



# Principles of Electrical Safety

Peter E. Sutherland

 **IEEE**  
IEEE PRESS

IEEE  
PRESS  
SERIES  
ON  
POWER  
ENGINEERING



Mohamed E. El-Hawary, *Series Editor*

**WILEY**



*PRINCIPLES OF  
ELECTRICAL SAFETY*

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

**IEEE Press Editorial Board**

Tariq Samad, *Editor in Chief*

George W. Arnold  
Dmitry Goldgof  
Ekram Hossain

Mary Lanzerotti  
Pui-In Mak  
Ray Perez

Linda Shafer  
MengChu Zhou  
George Zobrist

Kenneth Moore, *Director of IEEE Book and Information Services (BIS)*

---

# *PRINCIPLES OF ELECTRICAL SAFETY*

**PETER E. SUTHERLAND**

IEEE  
PRESS  
SERIES  
ON POWER  
ENGINEERING

 **IEEE**  
IEEE PRESS

**WILEY**

Copyright © 2015 by The Institute of Electrical and Electronics Engineers, Inc.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey. All rights reserved  
Published simultaneously in Canada

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, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at [www.copyright.com](http://www.copyright.com). Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at <http://www.wiley.com/go/permission>.

**Limit of Liability/Disclaimer of Warranty:** While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at [www.wiley.com](http://www.wiley.com).

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

Sutherland, Peter E.

Principles of electrical safety / Peter E. Sutherland.  
pages cm

ISBN 978-1-118-02194-1 (cloth)

1. Electrical engineering—Safety measures. 2. Electricity—Safety measures. 3. Electric apparatus and appliances—Safety measures. I. Title.

TK152.S8174 2015

621.3028'9—dc23

2015012677

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

*To all the victims*



---

# CONTENTS

<i>LIST OF FIGURES</i>	xiii
<i>LIST OF TABLES</i>	xxv
<i>PREFACE</i>	xxix
<i>ACKNOWLEDGMENTS</i>	xxxvii

---

**CHAPTER 1**    *MATHEMATICS USED IN ELECTROMAGNETISM*    **1**

---

1.1	Introduction	1
1.2	Numbers	2
1.3	Mathematical Operations with Vectors	17
1.4	Calculus with Vectors—The Gradient	18
1.5	Divergence, Curl, and Stokes' Theorem	23
1.6	Maxwell's Equations	25

---

**CHAPTER 2**    *ELECTRICAL SAFETY ASPECTS OF THE RESISTANCE PROPERTY OF MATERIALS*    **30**

---

2.1	Introduction	30
2.2	Hazards Caused by Electrical Resistance	31
2.3	Resistance and Conductance	38
2.4	Example—Trunk of a Human Body	42
2.5	Example—Limb of a Human Body	43
2.6	Power and Energy Flow	44
2.7	Sheet Resistivity	47
2.8	Example—Square of Dry Skin	48
2.9	Spreading Resistance	48
2.10	Example—Circle of Dry Skin	49
2.11	Particle Conductivity	50
2.12	Examples—Potassium, Sodium, and Chlorine Ions	53
2.13	Cable Resistance	53

---

**CHAPTER 3**    *CAPACITANCE PHENOMENA*    **59**

---

3.1	Fundamentals of Capacitance	59
3.2	Capacitance and Permittivity	62
3.3	Capacitance in Electrical Circuits	65
3.4	Capacitance of Body Parts	69
3.4.1	Example—Skin Capacitance	69
3.4.2	Example—Capacitance of Trunk and Limb	70
3.5	Electrical Hazards of Capacitance	71
3.6	Capacitance of Cables	72

**CHAPTER 4** *INDUCTANCE PHENOMENA* **74**

---

- 4.1 Inductance in Electrical Theory **74**
- 4.2 Inductance of Wires **76**
- 4.3 Example—Inductance of a Conductor **76**
- 4.4 Example—Inductance of Trunk and Limb **77**
- 4.5 Inductors or Reactors **77**
- 4.6 Skin Effect **77**
- 4.7 Cable Inductance **81**
- 4.8 Surge Impedance **83**
- 4.9 Bus Bar Impedance Calculations **84**

**CHAPTER 5** *CIRCUIT MODEL OF THE HUMAN BODY* **90**

---

- 5.1 Calculation of Electrical Shock Using the Circuit Model of the Body **90**
- 5.2 Frequency Response of the Human Body **93**

**CHAPTER 6** *EFFECT OF CURRENT ON THE HUMAN BODY* **101**

---

- 6.1 Introduction to Electrical Shock **101**
- 6.2 Human and Animal Sensitivities to Electric Current **102**
- 6.3 Human Body Impedance **104**
- 6.4 Effects of Various Exposure Conditions **107**
  - 6.4.1 Bare Feet, Wet Conditions, and Other Variations **107**
  - 6.4.2 Shoes and Other Insulated Objects and the Earth **108**
- 6.5 Current Paths Through the Body **108**
- 6.6 Human Response to Electrical Shock Varies with Exposure Conditions, Current Magnitude, and Duration **113**
- 6.7 Medical Imaging and Simulations **114**

**CHAPTER 7** *FUNDAMENTALS OF GROUND GRID DESIGN* **118**

---

- 7.1 Introduction to Ground Grid Design **118**
- 7.2 Summary of Ground Grid Design Procedures **119**
  - 7.2.1 Site Survey **119**
  - 7.2.2 Conductor Sizing **119**
  - 7.2.3 Step and Touch Voltages **122**
  - 7.2.4 Ground Grid Layout **124**
  - 7.2.5 Ground Resistance Calculation **124**
  - 7.2.6 Calculation of Maximum Grid Current **125**
  - 7.2.7 Calculation of Ground Potential Rise (GPR) **125**
  - 7.2.8 Calculation of Mesh Voltage,  $E_m$  **125**
  - 7.2.9 Calculation of Step Voltage,  $E_s$  **127**
  - 7.2.10 Detailed Design **127**
- 7.3 Example Design from IEEE Standard 80 **128**

**CHAPTER 8** *SAFETY ASPECTS OF GROUND GRID OPERATION AND MAINTENANCE* **138**

---

- 8.1 Introduction **138**
- 8.2 Effects of High Fault Currents **138**

8.3	Damage or Failure of Grounding Equipment	142
8.3.1	Thermal Damage to Conductors Due to Excessive Short-Circuit Currents	142
8.3.2	Connector Damage Due to Excessive Short-Circuit Stresses	143
8.3.3	Drying of the Soil Resulting in Increased Soil Resistivity	144
8.4	Recommendations	145
<hr/>		
<b>CHAPTER 9</b>	<b><i>GROUNDING OF DISTRIBUTION SYSTEMS</i></b>	<b>147</b>
9.1	Stray Currents in Distribution Systems	147
9.2	Three-Phase Multigrounded Neutral Distribution Line	148
9.3	Secondary Systems: 120/240 V Single Phase	154
9.3.1	Example of Stray Currents—Touching a Grounded Conductor	158
9.3.2	Example of Stray Currents—With One Conductor Shorted to Neutral	159
9.4	Remediation of Stray-Current Problems	160
9.5	Grounding and Overvoltages in Distribution Systems	163
9.6	High-Resistance Grounding of Distribution Systems	167
9.6.1	Methods of Determining Charging Current	169
<hr/>		
<b>CHAPTER 10</b>	<b><i>ARC FLASH HAZARD ANALYSIS</i></b>	<b>172</b>
10.1	Introduction to Arc Flash Hazards	172
10.2	Factors Affecting the Severity of Arc Flash Hazards	176
10.3	Example Arc Flash Calculations	179
10.4	Remediation of Arc Flash Hazards	180
10.4.1	Example: Correcting an Arc Flash Problem When a Coordination Problem Requires Replacing Trip Units	180
10.4.2	Example: Correcting a Coordination Problem Without Introducing an Arc Flash Problem	182
10.5	Coordination of Low-Voltage Breaker Instantaneous Trips for Arc Flash Hazard Reduction	185
10.5.1	Hospital #1—Time–Current Curve Examples	189
10.5.2	Hospital #2—Time–Current Curve Examples	194
10.5.3	Hospital #3—Time–Current Curve Examples	200
10.6	Low-Voltage Transformer Secondary Arc Flash Protection using Fuses	205
<hr/>		
<b>CHAPTER 11</b>	<b><i>EFFECT OF HIGH FAULT CURRENTS ON PROTECTION AND METERING</i></b>	<b>216</b>
11.1	Introduction	216
11.2	Current Transformer Saturation	217
11.3	Saturation of Low-Ratio CTs	219
11.3.1	AC Saturation	219
11.3.2	DC Saturation	221
11.4	Testing of Current Transformer Saturation	224
11.5	Effect of High Fault Currents on Coordination	228
11.6	Protective Relay Ratings and Settings	230
11.7	Effects of Fault Currents on Protective Relays	232
11.7.1	Examples	233
11.8	Methods for Upgrading Protection Systems	233
11.8.1	Update Short-Circuit Study	233
11.8.2	Update Protective Device Coordination Study	233

12.1	Insufficient Interrupting Capability	236
12.2	High Voltage Air Circuit Breakers	236
12.3	Vacuum Circuit Breakers	237
12.4	SF <sub>6</sub> Circuit Breakers	239
12.5	Loss of Interruption Medium	241
12.6	Interrupting Ratings of Switching Devices	242
12.7	Circuit Breakers	243
12.8	Fuses	244
12.9	Case Studies	245
	12.9.1 Example: Diablo Canyon	245
	12.9.2 Example: Dresden and Quad Cities	248
12.10	Low-Voltage Circuit Breakers	249
12.11	Testing of Low-Voltage Circuit Breakers	251
	12.11.1 Testing of Low-Voltage Molded-Case Circuit Breakers According to UL Standard 489	252
	12.11.2 Testing of Low-Voltage Molded-Case Circuit Breakers for Use With Uninterruptible Power Supplies According to UL Standard 489	259
	12.11.3 Testing of Supplementary Protectors for Use in Electrical Equipment According to UL Standard 1077	261
	12.11.4 Testing of Transfer Switch Equipment According to UL Standard 1008	272
	12.11.5 Testing of Low-Voltage AC Power Circuit Breakers According to ANSI Standard C37.50-1989	276
	12.11.6 Testing of Low-Voltage DC Power Circuit Breakers According to IEEE Standard C37.14-2002	280
	12.11.7 Testing of Low-Voltage Switchgear and Controlgear According to IEC Standard 60947-1	284
	12.11.8 Testing of Low-Voltage AC and DC Circuit Breakers According to IEC Standard 60947-2	285
	12.11.9 Testing of Circuit Breakers Used for Across-the-Line Starters for Motors According to IEC Standard 60947-4-1	288
	12.11.10 Testing of Circuit Breakers Used in Households and Similar Installations According to IEC Standard 60898-1 and -2	290
	12.11.11 Testing of Circuit Breakers Used in Equipment such as Electrical Appliances According to IEC Standard 60934	293
12.12	Testing of High-Voltage Circuit Breakers	296

13.1	Introduction	299
13.2	Definitions	299
13.3	Short-Circuit Mechanical Forces on Rigid Bus Bars	300
	13.3.1 Short-Circuit Mechanical Forces on Rigid Bus Bars—Circular Cross Section	300
	13.3.2 Short-Circuit Mechanical Forces—Rectangular Cross Section	302
13.4	Dynamic Effects of Short Circuits	302
13.5	Short-Circuit Thermal Effects	304

13.6	Flexible Conductor Buses	305	
13.6.1	Conductor Motion During a Fault	307	
13.6.2	Pinch Forces on Bundled Conductors	311	
13.7	Force Safety Devices	316	
13.8	Substation Cable and Conductor Systems	318	
13.8.1	Cable Thermal Limits	318	
13.8.2	Cable Mechanical Limits	319	
13.9	Distribution Line Conductor Motion	319	
13.10	Effects of High Fault Currents on Substation Insulators	320	
13.10.1	Station Post Insulators for Rigid Bus Bars	320	
13.10.2	Suspension Insulators for Flexible Conductor Buses	322	
13.11	Effects of High Fault Currents on Gas-Insulated Substations (GIS)	322	
<b>CHAPTER 14</b> <i>EFFECT OF HIGH FAULT CURRENTS ON TRANSMISSION LINES</i>			<b>325</b>
14.1	Introduction	325	
14.2	Effect of High Fault Current on Non-Ceramic Insulators (NCI)	325	
14.3	Conductor Motion Due to Fault Currents	328	
14.4	Calculation of Fault Current Motion for Horizontally Spaced Conductors	329	
14.5	Effect of Conductor Shape	330	
14.6	Conductor Equations of Motion	331	
14.7	Effect of Conductor Stretch	332	
14.8	Calculation of Fault Current Motion for Vertically Spaced Conductors	332	
14.9	Calculation Procedure	333	
14.10	Calculation of Tension Change with Motion	334	
14.11	Calculation of Mechanical Loading on Phase-to-Phase Spacers	335	
14.12	Effect of Bundle Pinch on Conductors and Spacers	336	
<b>CHAPTER 15</b> <i>LIGHTNING AND SURGE PROTECTION</i>			<b>338</b>
15.1	Surge Voltage Sources and Waveshapes	338	
15.2	Surge Propagation, Refraction, and Reflection	343	
15.3	Insulation Withstand Characteristics and Protection	346	
15.4	Surge Arrester Characteristics	349	
15.5	Surge Arrester Application	350	
<i>REFERENCES</i>			<b>352</b>
<i>INDEX</i>			<b>361</b>



---

# LIST OF FIGURES

<b>Figure 1.1</b>	The number line.	2
<b>Figure 1.2</b>	The real numbers on the number line.	3
<b>Figure 1.3</b>	Angular measure in radians and degrees.	4
<b>Figure 1.4</b>	Complex numbers in rectangular form.	5
<b>Figure 1.5</b>	Complex numbers in polar form.	6
<b>Figure 1.6</b>	One-dimensional vectors.	7
<b>Figure 1.7</b>	Two-dimensional vectors in rectangular form.	9
<b>Figure 1.8</b>	Two-dimensional vectors in polar form.	10
<b>Figure 1.9</b>	Three-dimensional vectors in rectangular form.	12
<b>Figure 1.10</b>	Three-dimensional vectors in cylindrical form.	13
<b>Figure 1.11</b>	Three-dimensional vectors in spherical form.	16
<b>Figure 1.12</b>	Dot product of two vectors.	18
<b>Figure 1.13</b>	Right-hand rule for the cross product of two vectors.	18
<b>Figure 1.14</b>	Cross product of two vectors.	19
<b>Figure 1.15</b>	Scalar field in one dimension.	21
<b>Figure 1.16</b>	Two-dimensional scalar field $f(x,y) = 2x^2 + 5y$ and its gradient $\text{grad } f$ .	23
<b>Figure 1.17</b>	Closed path $L$ of circulation $C$ with normal vector $\mathbf{n}$ defining the direction of $\mathbf{A} \cdot d\mathbf{l}$ in accordance with the right-hand rule.	24
<b>Figure 1.18</b>	Faraday's law: the moving magnetic field induces an electric field which produces a current that induces a magnetic field opposing that which caused it.	25
<b>Figure 1.19</b>	Illustration of Ampère's law for a resistor and capacitor.	26
<b>Figure 1.20</b>	Illustration of Gauss's law for the field around a point charge.	27
<b>Figure 1.21</b>	Illustration of Gauss's law for magnetic fields.	28
<b>Figure 2.1</b>	Resistors used as electronic components. (a) Carbon composition resistor, axial lead, $\frac{1}{2}$ W, 470 W, 10% tolerance. (b) Carbon film, axial lead, 1/4 Watt, 10 kW, 5% tolerance. (c) Vitreous enamel-coated wire-wound power resistor, 1500 W. (d) Plate resistors in vacuum tube amplifier. (e) Vacuum tube amplifier where plate resistors would be used. (f) Schematic of vacuum tube amplifier where plate resistors would be used. (g) Isolation transformer (115 V, 250 VA) for servicing "transformerless" electronic equipment.	34

<b>Figure 2.2</b>	Resistors used in electric power systems. (a) Plate resistor. (b) Ribbon resistor. (c) Noninductive resistor. (d) Ribbon-wound resistor. (e) Plate rheostat (GE). (f) Schematic of plate rheostat (GE).	36
<b>Figure 2.3</b>	Resistance, $R$ , is derived from the resistivity, $\rho$ , of an object.	38
<b>Figure 2.4</b>	Conductance, $G$ , is derived from the conductivity, $\sigma$ , of an object.	39
<b>Figure 2.5</b>	Water pipe analogy.	40
<b>Figure 2.6</b>	Circuit model of a resistive circuit.	42
<b>Figure 2.7</b>	Model of body trunk with elliptical cross section.	42
<b>Figure 2.8</b>	Model of limb with elliptical cross section and circular bone at the center.	43
<b>Figure 2.9</b>	Electric and magnetic fields around a circular conductor.	45
<b>Figure 2.10</b>	Power density is highest closest to the conductors.	46
<b>Figure 2.11</b>	Cylindrical conductor with applied voltage.	47
<b>Figure 2.12</b>	Sheet resistivity.	47
<b>Figure 2.13</b>	Simplified equivalent circuit of skin.	48
<b>Figure 2.14</b>	Surface current flows.	49
<b>Figure 2.15</b>	Example of skin impedance.	50
<b>Figure 2.16</b>	Voltage around a charged particle and Debye length.	51
<b>Figure 2.17</b>	Cellular membrane with ionic movements.	52
<b>Figure 2.18</b>	Nernst potentials in cellular membrane.	52
<b>Figure 2.19</b>	Skin depth, $\delta$ , of a copper conductor.	54
<b>Figure 2.20</b>	Skin depth versus frequency and radii of conductors and shields for several common cable sizes (kcmil).	56
<b>Figure 2.21</b>	Resistance versus frequency of conductors and shields for several common cable sizes (kcmil).	58
<b>Figure 2.22</b>	Conductor plus shield resistance.	58
<b>Figure 3.1</b>	Capacitors used in electronic applications. (a) Ceramic disk capacitor. (b) Film capacitor. (c) Electrolytic capacitor. (d) Tantalum capacitors.	60
<b>Figure 3.2</b>	(a) Stack rack capacitors used in electric power systems. (b) Distribution capacitor bank with switches.	61
<b>Figure 3.3</b>	Capacitive energy storage.	63
<b>Figure 3.4</b>	Circuit model of a lossless capacitive circuit.	63
<b>Figure 3.5</b>	Capacitor charged from a DC source.	65
<b>Figure 3.6</b>	Voltage on $1.0 \mu\text{F}$ capacitor charged through a $100 \Omega$ resistor to $1 \text{ kV}$ with $t = 100 \text{ ms}$ .	66
<b>Figure 3.7</b>	Discharge of capacitor charged from a DC source.	66
<b>Figure 3.8</b>	Voltage on $1.0 \mu\text{F}$ capacitor discharged from $1 \text{ kV}$ through a $100 \Omega$ resistor with $t = 100 \text{ ms}$ .	66
<b>Figure 3.9</b>	Oscillatory LC circuit.	67
<b>Figure 3.10</b>	Voltage on $1.0 \mu\text{F}$ capacitor in oscillatory LC circuit with $L = 20 \text{ mH}$ and $\omega_0 = 5.010 \times 10^{-7}$ .	67
<b>Figure 3.11</b>	Series RLC circuit.	67

<b>Figure 3.12</b>	Oscillatory current transient in series RLC circuit with $L = 12 \mu\text{H}$ , $C = 0.08 \mu\text{F}$ , and $R = 14 \Omega$ .	70
<b>Figure 3.13</b>	Example of skin impedance.	71
<b>Figure 3.14</b>	Shielded cable cross section showing radius of the wire and shield.	73
<b>Figure 4.1</b>	Surfaces of integration for internal and external inductance.	75
<b>Figure 4.2</b>	Inductance versus separation for an open-wire line.	76
<b>Figure 4.3</b>	Power Reactors. (a) Cast in concrete reactor. (b) Modern fiberglass epoxy outdoor air core reactors.	78
<b>Figure 4.4</b>	Electromagnetic wave entering a conducting medium.	79
<b>Figure 4.5</b>	Magnitude of incident wave with $\omega = 10^5$ , $E_0 = 1$ , $\epsilon_r = 10^7$ , $\mu_r = 1.0$ , $\sigma = 0$ .	79
<b>Figure 4.6</b>	Ratio $\sigma/\omega\epsilon$ for biological materials, copper shown for comparison. Materials are conductors above the “conductor” line, dielectrics below the “dielectric” line, and quasi-conductors in between.	80
<b>Figure 4.7</b>	Skin depth for biological materials, compared to a radius of 0.5 m.	80
<b>Figure 4.8</b>	Single-conductor medium-voltage cable construction (Southwire <sup>®</sup> , 2010).	81
<b>Figure 4.9</b>	Internal and external inductance versus frequency for several common cable sizes (kcmil).	82
<b>Figure 4.10</b>	Total internal and external inductance versus frequency for several common cable sizes (kcmil).	82
<b>Figure 4.11</b>	Surge impedance versus frequency for several common cable sizes (kcmil).	84
<b>Figure 4.12</b>	Skin effect in isolated rectangular conductors, $R_{dc}$ in ohms per 1000 ft (Dwight, 1945, p. 225).	85
<b>Figure 4.13</b>	Proximity effect ratio in wires, $R_{dc}$ in Ohms per 1000 ft (Dwight, 1945, p. 225).	86
<b>Figure 4.14</b>	Dimensions of two parallel rectangular bus bars.	87
<b>Figure 4.15</b>	Dimensions of three-phase system with two parallel rectangular bus bars per phase.	88
<b>Figure 4.16</b>	Three-phase system with two parallel rectangular bus bars per phase.	88
<b>Figure 5.1</b>	Circuit model of hand-to-foot conduction, with dry skin.	91
<b>Figure 5.2</b>	Circuit reduction of human body impedance with dry skin.	92
<b>Figure 5.3</b>	Circuit reduction of human body impedance with wet skin.	94
<b>Figure 5.4</b>	Equivalent circuit of a body part.	95
<b>Figure 5.5</b>	Impedance versus frequency plots for trunk and limb.	96
<b>Figure 5.6</b>	Phase angle versus frequency plots for trunk and limb.	97
<b>Figure 5.7</b>	Impedance versus frequency plot for skin.	98
<b>Figure 5.8</b>	Phase angle versus frequency plot for skin.	98
<b>Figure 5.9</b>	Total body impedance magnitude ( $Z_{BS}$ ) and internal body impedance ( $Z_B$ ) versus frequency. $P_{TN}$ is the negative trunk pole at 18 kHz.	99

<b>Figure 5.10</b>	Total body impedance angle ( $Z_{BS}$ ) and internal body impedance ( $Z_B$ ) versus frequency. $P_{TN}$ is the negative trunk pole at 18 kHz.	100
<b>Figure 6.1</b>	Electrocution threshold current ranges for 0.5% percentile of 50 kg adults (solid) and 18 kg children (dashed). © IEEE (2009a).	104
<b>Figure 6.2</b>	Human body impedance components. © IEEE (2009a).	105
<b>Figure 6.3</b>	Human body impedance percentages. © IEEE (2009a).	106
<b>Figure 6.4</b>	Total body impedance ranges for hand-to-hand or hand-to-foot contacts. © IEEE (2009a).	107
<b>Figure 6.5</b>	Circuit model of human body based on the fifth percentile of hand-to-foot conduction. © IEEE (2009a).	110
<b>Figure 6.6</b>	Hand-to-foot conduction, resistances in kilowatts. RC represents the variable earth resistance. Note that the current flows through the torso. © IEEE (2009a).	111
<b>Figure 6.7</b>	Foot-to-foot conduction, resistances in kilowatts. RC represents the variable earth resistance. Note that current flow does not go through the heart. © IEEE (2009a).	112
<b>Figure 6.8</b>	Comparison of $I^2t$ curves from the electrocution equation with IEC fibrillation curves (b, c1, c2, and c3). © IEEE (2009a).	114
<b>Figure 6.9</b>	IEC damage curve b (reversible disturbances) adjusted by IEC heart-current factor for various current paths. © IEEE (2009a).	115
<b>Figure 6.10</b>	IEC fibrillation curve c1 (lower limit of 5% probability) adjusted by IEC heart-current factor for various current paths. © IEEE (2009a).	115
<b>Figure 6.11</b>	IEC fibrillation curve c2 (upper limit of 5% probability and lower limit of 50% probability) adjusted by IEC heart-current factor for various current paths. © IEEE (2009a).	116
<b>Figure 6.12</b>	IEC fibrillation curve c3 (upper limit of 50% probability) adjusted by IEC heart-current factor for various current paths. © IEEE (2009a).	116
<b>Figure 7.1</b>	Decrement factor versus fault duration for four different $X/R$ ratios.	122
<b>Figure 7.2</b>	Touch voltage.	123
<b>Figure 7.3</b>	Step voltage will approach 1.0 as $h_s \rightarrow \rho$ increases and as $\rho_s \rightarrow \rho$ . It will approach 0 as $\rho_s \rightarrow 0$ .	123
<b>Figure 7.4</b>	Single-line diagram for example.	128
<b>Figure 7.5</b>	$X/R$ ratio of transformers. (Source: © IEEE (1993))	129
<b>Figure 7.6</b>	Positive sequence equivalent circuit.	130
<b>Figure 7.7</b>	Negative sequence equivalent circuit.	130
<b>Figure 7.8</b>	Zero sequence equivalent circuit.	130
<b>Figure 7.9</b>	Symmetrical components solution of 115 kV single-line-to-ground ground fault.	131

<b>Figure 7.10</b>	Symmetrical components solution of 13.2 kV single-line-to-ground ground fault.	132
<b>Figure 8.1</b>	Deteriorated grounding conductor and cracked concrete foundation.	139
<b>Figure 8.2</b>	Deteriorated grounding conductor, broken concrete support, and insulator debris.	140
<b>Figure 8.3</b>	Deteriorated grounding conductor and broken insulator debris.	140
<b>Figure 8.4</b>	Vegetation and deteriorated concrete.	141
<b>Figure 8.5</b>	Typical time–current curves showing thermal and mechanical withstand for 500 kcmil copper ground grid conductors (assuming 0.5 s fault-clearing time) and connectors.	143
<b>Figure 8.6</b>	Short-circuit testing of ground grid connectors. The test loop contains one through four connector assemblies.	144
<b>Figure 8.7</b>	Effect of moisture content on soil resistivity.	145
<b>Figure 9.1</b>	Portion of single-phase distribution line with multigrounded neutral (frequency of grounding exaggerated).	148
<b>Figure 9.2</b>	Portion of three-phase distribution line with multigrounded neutral (frequency of grounding exaggerated) ( <i>Source: © IEEE (2011)</i> ).	149
<b>Figure 9.3</b>	Line configuration: three-phase multigrounded neutral distribution line.	150
<b>Figure 9.4</b>	Simplified equivalent circuit of one segment of a single-phase multigrounded neutral distribution line.	152
<b>Figure 9.5</b>	Equivalent circuit of one segment of a three-phase multigrounded neutral distribution line, showing mutual impedances ( <i>Source: © IEEE (2011)</i> ).	155
<b>Figure 9.6</b>	Equivalent circuit of domestic service with premises wiring and load ( <i>Source: © IEEE (2011)</i> ).	157
<b>Figure 9.7</b>	Detailed model of distribution transformer ( <i>Source: © IEEE (2011)</i> ).	158
<b>Figure 9.8</b>	Equivalent circuit of 120 V system with ground removed from the secondary of the utility transformer for analysis ( <i>Source: © IEEE (2011)</i> ).	160
<b>Figure 9.9</b>	Equivalent circuit of modified domestic service with ground removed from the secondary of the utility transformer ( <i>Source: © IEEE (2011)</i> ).	161
<b>Figure 9.10</b>	Equivalent circuit of modified 120 V system with ground removed from secondary of transformer for analysis ( <i>Source: © IEEE (2011)</i> ).	161
<b>Figure 9.11</b>	Equivalent circuit of modified domestic service with ground removed from secondary of transformer ( <i>Source: © IEEE (2011)</i> ).	162
<b>Figure 9.12</b>	Equivalent circuit of modified 120 V system with ground removed from secondary of transformer for analysis ( <i>Source: © IEEE (2011)</i> ).	162

<b>Figure 9.13</b>	Ungrounded three-phase feeder.	164
<b>Figure 9.14</b>	Distributed capacitances in ungrounded three-phase feeder.	164
<b>Figure 9.15</b>	Interconnected sequence networks of ungrounded feeder.	165
<b>Figure 9.16</b>	Simplified sequence network for phase-to-ground fault.	165
<b>Figure 9.17</b>	Simulation of overvoltages due to multiple restrike. Breaker opens and arc extinguishes at 0.25 cycles, restrikes occur at 0.75 cycles and again at 1.25 cycles, resulting in overvoltages of 3 and 5 per unit.	166
<b>Figure 9.18</b>	High-resistance wye-broken delta grounding bank added to the system of Figure 9.13.	167
<b>Figure 9.19</b>	Interconnected sequence networks with high-resistance grounding bank.	168
<b>Figure 9.20</b>	Restrike overvoltages of Figure 9.17 limited by high-resistance grounding with $R = XC$ to less than 2.5 per unit.	168
<b>Figure 9.21</b>	Fault current versus resistance in a typical high-resistance grounded system.	168
<b>Figure 9.22</b>	Overvoltage due to restrike versus resistance in a typical high-resistance grounded system.	169
<b>Figure 9.23</b>	Measurement of charging current using voltage source and grounding bank. (a) Three-line diagram and (b) zero-sequence diagram.	170
<b>Figure 9.24</b>	Field tuning of grounding resistor. (a) Three-line diagram and (b) zero-sequence diagram.	171
<b>Figure 10.1</b>	Single line diagram of older substation whose low-voltage circuit breakers use electromechanical dashpot-type trip units. ( <i>Source</i> : © IEEE (2009a)).	180
<b>Figure 10.2</b>	Typical electromechanical trip unit for low-voltage circuit breaker.	181
<b>Figure 10.3</b>	Coordination curves for substation of Figure 10.1, as found. © IEEE (2009a).	182
<b>Figure 10.4</b>	Arc flash results for substation of Figure 10.1, as found. © IEEE (2009a).	183
<b>Figure 10.5</b>	Coordination curves for substation of Figure 10.1, showing recommended changes © IEEE (2009a).	184
<b>Figure 10.6</b>	Arc flash results for substation of Figure 10.1, showing recommended changes. © IEEE (2009a).	185
<b>Figure 10.7</b>	Original configuration of 600 V substations on a 13.8 kV feeder with normal inverse relays ( <i>Source</i> : © IEEE (2009a)).	186
<b>Figure 10.8</b>	Original coordination of 600 V substations on a 13.8 kV feeder ( <i>Source</i> : © IEEE (2009a)).	187
<b>Figure 10.9</b>	Two 600 V substations on a 13.8 kV feeder with very inverse relays; protection of 500 kVA transformer ( <i>Source</i> : © IEEE (2009a)).	188
<b>Figure 10.10</b>	Protection of 500 kVA transformer ( <i>Source</i> : IEEE (2009a)).	189

<b>Figure 10.11</b>	Protection of 1500 kVA transformer with 500 kVA settings ( <i>Source</i> : © IEEE (2009a)).	190
<b>Figure 10.12</b>	Two 600 V substations on a 13.8 kV feeder with very inverse relays; protection of 1500 kVA transformer ( <i>Source</i> : © IEEE (2009a)).	191
<b>Figure 10.13</b>	Protection of 1500 kVA transformer with settings for arc flash reduction ( <i>Source</i> : © IEEE (2009a)).	192
<b>Figure 10.14</b>	Protection of 500 kVA transformer with 1500 kVA settings ( <i>Source</i> : © IEEE (2009a)).	193
<b>Figure 10.15</b>	Two 600 V substations on a 13.8 kV feeder, with fast fuses on the smaller substation ( <i>Source</i> : © IEEE (2009a)).	194
<b>Figure 10.16</b>	Two 600 V substations on a 13.8 kV feeder, with slow fuses on the smaller substation ( <i>Source</i> : © IEEE (2009a)).	195
<b>Figure 10.17</b>	Comparison of fuse-time-current curves ( <i>Source</i> : © IEEE (2009a)).	196
<b>Figure 10.18</b>	One-line diagram EMSW, Hospital #1.	197
<b>Figure 10.19</b>	Time-current curves EMSW, Hospital#1, $>40 \text{ cal/cm}^2$ .	198
<b>Figure 10.20</b>	Time-current curves EMSW, Hospital#1, $<1.2 \text{ cal/cm}^2$ .	199
<b>Figure 10.21</b>	One-line diagram normal feed, Hospital #1.	200
<b>Figure 10.22</b>	Time-current curves for Hospital#1, normal.	201
<b>Figure 10.23</b>	One-line diagram emergency feed, Hospital #2.	202
<b>Figure 10.24</b>	Time-current curves emergency feed, Hospital #2.	203
<b>Figure 10.25</b>	Let-through current curve for 600 A breaker in Hospital #2. Available fault current is 8096 A. The diagonal line is square root of two line.	204
<b>Figure 10.26</b>	Let-through energy curves for 400 A thermal magnetic circuit breaker in Hospital #2.	205
<b>Figure 10.27</b>	One-line diagram normal feed, Hospital #2.	206
<b>Figure 10.28</b>	Time-current curves normal feed, Hospital #2.	207
<b>Figure 10.29</b>	Hospital #3, emergency generator system one-line diagram.	208
<b>Figure 10.30</b>	Hospital #3, emergency generator system time-current curves.	208
<b>Figure 10.31</b>	Let-through current curve for 400 A circuit breaker in Hospital #3 emergency system.	209
<b>Figure 10.32</b>	Hospital #3, normal feed one-line diagram.	210
<b>Figure 10.33</b>	Hospital #3, normal system time-current curves.	210
<b>Figure 10.34</b>	Let-through current curve for 400 A breaker in Hospital #3 normal system. The available fault current is 76 kA.	211
<b>Figure 10.35</b>	Elevation view of low-voltage substation showing arc flash hazard areas.	212
<b>Figure 10.36</b>	Three-line diagram of low-voltage substation showing arc flash hazard areas.	212
<b>Figure 10.37</b>	Three-line diagram of low-voltage substation showing arc flash reduction using high-speed fuses (HSF).	213
<b>Figure 10.38</b>	Appearance of typical high-speed, high-current, low-voltage fuse (Cooper Bussman).	213

<b>Figure 10.39</b>	Typical time–current curve for high-speed, high-current, low-voltage fuse (Cooper Bussman).	214
<b>Figure 10.40</b>	Typical peak let-through curve for high-speed, high-current, low-voltage fuse (Cooper Bussman).	215
<b>Figure 11.1</b>	Current transformer equivalent circuit ( <i>Source</i> : EPRI, 2006).	217
<b>Figure 11.2</b>	The “knee point” of a CT saturation curve is the point where a tangent to the curve forms a 45° angle with the horizontal axis ( <i>Source</i> : EPRI, 2006).	220
<b>Figure 11.3</b>	Typical waveforms of CT primary and secondary current with DC saturation (Power Systems Relaying Committee, 1976) (c) 1976 IEEE.	223
<b>Figure 11.4</b>	View of a test setup located in test cell.	224
<b>Figure 11.5</b>	Relay shown connected to a test setup. OCP modules shown immediately to the right.	225
<b>Figure 11.6</b>	Example test report for CT saturation ( <i>Source</i> : EPRI (2006)).	226
<b>Figure 11.7</b>	IEEE inverse-time overcurrent curves; time dial set at the midpoint.	229
<b>Figure 11.8</b>	Coordination of a distribution feeder ( <i>Source</i> : EPRI (2006)).	229
<b>Figure 11.9</b>	Numerical protective relays.	230
<b>Figure 11.10</b>	Electromechanical protective relay.	231
<b>Figure 12.1</b>	Schematic of vacuum interrupter ( <i>Source</i> : EPRI (2006)).	238
<b>Figure 12.2</b>	Cutaway view of vacuum interrupter ( <i>Source</i> : EPRI (2006)).	238
<b>Figure 12.3</b>	Thermal expansion method ( <i>Source</i> : EPRI (2006)).	240
<b>Figure 12.4</b>	Rotary arc quenching method ( <i>Source</i> : EPRI (2006)).	240
<b>Figure 12.5</b>	Arc quenching performance versus interrupting current ( <i>Source</i> : EPRI (2006)).	241
<b>Figure 12.6</b>	Relation between O-ring life and temperature ( <i>Source</i> : EPRI (2006)).	243
<b>Figure 12.7</b>	Current-limiting fuses (Mersen).	247
<b>Figure 12.8</b>	Expulsion fuses are contained in a pole mounted fuse cutout (Cooper Power Systems).	248
<b>Figure 12.9</b>	Low-voltage power circuit breaker (General Electric Company).	250
<b>Figure 12.10</b>	Low-voltage insulated-case circuit breakers (General Electric Company).	250
<b>Figure 12.11</b>	Low-voltage molded-case circuit breakers (General Electric Company).	251
<b>Figure 12.12</b>	Overload test circuits based on UL 489 (UL, 2009). (a) Single pole; (b) two single-pole breakers with neutral; for testing each pole separately. (c) two single-pole breakers with neutral; (d) two-pole breaker “slant” rating, for example, 120/240 V, with neutral; (e) two-pole breaker with single rating, no neutral; (f) three-pole breaker; (g) three-pole breaker, three-phase, four-wire circuit, 208Y/120 V, 480Y/277 V, or 600Y/347 V; (h) two-pole breaker for three-phase rating.	255

<b>Figure 12.13</b>	AC overload power factors.	256
<b>Figure 12.14</b>	DC overload time constant.	256
<b>Figure 12.15</b>	Overload test, $\leq 100$ A frame (not to scale).	257
<b>Figure 12.16</b>	Overload test, 101-225 A frame (not to scale).	257
<b>Figure 12.17</b>	Overload test, 226-1600 A frame (not to scale).	258
<b>Figure 12.18</b>	Overload test, 1601-2500 A frame (not to scale).	258
<b>Figure 12.19</b>	Overload test, 2501-6000 A frame (not to scale).	259
<b>Figure 12.20</b>	Endurance test circuits based on UL 489 (UL, 2009). (a) Single pole; (b) two single-pole breakers with neutral; (c) two-pole breaker “slant” rating, for example, 120/240 V, with neutral; (d) two-pole breaker with single rating, no neutral; (e) three-pole breaker; (f) three-pole breaker, three-phase, four-wire circuit, 208Y/120 V, 480Y/277 V, or 600Y/347 V; (g) two-pole breaker for three-phase rating.	260
<b>Figure 12.21</b>	AC endurance power factors.	261
<b>Figure 12.22</b>	DC endurance time constant.	261
<b>Figure 12.23</b>	Endurance test, 100 A frame (not to scale).	262
<b>Figure 12.24</b>	Endurance test, 150 A and 225 A frames (not to scale).	262
<b>Figure 12.25</b>	Endurance test, 600 A frame (not to scale).	262
<b>Figure 12.26</b>	Endurance test, 800 A frame (not to scale).	263
<b>Figure 12.27</b>	Endurance test, 1200 A and 2500 A frames (not to scale).	263
<b>Figure 12.28</b>	Endurance test, 6000 A frame (not to scale).	263
<b>Figure 12.29</b>	Interrupting test circuits based on UL 489 (UL, 2009). (a) Single pole; (b) two single-pole breakers with neutral; (c) two-pole breaker “slant” rating, for example, 120/240 V, with neutral; (d) two-pole breaker with single rating, no neutral for two pole testing; (e) two-pole breaker with single rating, no neutral for single pole testing; (f) three-pole breaker; (g) three-pole breaker; (h) two-pole breaker; (i) three-pole breaker, three-phase four-wire circuit, 208Y/120 V, 480Y/277 V, or 600Y/347 V for three pole test; (j) three-pole breaker 120/240 V; (k) three-pole breaker, three-phase, four-wire circuit, 208Y/120 V, 480Y/277 V, or 600Y/347 V for single pole test. (l) two pole breaker for three-phase rating.	264
<b>Figure 12.30</b>	AC interrupting power factors.	265
<b>Figure 12.31</b>	DC interrupting time constants.	267
<b>Figure 12.32</b>	Interrupting tests (not to scale). (a) Three operations (not to scale); (b) five operations (not to scale); and (c) seven operations (not to scale).	267
<b>Figure 12.33</b>	Supplementary protectors for use in electrical equipment according to UL Standard 1077 (General Electric Company). (a) Single-pole supplementary protector; (b) two-pole supplementary protector; and (c) three-pole supplementary protector.	268

<b>Figure 12.34</b>	Overload and endurance test circuits for supplementary protectors based on UL 1077 (UL, 2005). (a) Single-pole supplementary protector; (b) two single-pole supplementary protectors with neutral; (c) two-pole supplementary protector “slant” rating, 120/240 V, with neutral; (d) two-pole supplementary protector with single rating, no neutral; (e) three-pole supplementary protector; (g) three-pole supplementary protector, three-phase, four-wire circuit, 208Y/120 V, 480Y/277 V or 600Y/347 V; (h) two-pole supplementary protector for three-phase rating.	269
<b>Figure 12.35</b>	Short-circuit test circuits for supplementary protectors based on UL 1077 (UL, 2005). (a) Single-pole supplementary protector; (b) two single-pole supplementary protectors with neutral; (c) two-pole supplementary protector “slant” rating, for example, 120/240 V, with neutral; (d) two-pole supplementary protector with single rating, no neutral; (e) three-pole supplementary protector in three wire circuit; (f) two-pole supplementary protector for three-phase rating; (g) three-pole supplementary protector in four wire circuit; (h) three-pole supplementary protector, 120/240 V; (i) three-pole supplementary protector, three-phase, four-wire circuit, 480Y/277 V or 600Y/347 V; (j) two-pole supplementary protector for three-phase, four-wire circuit, 480Y/277 V or 600Y/347 V.	271
<b>Figure 12.36</b>	Automatic transfer switch ( <i>Source</i> : General Electric Company (2010)).	273
<b>Figure 12.37</b>	Short-circuit test circuit for transfer switches based on UL 1008 (UL, 2011). Three-pole supplementary protector.	276
<b>Figure 12.38</b>	Circuit diagram for EMTP simulation of three-phase rectifier circuit.	281
<b>Figure 12.39</b>	Current–time curve of rectifier short-circuit current for fault in DC system with appreciable inductance and resistance in the DC system, illustrating the components of the fault current waveform.	281
<b>Figure 12.40</b>	Load regulation curve for 70 kA output.	282
<b>Figure 12.41</b>	Load regulation curve for 1.1 kA output.	283
<b>Figure 12.42</b>	Overload and operational performance making and breaking test circuits based on IEC 60947-1 (IEC, 2011b). (a) Single-pole making and breaking equipment on single-phase AC or DC; (b) two-pole making and breaking equipment on single-phase AC or DC; (c) three-pole making and breaking equipment; (d) four-pole making and breaking equipment.	286

<b>Figure 12.43</b>	Short-circuit making and breaking test circuits, based on IEC 60947-1 (IEC, 2011b). (a) Single-pole, short-circuit making and breaking equipment on single-phase AC or DC; (b) two-pole, short-circuit making and breaking equipment on single-phase AC or DC; (c) three-pole, short-circuit making and breaking equipment; (d) four-pole, short-circuit making and breaking equipment.	287
<b>Figure 12.44</b>	Test circuits based on IEC 60898 (IEC, 2011b) ac circuit breakers for households and similar installations. (a) Test circuit for a single-pole circuit breaker; (b) test circuit for a two-pole circuit breaker with one protected pole; (c) test circuit for a two-pole circuit breaker with two protected poles; (d) test circuit for a three-pole circuit breaker; (e) test circuit for a four-pole circuit breaker.	292
<b>Figure 12.45</b>	Test circuits based on IEC 60934 (IEC, 2013b). (a) Test circuit for a single-pole circuit breaker; (b) test circuit for a two-pole circuit breaker with one protected pole; (d) test circuit for a three-pole circuit breaker; (e) test circuit for a four-pole circuit breaker.	295
<b>Figure 13.1</b>	Three-phase side-by-side bus bar configuration.	300
<b>Figure 13.2</b>	Dwight curves for proximity factor (Dwight, 1945).	303
<b>Figure 13.3</b>	Strain bus from suspension insulators (EPRI, 2006).	305
<b>Figure 13.4</b>	Slack bus from post insulators (EPRI, 2006).	306
<b>Figure 13.5</b>	Details of flexible conductor bundle with spacers (EPRI, 2006).	306
<b>Figure 13.6</b>	Curves for determining the factor $\Psi$ from IEC Standard 60865, Figure 7 (EPRI, 2006).	309
<b>Figure 13.7</b>	Horizontal displacement and distance between midpoints of a slack bus (EPRI, 2006).	310
<b>Figure 13.8</b>	Curves for determining the factors $v_1$ and $v_2$ from IEC Standard 60865, Figure 9 (EPRI, 2006).	312
<b>Figure 13.9</b>	Curves for determining the factor $v_3$ from IEC Standard 60865, Figure 10 (EPRI, 2006).	312
<b>Figure 13.10</b>	Curves for determining the factor $\zeta$ as a function of $j$ and from IEC Standard 60865, Figure 11 (EPRI, 2006).	313
<b>Figure 13.11</b>	Curves for determining the factor $\eta$ from IEC Standard 60865, when $2.5 < a_s/d_s \leq 5.0$ , Figure 12a (EPRI, 2006).	314
<b>Figure 13.12</b>	Curves for determining the factor $\eta$ from IEC Standard 60865, when $5.0 < a_s/d_s \leq 10.0$ , Figure 12b (EPRI, 2006).	315
<b>Figure 13.13</b>	Additional curves for determining the factor $\eta$ from IEC Standard 60865, when $10.0 < a_s/d_s \leq 15.0$ , Figure 11 (EPRI, 2006).	316
<b>Figure 13.14</b>	Operation of force safety device (EPRI, 2006).	317
<b>Figure 13.15</b>	Connection of FSD to flexible substation bus structure (EPRI, 2006).	317
<b>Figure 13.16</b>	Limitation of bus tension by FSD (EPRI, 2006).	318

<b>Figure 13.17</b>	Insulator configuration for vertical bus (EPRI, 2006).	320
<b>Figure 13.18</b>	Insulator configuration for horizontal bus (EPRI, 2006).	321
<b>Figure 13.19</b>	GIS enclosure punctured by a rotating arc (EPRI, 2006).	323
<b>Figure 14.1</b>	Cross section of a typical transmission non-ceramic insulator ( <i>Source</i> : EPRI (2006)).	326
<b>Figure 14.2</b>	Flashover damage sustained by an NCI ( <i>Source</i> : EPRI (2006)).	327
<b>Figure 14.3</b>	Horizontal conductor motion during through-fault. (a) End view; (b) side view; and (c) plan view ( <i>Source</i> : EPRI (2006)).	329
<b>Figure 14.4</b>	Conductor geometry ( <i>Source</i> : EPRI (2006)).	330
<b>Figure 14.5</b>	Forces on a conductor ( <i>Source</i> : EPRI (2006)).	331
<b>Figure 14.6</b>	Typical vertical conductor arrangement. (a) Side view and (b) end view ( <i>Source</i> : EPRI (2006)).	333
<b>Figure 14.7</b>	Vertical displacement during fault. (a) At rest and (b) during fault ( <i>Source</i> : EPRI (2006)).	333
<b>Figure 14.8</b>	Conductor angle at support ( <i>Source</i> : EPRI (2006)).	334
<b>Figure 14.9</b>	Derivation of forces on spacers. (a) General view of subspan and (b) midspan cross section of subspan ( <i>Source</i> : EPRI (2006)).	335
<b>Figure 14.10</b>	Details of transmission line conductor bundle with spacers ( <i>Source</i> : EPRI (2006)).	336
<b>Figure 14.11</b>	Parabolic model of subconductor pinch forces ( <i>Source</i> : EPRI (2006)).	337
<b>Figure 15.1</b>	$1.2 \mu\text{s} \times 50 \mu\text{s}$ lightning surge for full-wave BIL test.	339
<b>Figure 15.2</b>	$1.2 \mu\text{s}$ waveform for chopped-wave test.	340
<b>Figure 15.3</b>	$250 \mu\text{s} \times 2500 \mu\text{s}$ switching surge for BSL test.	340
<b>Figure 15.4</b>	Modeling of current limiting fuse. (a) One-line diagram of current-limiting fuse (CLF); (b) simplified simulation model of CLF using switch and nonlinear resistance.	341
<b>Figure 15.5</b>	Overvoltage caused by CLF opening.	342
<b>Figure 15.6</b>	Current limitation caused by CLF interruption of a fault.	342
<b>Figure 15.7</b>	Equivalent circuit for capacitor switching restrike phenomena.	343
<b>Figure 15.8</b>	Transient response for capacitor switching restrike phenomena.	343
<b>Figure 15.9</b>	Cable conductor distributed constant equivalent circuit	344
<b>Figure 15.10</b>	Surge-voltage wave in transit along a line of surge impedance $Z_0$ .	344
<b>Figure 15.11</b>	Traveling current wave reflection and refraction at low to high impedance junction.	345
<b>Figure 15.12</b>	Traveling current wave reflection and refraction at high to low impedance junction.	346

---

# LIST OF TABLES

<b>Table 2.1</b>	Ohmic Conductivity of Some Common Materials (at Room Temperature)	41
<b>Table 2.2</b>	Ohmic Conductivity of Some Body Parts (at Power Frequency)	41
<b>Table 2.3</b>	Surface Resistivity of Wet and Dry Skin (at Power Frequency)	50
<b>Table 2.4</b>	Skin Depth, $\delta$ , of a Copper Conductor	55
<b>Table 2.5</b>	Resistance of Copper Conductors	56
<b>Table 2.6</b>	Resistance of 5 mil (0.127 mm) Copper Shield	57
<b>Table 3.1</b>	Relative Permittivity ( $\epsilon_r$ ) of Some Common Materials (at Room Temperature)	64
<b>Table 3.2</b>	Relative Permittivity ( $\epsilon_r$ ) of Some Body Parts (at Power Frequency)	64
<b>Table 3.3</b>	Dielectric Constants of Some Cable Insulation Materials	73
<b>Table 4.1</b>	Inductance of 5 mil (0.127 mm) Copper Shield	83
<b>Table 4.2</b>	Typical Cable Resistance, Inductance, Capacitance, and Surge Impedance at 20 kHz	84
<b>Table 4.3</b>	Sequence Impedances for the Example of Two Parallel 6" $\times$ 1/2" Bus Bars Per Phase	89
<b>Table 6.1</b>	Current Thresholds (mA) for 60 Hz Exposure	103
<b>Table 6.2</b>	Adult Total Body Impedance ( $\Omega$ ) Including Skin Resistance, at Power Frequencies for Contact of Large Surface Area, as a Function of Exposure Voltage	107
<b>Table 6.3</b>	Typical Ranges of Current Which flow Through the Heart	109
<b>Table 6.4</b>	IEC Heart-Current Factor	109
<b>Table 6.5</b>	Typical Ranges of Resistance ( $\Omega$ ) for Hand to Foot Conduction	110
<b>Table 6.6</b>	Typical Ranges of Resistance ( $\Omega$ ) for Foot to Foot Conduction	110
<b>Table 6.7</b>	Typical Ranges of Resistance ( $\Omega$ ) for Hand to Hand Conduction	111
<b>Table 6.8</b>	Contact Resistance of a Single Bare Foot and Calculated Foot to Foot Current	112
<b>Table 6.9</b>	Contact Resistance of a Single Bare Foot and Calculated Hand to Foot Current	113
<b>Table 7.1</b>	Critical Parameters in Ground Grid Design	119
<b>Table 7.2</b>	Sample Procedure for Ground Grid Design	120
<b>Table 7.3</b>	Fusing Currents in Symmetrical kA for Annealed Soft-Drawn 100% Conductivity Copper Conductors Versus $X/R$ Ratio. All Clearing Times 0.5 s.	122
<b>Table 7.4</b>	Design Data for Ground Grid Example	128
<b>Table 8.1</b>	Test Currents and Fusing Currents for Annealed Soft-Drawn 100% Conductivity Copper Conductors	142

<b>Table 8.2</b>	Fault Current Tests for Connectors	144
<b>Table 10.1</b>	Arc Flash Results at BUS-4 Versus Time Dial Setting for Relay 50/51-1 for Figure 10.1	183
<b>Table 10.2</b>	Arc Flash Results at BUS-16 Versus Time Dial Setting for Relay R1	186
<b>Table 10.3</b>	Arc Flash Results at BUS-16 Versus Fuse Type (R1 at 6.0AT, 0.5TD)	195
<b>Table 12.1</b>	Typical Class S1 (formerly classified as indoor) Circuit Breakers for Cable Systems Rated Below 100 kV	244
<b>Table 12.2</b>	Typical Class S2 (formerly classified as outdoor) Circuit Breakers for Line Systems Rated Below 100 kV	245
<b>Table 12.3</b>	Typical Circuit Breakers Rated 100 kV and Above Including Circuit Breakers Applied in Gas-Insulated Substations	246
<b>Table 12.4</b>	Preferred Ratings for Fuses	247
<b>Table 12.5</b>	Standard Ampere Ratings for Circuit Breakers	253
<b>Table 12.6</b>	Voltage Ratings for MCCBs from UL 489 Clause 8.2	253
<b>Table 12.7</b>	Applicable Current-Interrupting Ratings (AC or DC) From UL 489, Table 8-1	254
<b>Table 12.8</b>	Overload Tests at 600% of Rated Amperes (UL 489, Clause. 7.1.3.7-8 and 7.1.3.14)	254
<b>Table 12.9</b>	Operations for Overload Test Operations (600% of Rated Current Unless Otherwise Noted)	257
<b>Table 12.10</b>	Operations for Endurance Test Operations (100% of Rated Current)	259
<b>Table 12.11</b>	Test Currents, Power Factors, and DC Time Constants for Interrupting Tests	265
<b>Table 12.12</b>	Operations for Interrupting Test Operations	266
<b>Table 12.13</b>	Maximum Voltage for Tests to be Applied for Breakers Used in UPS	266
<b>Table 12.14</b>	Overload Test for Breakers Used in UPS	266
<b>Table 12.15</b>	Endurance Test for Breakers Used in UPS	266
<b>Table 12.16</b>	Overload Test Currents and Power Factor for Supplementary Protectors	268
<b>Table 12.17</b>	Short-Circuit Test Currents and Power Factor for Supplementary Protectors	270
<b>Table 12.18</b>	Applicable Voltage Ratings for Transfer Switches	273
<b>Table 12.19</b>	Short-Circuit Ratings for Transfer Switches	274
<b>Table 12.20</b>	Overload Test Currents and Power Factor for Transfer Switches	274
<b>Table 12.21</b>	Duty Cycles for Overload Tests of Transfer Switches	275
<b>Table 12.22</b>	Duty Cycles for Endurance Tests of Transfer Switches	275
<b>Table 12.23</b>	Short-Circuit Test Currents and Power Factor for Transfer Switches	275
<b>Table 12.24</b>	Standard Frame Sizes for AC and DC LVPCBs	277
<b>Table 12.25</b>	Standard Fuse Sizes for AC LVPCBs	277
<b>Table 12.26</b>	Applicable Voltage Ratings for AC LVPCBs	277
<b>Table 12.27</b>	Overload Tests for AC LVPCBs at 600% of Rated Amperes	278

<b>Table 12.28</b>	Endurance Tests for AC LVPCBs at 600% of Rated Amperes	279
<b>Table 12.29</b>	Maximum and Minimum Short-Circuit Ratings (kA) for AC LVPCBs	279
<b>Table 12.30</b>	Standard Nominal and Maximum Rated Voltage for DC LVPCBs	280
<b>Table 12.31</b>	Standard Nominal Rated AC Voltages for IEC Rated Equipment	284
<b>Table 12.32</b>	Standard DC Voltages for IEC Rated Traction Systems	284
<b>Table 12.33</b>	Standard IEC Current Ratings for Equipment	285
<b>Table 12.34</b>	IEC Short-Circuit Tests for Switchgear and Controlgear at Rated Short-Circuit Amperes	288
<b>Table 12.35</b>	IEC Short-Circuit Tests and Overload Test Currents for Circuit Breakers	288
<b>Table 12.36</b>	Operating Rates for Overload Performance and Operational Performance Tests According to IEC 60947-2	289
<b>Table 12.37</b>	Time Interval Between Operations for Making and Breaking Tests of Contactors and Starters IEC 60947-4-1	289
<b>Table 12.38</b>	Preferred Values of Rated Current (A) Per IEC 60898-1	290
<b>Table 12.39</b>	Standard and Preferred (*) Values of Rated Short Circuit Capacity (A) per IEC 60898-1	291
<b>Table 12.40</b>	Ratio “ <i>k</i> ” Between Service Short-Circuit Capacity and Rated Short-Circuit Capacity, Per IEC 60898-1	291
<b>Table 12.41</b>	Test Power Factor for AC Short-Circuit Tests, Per IEC 60898-1	294
<b>Table 12.42</b>	Rated Voltages for Circuit Breakers Under IEC 60934	294
<b>Table 12.43</b>	Test Power Factor for AC Conditional Short-Circuit Current Tests, Per IEC 60934	297
<b>Table 12.44</b>	Test Time Constants for DC Conditional Short-Circuit Current Tests, per IEC 60934	297
<b>Table 13.1</b>	Allowable Stress for Common Conductor Materials	301
<b>Table 13.2</b>	Conductor Span Constant $K_S$	302
<b>Table 13.3</b>	Modulus of Elasticity for Common Conductor Materials	304
<b>Table 13.4</b>	Insulator Force Multipliers	322
<b>Table 13.5</b>	GIS Short-Circuit Ratings	322
<b>Table 13.6</b>	GIS Phase-to-Ground Burn-Through Times	323
<b>Table 15.1</b>	Basic Impulse Insulation Levels (BILs) of Power Circuit Breakers, Switchgear Assemblies, and Metal-Enclosed Buses	347
<b>Table 15.2</b>	Impulse Test Levels for Liquid-Immersed Power Transformers	347
<b>Table 15.3</b>	Impulse Test Levels for Liquid-Immersed Distribution Transformers	348
<b>Table 15.4</b>	Impulse Test Levels for Dry-Type Transformers, Delta or Ungrounded Wye	348
<b>Table 15.5</b>	Impulse Test Levels for Dry-Type Transformers, Grounded Wye	348
<b>Table 15.6</b>	Rotating Machine 60 Hz, 1 min High Potential Test Voltages, Phase to Ground	349
<b>Table 15.7</b>	Rotating-Machine 60 Hz Winding Impulse Voltages, Phase to Ground	349

