## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foreword</td>
<td>xiii</td>
</tr>
<tr>
<td>Preface</td>
<td>xv</td>
</tr>
<tr>
<td>Acronyms</td>
<td>xix</td>
</tr>
<tr>
<td>Symbols</td>
<td>xxi</td>
</tr>
<tr>
<td><strong>1 Fundamentals</strong></td>
<td>1</td>
</tr>
<tr>
<td>1.1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Rationale Behind MTDC Grids</td>
<td>5</td>
</tr>
<tr>
<td>1.3 Network Architectures of MTDC Grids</td>
<td>6</td>
</tr>
<tr>
<td>1.3.1 Series Architecture</td>
<td>6</td>
</tr>
<tr>
<td>1.3.2 Parallel Architecture</td>
<td>7</td>
</tr>
<tr>
<td>1.4 Enabling Technologies and Components of MTDC Grids</td>
<td>9</td>
</tr>
<tr>
<td>1.4.1 LCC Technology</td>
<td>9</td>
</tr>
<tr>
<td>1.4.1.1 Control Modes in LCC-based MTDC Grid</td>
<td>10</td>
</tr>
<tr>
<td>1.4.1.2 Examples of Existing LCC MTDC Systems</td>
<td>10</td>
</tr>
<tr>
<td>1.4.2 VSC Technology</td>
<td>12</td>
</tr>
</tbody>
</table>
CONTENTS

1.5 Control Modes in MTDC Grid 14
1.6 Challenges for MTDC Grids 15
1.7 Configurations of MTDC Converter Stations 16
1.8 Research Initiatives on MTDC Grids 19
1.9 Focus and Scope of the Monograph 21

2 The Voltage-Sourced Converter (VSC) 23

2.1 Introduction 23
2.2 Ideal Voltage-Sourced Converter 24
2.3 Practical Voltage-Sourced Converter 28
2.3.1 Two-Level Voltage-Sourced Converter 28
2.3.2 Three-Level Voltage-Sourced Converter 31
2.3.3 Multi-Level Voltage-Sourced Converter 35
2.4 Control 38
2.4.1 Control of Real and Reactive Powers 38
2.4.2 Design and Implementation of Control 39
2.4.2.1 Space Phasors 39
2.4.2.2 Space-Phasor Representation of the AC Side 42
2.4.2.3 Current Control in the Stationary Frame 43
2.4.2.4 Current Control in a Rotating Frame 44
2.4.2.5 Phase-Locked Loop 52
2.4.3 Control of the DC-Side Voltage 56
2.4.4 Control of the AC Grid Voltage 58
2.4.5 Multi-unit Control of DC Grid Voltage and/or AC Grid Voltage 59
2.4.6 Control of Islands 61
2.5 Simulation 65
2.6 Symbols of the VSC 75

3 Modeling, Analysis, and Simulation of AC–MTDC Grids 77

3.1 Introduction 77
3.2 MTDC Grid Model 78
3.2.1 Modeling Assumptions 78
3.2.2 Converter Model 81
3.2.3 Converter Controller Model 83
3.2.3.1 Outer Control Loops 83
3.2.3.2 Inner Current Control Loop 87
3.2.4 DC Network Model 87
   3.2.4.1 Algebraic Equations 89
   3.2.4.2 Differential Equations 91
3.2.5 State-Space Representation 91
   3.2.5.1 Dynamic Equations of Converters and Controllers 92
   3.2.5.2 Output Equations 93
   3.2.5.3 Control Modes 93
   3.2.5.4 Dynamic Equations of DC Network 95
   3.2.5.5 Output Equations of DC Network 96
3.2.6 Phasor from Space Phasor 96
   3.2.6.1 Base Values and Per-unit Systems 97
   3.2.6.2 Phase Angle of Space Phasors 97
3.3 AC Grid Model 98
  3.3.1 Generator Model 99
    3.3.1.1 State-Space Representation of Synchronous Generator (SG) Model 99
    3.3.1.2 Inclusion of Generator in the Network 101
    3.3.1.3 Treatment of Sub-transient Saliency 102
    3.3.1.4 State-Space Model of Excitation Systems for SGs 104
    3.3.1.5 State-Space Model of Turbine and Governor 104
  3.3.2 Load Model 105
  3.3.3 AC Network Model 106
3.4 AC–MTDC Load flow Analysis 108
  3.4.1 AC Grid Load flow Model 109
  3.4.2 MTDC Grid Load flow Model 110
    3.4.2.1 MTDC Interface with AC System 110
    3.4.2.2 MTDC AC Side Load flow Model 110
    3.4.2.3 Interface of MTDC AC and DC Sides 111
    3.4.2.4 MTDC DC Side Load flow Model 112
    3.4.2.5 MTDC Converter Control Modes 112
  3.4.3 AC–MTDC Grid Load flow Solution 114
3.5 AC–MTDC Grid Model for Nonlinear Dynamic Simulation 120
  3.5.1 Initialization of Dynamic Models 121
    3.5.1.1 MTDC Grid 122
    3.5.1.2 AC Grid 122
  3.6 Small-signal Stability Analysis of AC–MTDC Grid 122
    3.6.1 Linear Model of Converters and Controllers 123
CONTENTS

3.6.2 Linear Model of DC Network 128
3.6.3 Eigenvalue, Eigenvector, and Participation Factor 130

3.7 Transient Stability Analysis of AC–MTDC Grid 130
3.7.1 Large Disturbance Simulation 131
3.7.2 Representation of Rotor and Phase Angles 132

3.8 Case Studies 132

3.9 Case Study 1: The North Sea Benchmark System 133
3.9.1 Study Network 133
3.9.2 Nonlinear Simulation 134
3.9.2.1 Small Disturbances 134
3.9.2.2 Converter Outage 135
3.9.3 Small-signal Stability Analysis 137
3.9.3.1 Eigenvalue Analysis 137
3.9.3.2 Participation Factor Analysis 138

3.10 Case Study 2: MTDC Grid Connected to Equivalent AC Systems 139
3.10.1 Study Network 139
3.10.2 Nonlinear Simulation 140
3.10.2.1 Small Disturbances 142
3.10.2.2 Large Disturbances 142
3.10.3 Small-signal Stability Analysis 142

3.11 Case Study 3: MTDC Grid Connected to Multi-machine AC System 143
3.11.1 Study Network 143
3.11.2 AC–MTDC Grid Load flow Solution 145
3.11.3 Small-signal Stability Analysis 146
3.11.4 Nonlinear Simulation 147
3.11.4.1 AC Side Fault 147
3.11.4.2 DC Cable Fault 148
3.11.4.3 Converter Outage 150

4 Autonomous Power Sharing 153

4.1 Introduction 153
4.2 Steady-state Operating Characteristics 156
4.3 Concept of Power Sharing 157
4.3.1 Power Sharing Among Synchronous Generators 157
4.3.2 Power Sharing in AC Microgrids 158
4.4 Power Sharing in MTDC Grid 159
4.4.1 Voltage Margin Control 159
5 Frequency Support 187

5.1 Introduction 187
5.2 Fundamentals of Frequency Control 189
5.3 Inertial and Primary Frequency Support from Wind Farms 190
5.4 Wind Farms in Secondary Frequency Control (AGC) 191
5.5 Modified Droop Control for Frequency Support 192
5.6 AC–MTDC Load Flow Solution 194
5.7 Post-Contingency Operation 195
  5.7.1 Analysis for AC System 196
  5.7.2 Analysis for Converter Station 196
    5.7.2.1 AC Side Disturbances 197
    5.7.2.2 Converter Outage 197
  5.7.3 Analysis for AC System Connected to Converter Stations 198
  5.7.4 Analysis of AC–MTDC Grid 199
5.8 Case Study 200
  5.8.1 Study Network 200
  5.8.2 AC–MTDC Grid Load flow Solution 202
  5.8.3 Small-signal Stability Analysis 203
  5.8.4 Nonlinear Simulation 204
    5.8.4.1 AC Side Disturbances 204
    5.8.4.2 Converter Station Disturbances 212
6 Protection of MTDC Grids

6.1 Introduction 219
6.2 Converter Station Protection 220
6.3 DC Cable Fault Response 220
   6.3.1 Fault Response of Two-level VSC 221
      6.3.1.1 Analysis 224
   6.3.2 Fault Response of Half-bridge MMC 225
   6.3.3 Challenges 227
6.4 Fault-blocking Converters 228
   6.4.1 Full-bridge MMC 228
   6.4.2 Variants of Full-bridge MMC 230
6.5 DC Circuit Breakers 231
   6.5.1 Solid-state DC Breaker 232
   6.5.2 Proactive Hybrid DC Breaker 233
   6.5.3 DC/DC Converter 235
6.6 Protection Strategies 237
   6.6.1 Strategy I 238
   6.6.2 Strategy II 240
   6.6.3 Strategy III 241
      6.6.3.1 Detection and Identification 241
   6.6.4 Backup Protection 245

References 249

Index 257