

CONTENTS

PREFACE	XV
ACKNOWLEDGMENTS	XVII
ABOUT THE COMPANION WEBSITE	XIX
1 GLOBAL WARMING AND MITIGATION	1
1.1 Introduction—Motivation / 1	
1.2 Fossil Fuel / 1	
1.3 Energy Use and Industrialization / 2	
1.4 New Oil Boom—Hydraulic Fracturing (Fracking) / 3	
1.5 Nuclear Energy / 3	
1.6 Global Warming / 3	
1.7 Estimation of Future CO ₂ / 7	
1.8 Green and Renewable Energy Sources / 9	
1.8.1 Hydrogen / 9	
1.8.2 Solar and Photovoltaic / 10	
1.8.3 Wind Power / 11	
1.8.4 Geothermal / 11	
1.8.5 Biomass / 12	
1.8.6 Ethanol / 12	
1.9 Energy Units and Conversions / 12	
1.10 Estimating the Cost of Energy / 16	

1.11	Conclusion / 19
	Problems / 19
	References / 21
	Additional Resources / 23
	Energy Quest / 23

2 DESIGN OF PHOTOVOLTAIC MICROGRID GENERATING STATION

25

2.1	Introduction / 25
2.2	Photovoltaic Power Conversion / 30
2.3	Photovoltaic Materials / 31
2.4	Photovoltaic Characteristics / 32
2.5	Photovoltaic Efficiency / 35
2.6	PV Generating Station / 35
2.7	Design of Photovoltaic Grids / 39
2.7.1	Three-Phase Power / 42
2.8	Design Examples for PV Generating Stations / 44
2.9	Modeling of a Photovoltaic Module / 73
2.10	Measurement of Photovoltaic Performance / 74
2.11	Maximum Power Point of a Photovoltaic Plant / 76
2.12	Control of Maximum Power Point of Photovoltaic Plants / 78
2.13	Battery Storage Systems / 82
2.14	Storage Systems Based on a Single-Cell Battery / 84
2.15	The Energy Yield of a Photovoltaic Module and the Angle of Incidence / 94
2.16	Photovoltaic Generation Technology / 95
2.17	The Estimation of Photovoltaic Module Model Parameters / 95
2.18	Conclusion / 97
	Problems / 98
	References / 105
	Additional Resources / 107

3 FUNDAMENTALS OF POWER CIRCUIT ANALYSIS

109

3.1	Introduction / 109
3.2	Batteries / 110
3.3	DC Circuits and Ohms Law / 110
3.4	Common Terms / 112
3.5	Elements of Electrical Circuits / 112
3.5.1	Inductors / 113
3.5.2	Capacitors / 116

3.6	Calculating Power Consumption / 119
3.6.1	Complex Domain / 119
3.6.2	Diodes / 127
3.6.3	Controllable Switch / 127
3.6.4	The DC–DC Converters in Green Energy Grids / 128
3.6.5	The Step-Up Converter / 129
3.6.6	The Step-Down Converter / 132
3.6.7	The Buck–Boost Converter / 138
3.7	Solar and Wind Power Grids / 143
3.8	Single-Phase DC–AC Inverters with Two Switches / 144
3.9	Single-Phase DC–AC Inverters with a Four-Switch Bipolar Switching Method / 154
3.10	Pulse Width Modulation with Unipolar Voltage Switching for a Single-Phase Full-Bridge Inverter / 158
3.11	Three-Phase DC–AC Inverters / 160
3.12	Microgrid of Renewable Energy / 167
3.13	The Sizing of an Inverter for Microgrid Operation / 170
	Problems / 172
	References / 177

4 SMART DEVICES AND ENERGY EFFICIENCY MONITORING SYSTEMS

178

4.1	Introduction / 178
4.2	Measurement Methods / 179
4.2.1	Kilowatt-Hours Measurements / 179
4.2.2	Current and Voltage Measurements / 180
4.2.3	Power Measurements at 60 or 50 Hz / 180
4.2.4	Analog-to-Digital Conversions / 181
4.2.5	Root Mean Square (RMS) Measurement Devices / 182
4.3	Energy Monitoring Systems / 182
4.4	Smart Meters: Concepts, Features, and Roles in Smart Grid / 183
4.4.1	Power Monitoring and Scheduling / 183
4.4.2	Communication Systems / 185
4.4.3	Network Security and Software / 187
4.4.4	Smart Phone Applications / 190
4.5	Summary / 190
	Problems / 191
	References / 191

5	LOAD ESTIMATION AND CLASSIFICATION	193
5.1	Introduction / 193	
5.2	Load Estimation of a Residential Load / 193	
5.3	Service Feeder and Metering / 210	
5.3.1	Assumed Wattages / 210	
	Problems / 213	
	References / 216	
6	ENERGY SAVING AND COST ESTIMATION OF INCANDESCENT AND LIGHT EMITTING DIODES	217
6.1	Lighting / 217	
6.2	Comparative Performance of LED, Incandescent, and LFC Lighting / 218	
6.3	LED Energy Saving / 224	
6.4	Return on Investment on LED Lighting / 225	
6.5	The Annual Carbon Emissions / 226	
	References / 226	
7	THREE-PHASE POWER AND MICROGRIDS	228
7.1	Introduction / 228	
7.2	The Basic Concept of AC Generator / 228	
7.3	Three-Phase AC Generator / 229	
7.4	The Synchronization of Generator to Power Grids / 232	
7.5	Power Factor and Active and Reactive Power Concepts / 233	
7.6	Three-Phase Power Grids / 236	
7.7	Calculating Power Consumption / 239	
7.8	One-Line Diagram Representation of Three-Phase Power Grids / 241	
7.9	Load Models / 245	
7.10	Transformers in Electric Power Grids / 249	
7.10.1	A Short History of Transformers / 249	
7.10.2	Transmission Voltage / 250	
7.10.3	Transformers / 251	
7.11	Modeling a Microgrid System / 255	
7.11.1	The Per Unit System / 255	
7.12	Modeling Three-Phase Transformers / 265	
7.13	Tap Changing Transformers / 268	
7.14	Modeling Transmission Lines / 270	

7.15 The Construction of a Power Grid System / 282

7.16 Microgrid of Renewable Energy Systems / 289

Problems / 294

References / 302

8 MICROGRID WIND ENERGY SYSTEMS

304

8.1 Introduction / 304

8.2 Wind Power / 305

8.3 Wind Turbine Generators / 309

8.4 The Modeling of Induction Machines / 313

8.4.1 Calculation of Slip / 320

8.4.2 The Equivalent Circuit of an Induction Machine / 321

8.5 Power Flow Analysis of an Induction Machine / 325

8.6 The Operation of an Induction Generator / 329

8.7 Dynamic Performance / 342

8.8 The Doubly Fed Induction Generator / 349

8.9 Brushless Doubly Fed Induction Generator Systems / 351

8.10 Variable-Speed Permanent Magnet Generators / 352

8.11 A Variable-Speed Synchronous Generator / 353

8.12 A Variable-Speed Generator With A Converter Isolated from the Grid / 354

Problems / 356

References / 358

9 MARKET OPERATION OF SMART POWER GRIDS

361

9.1 Introduction—Classical Power Grids / 361

9.2 Power Grid Operation / 362

9.3 Vertically and Market-Structured Power Grid / 368

9.3.1 Who Controls the Power Grids? / 369

9.4 The Operation Control of a Power Grid / 371

9.5 Load-Frequency Control / 372

9.6 Automatic Generation Control / 378

9.7 Operating Reserve Calculation / 383

9.8 Basic Concepts of a Smart Power Grid / 383

9.9 The Load Factor / 392

9.10 The Load Factor and Real-Time Pricing / 394

9.11 A Cyber-Controlled Smart Grid / 397

9.12 Smart Grid Development / 400

9.13 Smart Microgrid Renewable and Green Energy Systems / 401

9.14 The Impact of Renewable Power on Voltage Stability and
Reactive Power Supply / 408

Problems / 409

References / 410

Additional Resources / 411

**10 LOAD FLOW ANALYSIS OF POWER GRIDS AND
MICROGRIDS**

413

10.1 Introduction / 413

10.2 Voltage Calculation in Power Grid Analysis / 414

10.3 The Power Flow Problem / 417

10.4 Load Flow Study as a Power System Engineering Tool / 418

10.5 Bus Types / 419

10.6 General Formulation of the Power Flow Problem / 423

10.7 The Bus Admittance Model / 426

10.8 The Bus Impedance Matrix Model / 427

10.9 Formulation of the Load Flow Problem / 429

10.10 The Gauss–Seidel Y_{Bus} Algorithm / 432

10.11 The Gauss–Seidel Z_{Bus} Algorithm / 437

10.12 Comparison of the Y_{Bus} and Z_{Bus} Power Flow Solution
Methods / 443

10.13 The Synchronous and Asynchronous
Operation of Microgrids / 444

10.14 An Advanced Power Flow Solution Method: The
Newton–Raphson Algorithm / 445

10.14.1 The Newton–Raphson Algorithm / 449

10.15 General Formulation of the Newton–Raphson
Algorithm / 455

10.16 The Decoupled Newton–Raphson Algorithm / 458

10.17 The Fast Decoupled Load Flow Algorithm / 460

10.18 Analysis of a Power Flow Problem / 461

Problems / 473

References / 485

Additional Resources / 486

11 POWER GRID AND MICROGRID FAULT STUDIES

488

11.1 Introduction / 488

11.2 Power Grid Fault Current Calculation / 489

11.3 Symmetrical Components / 492

11.4 Sequence Networks for Power Generators / 498

11.5	The Modeling of a Photovoltaic-Generating Station /	501
11.6	Sequence Networks for Balanced Three-Phase Transmission Lines /	501
11.7	Ground Current Flow in Balanced Three-Phase Transformers /	504
11.8	Zero Sequence Network /	506
11.8.1	Transformers /	506
11.8.2	Load Connections /	508
11.8.3	Power Grid /	508
11.9	Fault Studies /	512
11.9.1	Balanced Three-Phase Fault Analysis /	514
11.9.2	Unbalanced Faults /	531
11.9.3	Single Line-to-Ground Faults /	532
11.9.4	Double Line-to-Ground Faults /	534
11.9.5	Line-to-Line Faults /	536
	Problems /	550
	References /	555

INDEX