CONTENTS

LIST OF FIGURES xvii
LIST OF TABLES xxv
CONTRIBUTORS xxvii
FOREWORD xxix
PREFACE xxxi
ACKNOWLEDGMENTS xxxv
ACRONYMS xxxvii

PART I HVDC GRIDS IN THE ENERGY VISION OF THE FUTURE

CHAPTER 1 DRIVERS FOR THE DEVELOPMENT OF HVDC GRIDS 3
   Dirk Van Hertem
   1.1 Introduction 3
   1.2 From the Vertically Integrated Industry to Fast Moving Liberalized Market 3
      1.2.1 Brief History of the Transmission System Before Liberalization 3
   1.3 Drivers for Change 5
      1.3.1 Liberalized Energy Market 6
      1.3.2 More Renewables in the Energy Mix 8
   1.4 Investments in the Grid 12
      1.4.1 Why Investments Are Needed in the Transmission System 12
      1.4.2 Difficulties with New Transmission Lines 13
      1.4.3 Available Investments Technologies 15
      1.4.4 HVDC Technology 16
   1.5 Towards HVDC Grids 17
      1.5.1 Transmission Technology 18
      1.5.2 Why Not AC? 18
      1.5.3 HVDC Grids as a Supergrid 20
   1.6 Conclusions 22
   References 22

CHAPTER 2 ENERGY SCENARIOS: PROJECTIONS ON EUROPE’S FUTURE GENERATION AND LOAD 25
   Erik Delarue and Cedric De Jonghe
   2.1 Introduction 25
   2.2 System Setting 26
      2.2.1 Supply 26
CONTENTS

2.2.2 Demand 28
2.2.3 Matching Supply and Demand 30
2.2.4 European Energy Policy 32

2.3 Scenarios for Europe’s Energy Provision 34
2.3.1 The Role of Defining Scenarios 34
2.3.2 Supply Side 35
2.3.3 Demand Side 37
2.3.4 Implications Towards the Grid 38
2.3.5 International Cooperation and Market Perspective 40

2.4 Conclusions 40
References 41

PART II HVDC TECHNOLOGY AND TECHNOLOGY FOR OFFSHORE GRIDS

CHAPTER 3 HVDC TECHNOLOGY OVERVIEW 45
Gen Li, Chuanyue Li, and Dirk Van Hertem

3.1 Introduction 45
3.2 LCC-HVDC Systems 45
3.2.1 Configurations 47
3.2.2 Reactive Power Properties of LCC HVDC 48
3.3 LCC-HVDC Converter Station Technology 51
3.3.1 Converter Station 51
3.3.2 Transformers 52
3.3.3 Filters and Reactive Compensation 52
3.3.4 Other Required Components 52
3.4 VSC-HVDC Systems 53
3.5 VSC-HVDC Converter Station Technology 53
3.5.1 Converter Configurations 56
3.5.2 Switching Components 64
3.5.3 AC Filters 64
3.5.4 Transformers 65
3.5.5 AC Phase Reactor and Arm Inductor in a Multilevel Converter 66
3.5.6 DC Capacitors 67
3.5.7 DC Chopper 68
3.5.8 HVDC Switchgear 69
3.6 Transmission Lines 72
3.6.1 HVDC Overhead Lines 73
3.6.2 HVDC Cables 73
3.7 Conclusions 76
References 76

CHAPTER 4 COMPARISON OF HVAC AND HVDC TECHNOLOGIES 79
Hakan Ergun and Dirk Van Hertem

4.1 Introduction 79
4.2 Current Technology Limits 79
4.2.1 Onshore Equipment 80
4.2.2 Offshore Equipment 80
4.2.3 Current Ratings for HVDC Technology 81
### PART III PLANNING AND OPERATION OF HVDC GRIDS

#### CHAPTER 7 HVDC GRID PLANNING

Hakan Ergun and Dirk Van Hertem

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1 Context of Transmission System Planning</td>
<td>143</td>
</tr>
<tr>
<td>7.1.1 Functionality of Grids</td>
<td>144</td>
</tr>
<tr>
<td>7.1.2 The Four W’s of the Transmission Expansion Problem</td>
<td>145</td>
</tr>
<tr>
<td>7.1.3 Where to Invest?</td>
<td>145</td>
</tr>
<tr>
<td>7.1.4 What Type of Investment?</td>
<td>148</td>
</tr>
<tr>
<td>7.1.5 When to Invest?</td>
<td>149</td>
</tr>
<tr>
<td>7.1.6 Who Pays for the Investment?</td>
<td>150</td>
</tr>
<tr>
<td>7.1.7 Other Influential Factors</td>
<td>150</td>
</tr>
<tr>
<td>7.1.8 Transmission Grid Planning in the Liberalized Electricity Market</td>
<td>151</td>
</tr>
<tr>
<td>7.1.9 Cross Border Investments—The Investment Paradox</td>
<td>151</td>
</tr>
<tr>
<td>7.2 Transmission Expansion Optimization Methodologies</td>
<td>152</td>
</tr>
<tr>
<td>7.2.1 Classification by Solution Method</td>
<td>152</td>
</tr>
<tr>
<td>7.2.2 Classification by Planning Horizon</td>
<td>153</td>
</tr>
<tr>
<td>7.2.3 Classification by Power System Structure</td>
<td>154</td>
</tr>
<tr>
<td>7.2.4 Deterministic versus Nondeterministic Expansion Problems</td>
<td>154</td>
</tr>
<tr>
<td>7.3 Specialties of Grid Planning with HVDC Technology</td>
<td>155</td>
</tr>
<tr>
<td>7.3.1 Controllability</td>
<td>155</td>
</tr>
<tr>
<td>7.3.2 Offshore Applications</td>
<td>156</td>
</tr>
<tr>
<td>7.4 Illustrative Examples</td>
<td>157</td>
</tr>
<tr>
<td>7.4.1 Optimal Routing, Rating, and Technology</td>
<td>157</td>
</tr>
<tr>
<td>7.4.2 Effect of Security Constraints</td>
<td>159</td>
</tr>
<tr>
<td>7.4.3 Optimal Timing and Investment Coordination</td>
<td>162</td>
</tr>
<tr>
<td>7.4.4 Conclusions</td>
<td>167</td>
</tr>
</tbody>
</table>

#### References | 167

#### CHAPTER 8 HVDC GRID LAYOUTS

Jun Liang, Oriol Gomis-Bellmunt, and Dirk Van Hertem

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1 What is an HVDC Grid?</td>
<td>172</td>
</tr>
<tr>
<td>8.2 HVDC Grid Topologies</td>
<td>172</td>
</tr>
<tr>
<td>8.2.1 Radial Topologies</td>
<td>174</td>
</tr>
<tr>
<td>8.2.2 Meshed Topologies</td>
<td>174</td>
</tr>
<tr>
<td>8.3 Topologies of HVDC Grids for Offshore Wind Power Transmission</td>
<td>176</td>
</tr>
<tr>
<td>8.3.1 General Ring Topology</td>
<td>177</td>
</tr>
<tr>
<td>8.3.2 Star Topology (ST)</td>
<td>178</td>
</tr>
<tr>
<td>8.3.3 Star with a General Ring Topology (SGRT)</td>
<td>178</td>
</tr>
<tr>
<td>8.3.4 Wind Farm Ring Topology (WFRT)</td>
<td>179</td>
</tr>
<tr>
<td>8.3.5 Substations Ring Topology (SSRT)</td>
<td>181</td>
</tr>
<tr>
<td>8.3.6 Comparison of the Topologies</td>
<td>182</td>
</tr>
<tr>
<td>8.4 HVDC Converter Station Configuration</td>
<td>183</td>
</tr>
<tr>
<td>8.4.1 Asymmetrical Monopole</td>
<td>183</td>
</tr>
<tr>
<td>8.4.2 Symmetrical Monopolar Configuration</td>
<td>184</td>
</tr>
<tr>
<td>8.4.3 Bipolar Configurations</td>
<td>185</td>
</tr>
</tbody>
</table>
CONTENTS

8.4.4 HVDC Grid Grounding 185
8.4.5 HVDC Configurations Extended to HVDC Grids 187
8.5 Substation Configuration 189
8.6 Conclusions 189
References 190

CHAPTER 9  GOVERNANCE MODELS FOR FUTURE GRIDS
Muhajir Tadesse Mekonnen, Diyun Huang, and Kristof De Vos

9.1 Introduction 193
9.2 Transmission Grid Planning 194
  9.2.1 Planning of National Transmission Network Expansions 194
  9.2.2 Planning of Regional Transmission Network Expansions 195
  9.2.3 Planning Procedures of Third Party (Merchant) Transmission Projects 195
  9.2.4 Projects of Common Interest (PCIs) 195
  9.2.5 Coordination of Regional Transmission Plans 196
9.3 Transmission Grid Ownership 197
  9.3.1 Remuneration Schemes for Regulated Assets 197
9.4 Transmission Grid Financing 201
  9.4.1 Financing Sources 201
  9.4.2 Cost of Capital 202
  9.4.3 Risk and Cost of Capital 203
9.5 Transmission Grid Pricing 204
  9.5.1 Pricing of National Transmission Projects 204
  9.5.2 Cost Sharing of Transnational Transmission Projects 207
  9.5.3 Pricing of Third-Party Transmission Projects 208
9.6 Transmission Grid Operation 208
9.7 Conclusions 210
References 210

CHAPTER 10  POWER SYSTEM OPERATIONS WITH HVDC GRIDS
Dirk Van Hertem, Robert H. Renner, and Johan Rimez

10.1 Introduction 213
10.2 Who Operates the HVDC Link or Grid? 214
10.3 Reliability Considerations in Systems with HVDC 217
  10.3.1 Reliability at the DC Grid Side 217
  10.3.2 Reliability of the Hybrid AC/DC Grid 218
  10.3.3 Operating the Power System under Different Time Frames 219
  10.3.4 Steady-State Operations of HVDC Connections and Grids 219
10.4 Managing Energy Unbalances in the System 223
  10.4.1 Unbalances in HVDC Grids 224
  10.4.2 Integrated Scheme for the Hybrid AC/DC Grid 225
10.5 Active and Reactive Power Control 226
  10.5.1 Active and Reactive Power Exchange 227
  10.5.2 Power Capability Curve 228
  10.5.3 Active and Reactive Power Dynamics 229
10.6 Ancillary Services 230
  10.6.1 Different Ancillary Services Defined 232
  10.6.2 Ancillary Services from DC Equipment for AC Grids 234
CONTENTS

10.6.3 Ancillary Services from AC Equipment for DC Grids 234
10.6.4 Ancillary Services from DC Equipment for DC Grids 234

10.7 Grid Codes 235
10.8 Conclusions 235
References 236

CHAPTER 11  OPERATION AND CONTROL OF OFFSHORE WIND POWER PLANTS 239
Oriol Gomis-Bellmunt and Mònica Aragüés-Peñalba

11.1 Introduction 239
11.2 System Under Analysis 240
11.3 Control and Protection Requirements 240
  11.3.1 Requirements 240
  11.3.2 Possible Scenarios 241
11.4 Wind Power Plant Control Structure 245
  11.4.1 Wind Turbine Control 245
  11.4.2 Wind Power Plant Control 247
11.5 Dynamic Simulation of a Simplified Example 249
11.6 Conclusions 254
References 254

PART IV  MODELING HVDC GRIDS

CHAPTER 12  MODELS FOR HVDC GRIDS 257
Jef Beerten and Dirk Van Hertem

12.1 Introduction 257
12.2 Power System Computation Programs 257
12.3 Modeling Power Electronic Converters 258
  12.3.1 Converter Models for Different Time Frames 259
  12.3.2 Modeling of Other Grid Components for Different Time Frames 261
12.4 HVDC Grids Modeling Challenges 262
  12.4.1 Modular Multilevel Converter Modeling 263
  12.4.2 Modeling AC/DC Dynamic System Interactions 263
12.5 Conclusions 264
References 265

CHAPTER 13  POWER FLOW MODELING OF HYBRID AC/DC SYSTEMS 267
Jef Beerten

13.1 Introduction 267
13.2 Simplified Power Flow Modeling 268
  13.2.1 AC Power System Model 268
  13.2.2 DC Power System Model 269
13.3 Detailed Power Flow Modeling 272
  13.3.1 Converter Model 272
  13.3.2 Control Mode Representation 274
  13.3.3 Converter Limits 276
  13.3.4 DC Grid Model 278
CONTENTS

13.4 Sequential AC/DC Power Flow 279
13.4.1 Initialization 280
13.4.2 AC Network Power Flow 281
13.4.3 Converter Calculations 281
13.4.4 Converter Limit Check 282
13.4.5 DC Network Power Flow 284
13.4.6 DC Slack Bus and Droop Buses Iteration 285
13.5 Software Implementation 289
13.6 Test Case 289
13.7 Conclusions 290
References 292

CHAPTER 14  OPTIMAL POWER FLOW MODELING OF HYBRID AC/DC SYSTEMS
Johan Rimez

14.1 Introduction 293
14.2 Optimal Power Flow: Standard Formulation and Extension 293
14.2.1 Standard AC Formulation and Convergence 293
14.2.2 Extending the Formulation 298
14.3 Optimal Power Flow with DC Grids and Converters 299
14.3.1 General Approach and State-of-the-Art 299
14.3.2 Modeling VSC-HVDC Converters 300
14.3.3 Modeling DC Branches and Grid Topology 302
14.3.4 Inequality Constraints for the DC Network 304
14.3.5 Simulation Results 305
14.4 Adding Security Constraints 306
14.4.1 Preventive Measures 307
14.4.2 Curative Measures 307
14.4.3 Multistage Decisions 307
14.4.4 Implemented Approach 308
14.4.5 Mathematical Interpretation 308
14.4.6 Security Constraints Combined with DC Networks 311
14.4.7 Simulation Results for the Security-Constrained Optimal Power Flow 312
14.5 Conclusions 313
References 314

CHAPTER 15  CONTROL PRINCIPLES OF HVDC GRIDS
Jef Beerten, Agustí Egea, and Til Kristian Vrana

15.1 Introduction 315
15.2 Basic Control Principles 316
15.2.1 Current-Based Control 317
15.2.2 Power-Based Control 317
15.2.3 Converter and System Limits 317
15.3 Basic Converter Control Strategies 318
15.3.1 Voltage Droop Control (Positive Droop Constant) 319
15.3.2 Constant Current/Power Control (Infinite Droop Constant) 320
15.3.3 Constant Voltage Control (Zero Droop Constant) 320
References 314
CONTENTS

15.4 Advanced Converter Control Strategies 321
  15.4.1 Voltage Margin Control 322
  15.4.2 Deadband Droop Control 322
  15.4.3 Undead-Band Droop Control 322

15.5 Basic Grid Control Strategies 324
  15.5.1 Centralized Voltage Control 324
  15.5.2 Distributed Voltage Control 324

15.6 Advanced Grid Control Strategies 325
  15.6.1 Centralized Voltage Control with Centralized Backup 325
  15.6.2 Centralized Voltage Control with Distributed Backup 325
  15.6.3 Distributed Voltage Control with Distributed Backup 326

15.7 Converter Inner Current Control 326
  15.7.1 Current Control Reference Calculations 328

15.8 System Power Flow Control 328
  15.8.1 AC System Power Flow Control 329
  15.8.2 Hybrid AC/DC System Power Flow Control 329

15.9 Conclusions 330

References 331

CHAPTER 16 STATE-SPACE REPRESENTATION OF HVDC GRIDS 333
Eduardo Prieto-Araujo and Fernando Bianchi

16.1 Introduction 333

16.2 Multi-Terminal Grid Modeling 333
  16.2.1 Grid Structure 333
  16.2.2 AC Systems Connected to the HVDC Grid 334
  16.2.3 Branches 335
  16.2.4 Intermediate Nodes 336
  16.2.5 Equivalent Circuit Model 336
  16.2.6 State-Space Representation 337

16.3 Four-Terminal Grid Example 339
  16.3.1 Case 1: Droop Voltage Control in the AC Grid Side 340
  16.3.2 Case 2: Droop Voltage Control in the Wind Farm Side 342

16.4 Conclusions 343

References 343

CHAPTER 17 DC FAULT PHENOMENA AND DC GRID PROTECTION 345
Willem Leterme and Dirk Van Hertem

17.1 Introduction 345

17.2 Short-Circuit Faults in the DC Grid 346
  17.2.1 Sequence of Events of a DC Short-Circuit Fault 346
  17.2.2 Steady-State DC Fault Behavior 347
  17.2.3 Transient DC Fault Phenomena 350

17.3 DC Grid Protection 361
  17.3.1 Objectives of Protection 361
  17.3.2 Differences with AC Protection 362
  17.3.3 Protection Methodologies 363
  17.3.4 Relaying for DC Grids 364
CONTENTS

17.4 DC Protection Components 366
  17.4.1 DC Breakers 366
  17.4.2 Measurement Equipment 366
17.5 Conclusions 368
References 368

CHAPTER 18 REAL-TIME SIMULATION EXPERIMENTS OF DC GRIDS 371
Oluwole Daniel Adeuyi and Marc Cheah

18.1 Introduction 371
  18.1.1 Benefits of Real-Time Simulation 371
  18.1.2 Benefits of Experimental Investigations 372
  18.1.3 A Hardware-in-the-Loop (HIL) Test System 373
18.2 Real-Time Simulation in Power Systems 375
  18.2.1 Basic Architecture and Specifications 375
  18.2.2 Operation and Control of RTS 376
  18.2.3 Modeling of Power Electronic Converters in RTS 378
18.3 Design of Experimental Test Rig 379
  18.3.1 DC Grid Scaling Methods 380
  18.3.2 Instrumentation and Control Layout 385
18.4 Potential Applications of HIL Tests in DC Grids 386
  18.4.1 Subsynchronous Resonance (SSR) Studies 387
  18.4.2 DC Grid Protection 387
  18.4.3 Integration of Offshore Wind Power 387
  18.4.4 Converter Architecture and Design 388
References 388

PART V APPLICATIONS

CHAPTER 19 POWER SYSTEM OSCILLATION DAMPING BY MEANS OF VSC-HVDC SYSTEMS 391
José Luis Domínguez-García and Carlos E. Ugalde-Loo

19.1 Introduction 391
19.2 Power System Stability 392
  19.2.1 Low-Frequency Oscillations 393
  19.2.2 Subsynchronous Resonance 395
19.3 VSC-HVDC Systems Damping Contribution: Application Examples 397
  19.3.1 Power System Stabilizers for Offshore Wind Power Plants Connected by Means of a VSC-HVDC System 397
  19.3.2 Damping of SSR Using VSC-HVDC Links 401
19.4 Conclusions 409
References 410

CHAPTER 20 OPTIMAL DROOP CONTROL OF MULTI-TERMINAL VSC-HVDC GRIDS 413
Fernando D. Bianchi and Eduardo Prieto-Araujo

20.1 Introduction 413
20.2 Control of Multi-Terminal VSC-HVDC Grids 414
CONTENTS

20.3 Time-Varying Description for Droop Control Design 418
20.4 Design of Optimal Control Droops 421
20.5 Four-Terminal VSC-HVDC Network Example 422
20.6 Conclusions 426
References 427

CHAPTER 21 DC GRID POWER FLOW CONTROL DEVICES 429
Chunmei Feng, Sheng Wang, and Qing Mu

21.1 DC Power Flow Control Devices (DCPFC) 430
21.1.1 DC Transformer 430
21.1.2 Variable Series Resistor (VSR) 432
21.1.3 Series Voltage Source (SVS) 434
21.2 Generic Modeling of DC Power Flow Control Devices 437
21.3 Sensitivity Analysis of DCPFC in DC Grid 438
21.4 Case Study of Power Flow Control Devices in DC Grids 441
21.4.1 System Topology 441
21.4.2 Test Conditions 441
21.4.3 Simulation Results 441
21.5 Control Sensitivity of DCPFC in DC Grids 444
21.5.1 Test System 444
21.5.2 Test Results 446
21.6 Comparison of Power Control Devices 448
21.7 Conclusions 450
References 450

CHAPTER 22 MODELING AND CONTROL OF OFFSHORE AC HUB 451
Xiaobo Hu, Jun Liang, and Jose Luis Dominguez-Garcia

22.1 Reasons for Developing AC Hub 451
22.2 What is the AC Hub? 452
22.3 Frequency-Dependent Modeling of AC Hub Components 455
22.3.1 Cables 455
22.3.2 Transformer Design 457
22.3.3 Reactive Power Compensation 459
22.3.4 Offshore Substation Platform 459
22.3.5 Evaluation of Costs for an AC Hub: Dogger Bank Tranche A Case 460
22.4 AC Hub Control Using Variable Frequency 460
22.4.1 Control System Design 462
22.4.2 Case Study 465
22.5 Conclusions 469
References 469

INDEX 473