit protection. *Chapter 11* examines transient stability, which includes the swing equation, the equal-area criterion, and multi-machine stability with modeling of wind-energy systems. *Chapter 12* covers power system controls, including generator-voltage control, turbine-governor control, and load-frequency control. *Chapter 13* examines transient operation of transmission lines including power system overvoltages and surge protection.

Chapter 14 introduces the basic features of primary and secondary distribution systems as well as basic distribution components including distribution substation transformers, distribution transformers, and shunt capacitors. We list some of the major distribution software vendors followed by an introduction to distribution reliability, distribution automation, and smart grids.

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ADDITIONAL RESOURCES

Companion websites for this book are available for both students and instructors. These websites provide useful links and other support material.

Student Website

The **Student Companion Site** includes a link to download the free student version of PowerWorld and Student PowerPoint Notes.

Instructor Resource Center

The **Instructor Companion Site** includes

- Instructor's Solutions Manual
- Annotated PowerPoint Slides
- Lecture Notes
- Test Banks

To access the support material described here along with all additional course materials, please visit https://sso.cengage.com.

MINDTAP ONLINE COURSE AND READER

This textbook is also available online through Cengage Learning's MindTap, a personalized learning program. Students who purchase the MindTap have access to the book's multimedia-rich electronic Reader and are able to complete homework and assessment material online, on their desktops, laptops, or iPads. Instructors who use a Learning Management System (such as Blackboard, Canvas, or Moodle) for tracking course content, assignments, and grading, can seamlessly access the MindTap suite of content and assessments for this course.

With MindTap, instructors can

- Personalize the Learning Path to match the course syllabus by rearranging content or appending original material to the online content
- Connect a Learning Management System portal to the online course and Reader
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- Track student engagement, progress and comprehension
- Promote student success through interactivity, multimedia, and exercises

Additionally, students can listen to the text through ReadSpeaker, take notes in the digital Reader, study from and create their own Flashcards, highlight content for easy reference, and check their understanding of the material through practice quizzes and automatically-graded homework.

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In conclusion, the objective in writing this text and the accompanying software package will have been fulfilled if the book is considered to be student-oriented, comprehensive, and up to date, with consistent notation and necessary detailed explanation at the level for which it is intended.

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List of Symbols, Units, and Notation

Symbol	Description	Symbol	Description
a	operator 1/120°	P	real power
a_t	transformer turns ratio	q	Charge
A	area	Q	reactive power
A	transmission line parameter	r	radius
$\boldsymbol{A}$	symmetrical components transformation matrix	R	resistance
		R	turbine-governor regulation constant
B	loss coefficient		
B	frequency bias constant	$\mathbf{R}$	resistance matrix
B	phasor magnetic flux density	s	Laplace operator
B	transmission line parameter	S	apparent power
C	capacitance	S	complex power
C	transmission line parameter	t	time
D	damping	T	period
D	distance	T	temperature
D	transmission line parameter	T	torque
E	phasor source voltage	$v(t)$	instantaneous voltage
E	phasor electric field strength	V	voltage magnitude (rms unless otherwise indicated)
f	frequency		
G	conductance	V	phasor voltage
$\mathbf{G}$	conductance matrix	$\boldsymbol{V}$	vector of phasor voltages
H	normalized inertia constant	X	reactance
H	phasor magnetic field intensity	$\mathbf{X}$	reactance matrix
$i(t)$	instantaneous current	Y	phasor admittance
I	current magnitude (rms unless otherwise indicated)	$\boldsymbol{Y}$	admittance matrix
		Z	phasor impedance
I	phasor current	$\boldsymbol{Z}$	impedance matrix
$\boldsymbol{I}$	vector of phasor currents	α	angular acceleration
j	operator 1/90°	α	transformer phase shift angle
J	moment of inertia		
l	length	β	current angle

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Symbol	Description	Symbol	Description
l	length	β	area frequency response characteristic
L	inductance		
L	inductance matrix	δ	voltage angle
N	number (of buses, lines, turns, etc.)	δ	torque angle
p.f.	power factor	ε	permittivity
$p(t)$	instantaneous power	Γ	reflection or refraction coefficient
λ	magnetic flux linkage		
λ	Penalty factor	θ	impedance angle
Φ	magnetic flux	θ	angular position
ρ	resistivity	μ	permeability
τ	time in cycles	υ	velocity of propagation
τ	transmission line transit time	ω	radian frequency

SI Units		English Units	
A	ampere	BTU	British thermal unit
C	coulomb	Cmil	circular mil
F	farad	ft	foot
H	henry	hp	horsepower
Hz	hertz	in	inch
J	joule	mi	mile
kg	kilogram		
m	meter		
N	newton		
rad	radian		
s	second		
S	siemen		
VA	voltampere		
var	voltampere reactive		
W	watt		
Wb	weber		
Ω	ohm		

Notation

Lowercase letters such as v(t) and i(t) indicate instantaneous values.
Uppercase letters such as V and I indicate rms values.
Uppercase letters in italic such as V and I indicate rms phasors.
Matrices and vectors with real components such as **R** and **I** are indicated by boldface type.
Matrices and vectors with complex components such as $\boldsymbol{Z}$ and $\boldsymbol{I}$ are indicated by boldface italic type.
Superscript T denotes vector or matrix transpose.
Asterisk (*) denotes complex conjugate.
PW highlights problems that utilize PowerWorld Simulator.

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