UNDERSTANDING POWER QUALITY PROBLEMS

Voltage Sags and Interruptions

Math H. J. Bollen

Chalmers University of Technology Gothenburg, Sweden

IEEE Industry Applications Society, Sponsor

IEEE Power Electronics Society, Sponsor

IEEE Power Engineering Society, Sponsor



P. M. Anderson, Series Editor



The Institute of Electrical and Electronics Engineers, Inc., New York



Contents

PREFACE xiii FTP SITE INFORMATION xv ACKNOWLEDGMENTS xvii

CHAPTER 1 Overview of Power Quality and Power Quality Standards 1

- 1.1 Interest in Power Quality 2
- 1.2 Power Quality, Voltage Quality 4
- 1.3 Overview of Power Quality Phenomena 6
 - 1.3.1 Voltage and Current Variations 6
 - 1.3.2 Events 14
 - 1.3.3 Overview of Voltage Magnitude Events 19
- 1.4 Power Quality and EMC Standards 22
 - 1.4.1 Purpose of Standardization 22
 - 1.4.2 The IEC Electromagnetic Compatibility Standards 24
 - 1.4.3 The European Voltage Characteristics Standard 29

CHAPTER 2 Long Interruptions and Reliability Evaluation 35

- 2.1 Introduction 35
 - 2.1.1 Interruptions 35
 - 2.1.2 Reliability Evaluation of Power Systems 35
 - 2.1.3 Terminology 36
 - 2.1.4 Causes of Long Interruptions 36
- 2.2 Observation of System Performance 37
 - 2.2.1 Basic Indices 37
 - 2.2.2 Distribution of the Duration of an Interruption 40
 - 2.2.3 Regional Variations 42

- 2.2.4 Origin of Interruptions 43
- 2.2.5 More Information 46
- 2.3 Standards and Regulations 48
 - 2.3.1 Limits for the Interruption Frequency 48
 - 2.3.2 Limits for the Interruption Duration 48
- 2.4 Overview of Reliability Evaluation 50
 - 2.4.1 Generation Reliability 51
 - 2.4.2 Transmission Reliability 53
 - 2.4.3 Distribution Reliability 56
 - 2.4.4 Industrial Power Systems 58
- 2.5 Basic Reliability Evaluation Techniques 62
 - 2.5.1 Basic Concepts of Reliability Evaluation Techniques 62
 - 2.5.2 Network Approach 69
 - 2.5.3 State-Based and Event-Based Approaches 77
 - 2.5.4 Markov Models 80
 - 2.5.5 Monte Carlo Simulation 89
 - 2.5.6 Aging of Components 98
- 2.6 Costs of Interruptions 101
- 2.7 Comparison of Observation and Reliability Evaluation 106
- 2.8 Example Calculations 107
 - 2.8.1 A Primary Selective Supply 107
 - 2.8.2 Adverse Weather 108
 - 2.8.3 Parallel Components 110
 - 2.8.4 Two-Component Model with Aging and Maintenance 111

CHAPTER 3 Short Interruptions 115

- 3.1 Introduction 115
- 3.2 Terminology 115
- 3.3 Origin of Short Interruptions 116
 - 3.3.1 Basic Principle 116
 - 3.3.2 Fuse Saving 117
 - 3.3.3 Voltage Magnitude Events due to Reclosing 118
 - 3.3.4 Voltage During the Interruption 119
- 3.4 Monitoring of Short Interruptions 121
 - 3.4.1 Example of Survey Results 121
 - 3.4.2 Difference between Medium- and Low-Voltage Systems 123
 - 3.4.3 Multiple Events 124
- 3.5 Influence on Equipment 125
 - 3.5.1 Induction Motors 126
 - 3.5.2 Synchronous Motors 126
 - 3.5.3 Adjustable-Speed Drives 126
 - 3.5.4 Electronic Equipment 127
- 3.6 Single-Phase Tripping 127
 - 3.6.1 Voltage-During-Fault Period 127
 - 3.6.2 Voltage-Post-Fault Period 129
 - 3.6.3 Current-During-Fault Period 134
- 3.7 Stochastic Prediction of Short Interruptions 136

CHAPTER 4 Voltage Sags—Characterization 139

- 4.1 Introduction 139
- 4.2 Voltage Sag Magnitude 140
 - 4.2.1 Monitoring 140
 - 4.2.2 Theoretical Calculations 147
 - 4.2.3 Example of Calculation of Sag Magnitude 153
 - 4.2.4 Sag Magnitude in Non-Radial Systems 156
 - 4.2.5 Voltage Calculations in Meshed Systems 166
- 4.3 Voltage Sag Duration 168
 - 4.3.1 Fault-Clearing Time 168
 - 4.3.2 Magnitude-Duration Plots 169
 - 4.3.3 Measurement of Sag Duration 170
- 4.4 Three-Phase Unbalance 174
 - 4.4.1 Single-Phase Faults 174
 - 4.4.2 Phase-to-Phase Faults 182
 - 4.4.3 Two-Phase-to-Ground Faults 184
 - 4.4.4 Seven Types of Three-Phase Unbalanced Sags 187
- 4.5 Phase-Angle Jumps 198
 - 4.5.1 Monitoring 199
 - 4.5.2 Theoretical Calculations 201
- 4.6 Magnitude and Phase-Angle Jumps for Three-Phase Unbalanced Sags 206
 - 4.6.1 Definition of Magnitude and Phase-Angle Jump 206
 - 4.6.2 Phase-to-Phase Faults 209
 - 4.6.3 Single-Phase Faults 216
 - 4.6.4 Two-Phase-to-Ground Faults 222
 - 4.6.5 High-Impedance Faults 227
 - 4.6.6 Meshed Systems 230
- 4.7 Other Characteristics of Voltage Sags 231
 - 4.7.1 Point-on-Wave Characteristics 231
 - 4.7.2 The Missing Voltage 234
- 4.8 Load Influence on Voltage Sags 238
 - 4.8.1 Induction Motors and Three-Phase Faults 238
 - 4.8.2 Induction Motors and Unbalanced Faults 241
 - 4.8.3 Power Electronics Load 248
- 4.9 Sags due to Starting of Induction Motors 248

CHAPTER 5 Voltage Sags—Equipment Behavior 253

- 5.1 Introduction 253
 - 5.1.1 Voltage Tolerance and Voltage-Tolerance Curves 253
 - 5.1.2 Voltage-Tolerance Tests 255
- 5.2 Computers and Consumer Electronics 256
 - 5.2.1 Typical Configuration of Power Supply 257
 - 5.2.2 Estimation of Computer Voltage Tolerance 257
 - 5.2.3 Measurements of PC Voltage Tolerance 261
 - 5.2.4 Voltage-Tolerance Requirements: CBEMA and ITIC 263
 - 5.2.5 Process Control Equipment 264
- 5.3 Adjustable-Speed AC Drives 265
 - 5.3.1 Operation of AC Drives 266
 - 5.3.2 Results of Drive Testing 267
 - 5.3.3 Balanced Sags 272

- 5.3.4 DC Voltage for Three-Phase Unbalanced Sags 274
- 5.3.5 Current Unbalance 285
- 5.3.6 Unbalanced Motor Voltages 289
- 5.3.7 Motor Deacceleration 292
- 5.3.8 Automatic Restart 296
- 5.3.9 Overview of Mitigation Methods for AC Drives 298
- 5.4 Adjustable-Speed DC Drives 300
 - 5.4.1 Operation of DC Drives 300
 - 5.4.2 Balanced Sags 303
 - 5.4.3 Unbalanced Sags 308
 - 5.4.4 Phase-Angle Jumps 312
 - 5.4.5 Commutation Failures 315
 - 5.4.6 Overview of Mitigation Methods for DC Drives 317
- 5.5 Other Sensitive Load 318
 - 5.5.1 Directly Fed Induction Motors 318
 - 5.5.2 Directly Fed Synchronous Motors 319
 - 5.5.3 Contactors 321
 - 5.5.4 Lighting 322

CHAPTER 6 Voltage Sags—Stochastic Assessment 325

- 6.1 Compatibility between Equipment and Supply 325
- 6.2 Presentation of Results: Voltage Sag Coordination Chart 328
 - 6.2.1 The Scatter Diagram 328
 - 6.2.2 The Sag Density Table 330
 - 6.2.3 The Cumulative Table 331
 - 6.2.4 The Voltage Sag Coordination Chart 332
 - 6.2.5 Example of the Use of the Voltage Sag Coordination Chart 335
 - 6.2.6 Non-Rectangular Sags 336
 - 6.2.7 Other Sag Characteristics 338
- 6.3 Power Quality Monitoring 342
 - 6.3.1 Power Quality Surveys 342
 - 6.3.2 Individual Sites 357
- 6.4 The Method of Fault Positions 359
 - 6.4.1 Stochastic Prediction Methods 359
 - 6.4.2 Basics of the Method of Fault Positions 360
 - 6.4.3 Choosing the Fault Positions 362
 - 6.4.4 An Example of the Method of Fault Positions 366
- 6.5 The Method of Critical Distances 373
 - 6.5.1 Basic Theory 373
 - 6.5.2 Example-Three-Phase Faults 374
 - 6.5.3 Basic Theory: More Accurate Expressions 375
 - 6.5.4 An Intermediate Expression 376
 - 6.5.5 Three-Phase Unbalance 378
 - 6.5.6 Generator Stations 384
 - 6.5.7 Phase-Angle Jumps 384
 - 6.5.8 Parallel Feeders 385
 - 6.5.9 Comparison with the Method of Fault Positions 387

CHAPTER 7 Mitigation of Interruptions and Voltage Sags 389

- 7.1 Overview of Mitigation Methods 389
 - 7.1.1 From Fault to Trip 389
 - 7.1.2 Reducing the Number of Faults 390
 - 7.1.3 Reducing the Fault-Clearing Time 391
 - 7.1.4 Changing the Power System 393
 - 7.1.5 Installing Mitigation Equipment 394
 - 7.1.6 Improving Equipment Immunity 395
 - 7.1.7 Different Events and Mitigation Methods 395
- 7.2 Power System Design-Redundancy Through Switching 397
 - 7.2.1 Types of Redundancy 397
 - 7.2.2 Automatic Reclosing 398
 - 7.2.3 Normally Open Points 398
 - 7.2.4 Load Transfer 400
- 7.3 Power System Design—Redundancy through Parallel Operation 405
 - 7.3.1 Parallel and Loop Systems 405
 - 7.3.2 Spot Networks 409
 - 7.3.3 Power-System Design-On-site Generation 415
- 7.4 The System-Equipment Interface 419
 - 7.4.1 Voltage-Source Converter 419
 - 7.4.2 Series Voltage Controllers-DVR 420
 - 7.4.3 Shunt Voltage Controllers-StatCom 430
 - 7.4.4 Combined Shunt and Series Controllers 435
 - 7.4.5 Backup Power Source—SMES, BESS 438
 - 7.4.6 Cascade Connected Voltage Controllers-UPS 439
 - 7.4.7 Other Solutions 442
 - 7.4.8 Energy Storage 446

CHAPTER 8 Summary and Conclusions 453

- 8.1 Power Quality 453
 - 8.1.1 The Future of Power Quality 454
 - 8.1.2 Education 454
 - 8.1.3 Measurement Data 454
- 8.2 Standardization 455
 - 8.2.1 Future Developments 455
 - 8.2.2 Bilateral Contracts 456
- 8.3 Interruptions 456
 - 8.3.1 Publication of Interruption Data 456
- 8.4 Reliability 457
 - 8.4.1 Verification 457
 - 8.4.2 Theoretical Developments 457
- 8.5 Characteristics of Voltage Sags 458
 - 8.5.1 Definition and Implementation of Sag Characteristics 458
 - 8.5.2 Load Influence 458
- 8.6 Equipment Behavior due to Voltage Sags 459
 - 8.6.1 Equipment Testing 459
 - 8.6.2 Improvement of Equipment 460
- 8.7 Stochastic Assessment of Voltage Sags 460
 - 8.7.1 Other Sag Characteristics 460
 - 8.7.2 Stochastic Prediction Techniques 460

8.7.3 Power Quality Surveys 461 8.7.4 Monitoring or Prediction? 461

- 8.8 Mitigation Methods 462
- 8.9 Final Remarks 462

BIBLIOGRAPHY 465

APPENDIX A Overview of EMC Standards 477

APPENDIX B IEEE Standards on Power Quality 481

APPENDIX C Power Quality Definitions and Terminology 485

APPENDIX D List of Figures 507

APPENDIX E List of Tables 525

INDEX 529

ABOUT THE AUTHOR 543