NEWNES POWER ENGINEERING SERIES

Power Electronic Control in Electrical Systems

E Acha • V G Agelidis
O Anaya-Lara • T J E Miller

Newnes

Contents

Preface xi

1 Electrical power systems – an overview 1
- 1.1 Introduction 1
- 1.2 Background 1
- 1.3 General composition of the power network 4
  - 1.3.1 Generation 6
  - 1.3.2 Transmission 8
  - 1.3.3 Distribution 13
  - 1.3.4 Utilization 16
- 1.4 An overview of the dynamic response of electrical power networks 18
  - 1.4.1 Transient stability 20
- 1.5 Snapshot-like power network studies 23
  - 1.5.1 Power flow studies 23
  - 1.5.2 Optimal power flow studies 24
  - 1.5.3 Fault studies 24
  - 1.5.4 Random nature of system load 26
  - 1.5.5 Non-linear loads 27
- 1.6 The role of computers in the monitoring, control and planning of power networks 27
  - 1.6.1 Energy control centres 27
  - 1.6.2 Distribution networks 28
  - 1.6.3 Planning 29
- 1.7 Conclusion 29

2 Power systems engineering – fundamental concepts 31
- 2.1 Reactive power control 31
- 2.2 Conventions used in power engineering 34
- 2.3 Basic source/load relationships 35
  - 2.3.1 Fault level and circuit-breaker ratings 35
  - 2.3.2 Thévenin equivalent circuit model of a power system 36

	2.3.3	Loads and phasor diagrams	36
	2.3.4	The symmetrical system	38
2.4	Complex power, apparent power, real and reactive power		38
2.5	Leading and lagging loads		40
2.6	Power factor correction		42
2.7	Compensation and voltage control		44
	2.7.1	System load line	46
2.8	Control of power and frequency		47
	2.8.1	Relationships between power, reactive power, voltage levels and load angle	49
2.9	Three-phase systems		51
	2.9.1	Development of three-phase systems	51
	2.9.2	The wye–delta transformation	54
	2.9.3	Balancing an unbalanced load	54
2.10	Power flow and measurement		57
	2.10.1	Single-phase	57
	2.10.2	Two-phase	58
	2.10.3	Three-phase	58
	2.10.4	Power measurement	59
2.11	Polyphase transformers		64
	2.11.1	Definition	64
	2.11.2	Functions	65
	2.11.3	Parallel operation	68
	2.11.4	Zero-sequence effects in three-phase transformers	70
	2.11.5	Providing a path for zero-sequence currents	72
2.12	Harmonics		72
	2.12.1	Harmonic power	73
	2.12.2	RMS values in the presence of harmonics	73
	2.12.3	Phase sequence of harmonics in balanced three-phase systems	74
	2.12.4	Harmonics in balanced networks	75
	2.12.5	AC line harmonics of three-phase rectifier	76
2.13	Per-unit quantities		78
	2.13.1	Standard formulas for three-phase systems	79
	2.13.2	Changing base	80
	2.13.3	Transformers in per-unit systems	80
2.14	Conclusion		81
3	**Transmission system compensation**		82
3.1	Introduction		82
3.2	Uncompensated lines		83
	3.2.1	Voltage and current equations of a long, lossless transmission line	83
	3.2.2	Surge impedance and natural loading of a transmission line	86
	3.2.3	The uncompensated line on open-circuit	87

3.3 Uncompensated lines under load 89
3.3.1 Radial line with fixed sending-end voltage 89
3.3.2 Uncompensated symmetrical line: variation of voltage and reactive power with load 90
3.3.3 Maximum power and steady-state stability 92
3.4 Compensated transmission lines 94
3.4.1 Passive and active compensators 94
3.5 Static shunt compensation 95
3.5.1 Multiple shunt reactors along a long line 97
3.5.2 Voltage control by means of switched shunt compensation 98
3.5.3 The mid-point shunt compensator 99
3.6 Series compensation 101
3.6.1 Power-transfer characteristics and maximum transmissible power 102
3.7 Conclusion 104

4 Power flows in compensation and control studies 106
4.1 Introduction 106
4.2 FACTS equipment representation in power flows 107
4.2.1 The SVC 107
4.2.2 The TCSC 108
4.2.3 The static phase shifter 110
4.2.4 The STATCOM 111
4.2.5 The DVR 112
4.2.6 The UPFC 113
4.2.7 The HVDC-Light 115
4.3 Fundamental network equations 116
4.3.1 Nodal admittances 116
4.3.2 Numerical example 1 117
4.3.3 Rules for building the nodal admittance matrix 118
4.3.4 Nodal impedances 119
4.3.5 Numerical example 2 120
4.4 The power flow theory 121
4.4.1 Basic concepts 121
4.4.2 Conventional power plant representation 122
4.4.3 Nodal impedance based power flow method 124
4.4.4 Newton–Raphson power flow method 126
4.4.5 Numerical example 3 130
4.4.6 Numerical example 4 132
4.5 Reactive power control 134
4.5.1 General aspects 134
4.5.2 SVC power flow modelling 135
4.5.3 Numerical example 5 136
4.5.4 STATCOM power flow modelling 137
4.6 Active power control 139
4.6.1 General aspects 139

4.6.2 TCSC power flow modelling 139
4.6.3 Numerical example 6 140
4.6.4 SPS power flow modelling 140
4.6.5 Numerical example 7 142
4.7 Combined active and reactive power control 143
4.7.1 General aspects 143
4.7.2 Simple UPFC power flow modelling 143
4.7.3 Advanced UPFC power flow modelling 144
4.7.4 Numerical example 8 147
4.7.5 HVDC Light power flow modelling 149
4.7.6 Numerical example 9 150
4.8 Conclusion 152

5 Power semiconductor devices and converter hardware issues 153
5.1 Introduction 153
5.2 Power semiconductor devices 153
5.2.1 Diode 154
5.2.2 Thyristor 156
5.2.3 Light-triggered thyristor (LTT) 158
5.2.4 Desired characteristics of fully-controlled power semiconductors 159
5.2.5 Gate-turn-off thyristor 162
5.2.6 Metal-oxide-semiconductor field effect transistor 163
5.2.7 Insulated-gate bipolar transistor 164
5.2.8 MOS-controlled thyristor 165
5.2.9 Other semiconductor devices 166
5.2.10 Semiconductor switching-power performance 166
5.3 Power modules 167
5.4 Passive components 167
5.5 Ancillary equipment 168
5.6 Cooling systems 168
5.7 Component layout 171
5.8 Protection of semiconductors – snubber circuits 171
5.9 Current trends in power semiconductor technology 174
5.10 Conclusion 175

6 Power electronic equipment 177
6.1 Introduction 177
6.2 Thyristor-controlled equipment 178
6.2.1 Thyristor-controlled reactor (TCR) 178
6.2.1.1 Principles of operation of the TCR 178
6.2.1.2 Fundamental voltage/current characteristic 180
6.2.1.3 Harmonics 182
6.2.2 The thyristor-controlled transformer (TCT) 185
6.2.3 The TCR with shunt capacitors 186
6.2.4 The thyristor-switched capacitor (TSC) 188
6.2.4.1 Principles of operation 188

6.2.5 Switching transients and the concept of transient-free switching 190
6.2.5.1 Ideal transient-free switching 190
6.2.5.2 Switching transients in the general case 192
6.2.5.3 Switching a discharged capacitor 196
6.3 Voltage-source converters (VSCs) and derived controllers 197
6.3.1 Single-phase half-bridge VSC 197
6.3.2 Single-phase full-bridge VSC 201
6.3.3 Conventional three-phase six-step VSC 206
6.3.4 Single-phase half-bridge neutral-point-clamped (NPC) VSC 210
6.3.5 Single-phase full-bridge NPC VSC 212
6.3.6 Other multilevel converter topologies 215
6.3.7 Three-level three-phase NPC VSC 222
6.3.8 Pulse-width modulated (PWM) VSCs 222
6.4 Uninterruptible Power Supplies (UPSs) 229
6.5 Dynamic voltage restorer (DVR) 232
6.6 Energy storage systems 233
6.6.1 Flywheel energy storage systems 233
6.6.2 Superconducting magnetic energy storage (SMES) 238
6.6.3 Other energy storage systems 240
6.7 HVDC 241
6.7.1 HVDC schemes and control 244
6.7.2 Advanced concepts in conventional HVDC applications 249
6.7.3 HVDC based on voltage-source converters 249
6.7.4 Multilevel VSCs and HVDC 252
6.8 Active filters (AFs) 253
6.9 Combined active and passive filters 259
6.10 Advanced concepts in reactive power control equipment 261
6.11 Conclusion 261

7 Harmonic studies of power compensating plant 263
7.1 Introduction 263
7.2 Effect of harmonics on electrical equipment 264
7.3 Resonance in electric power systems 265
7.3.1 Numerical example 1 267
7.4 Thyristor-controlled reactors 269
7.4.1 TCR periodic characteristics 269
7.4.2 TCR currents in harmonic domain 271
7.4.2.1 Harmonic switching vectors 272
7.4.2.2 Harmonic admittances 273
7.4.2.3 Harmonic Norton and Thévenin equivalent circuits 273
7.4.2.4 Constraint equations 274
7.4.3 Three-phase TCRs 275
7.4.3.1 Numerical example 2 276
7.4.3.2 Numerical example 3 277

7.5 SVC representations 279
7.6 Thyristor-controlled series compensation 280
7.6.1 Main parameters and operating modes 280
7.6.2 TCSC harmonic domain modelling 286
7.6.2.1 Single-phase TCSC representation 286
7.6.2.2 Impedance characteristics 286
7.6.2.3 Three-phase TCSC representation 287
7.7 TCSC systems 287
7.8 Conclusion 289

8 Transient studies of FACTS and Custom Power equipment 290
8.1 Introduction 290
8.2 Electromagnetic transient analysis 291
8.3 Electromagnetic transient simulator PSCAD/EMTDC 292
8.3.1 Creation of a new project and data entry 293
8.3.2 Generation of the circuit schematic diagram using `Draft` 295
8.3.3 Transient simulation using `RunTime Executive` 298
8.3.4 Plotting and analysis of results using `MultiPlot` 298
8.4 Static Var Compensator (SVC) 300
8.5 Thyristor-Controlled Series Compensator (TCSC) 311
8.5.1 Example 1 312
8.5.2 Example 2 313
8.6 Static Compensator (STATCOM) 320
8.6.1 STATCOM used as a FACTS controller 324
8.6.2 Distribution Static Compensator (D-STATCOM) 330
8.7 Dynamic Voltage Restorer (DVR) 336
8.8 Power Factor Correction (PFC) 342
8.9 Active filters (AFs) 352
8.9.1 Shunt active filter 356
8.10 Solid-State Transfer Switch (SSTS) 367
8.11 Conclusion 372

9 Examples, problems and exercises 373
9.1 Simple exercises 373
9.2 A basic worked example – leading and lagging loads 375
9.3 Simple basic problems 376
9.3.1 Answers to problems in Section 9.3 377
9.4 Worked examples 378

Appendix 407

Bibliography 427

Index 439