

# UNDERSTANDING POWER QUALITY PROBLEMS

## VOLTAGE SAGS AND INTERRUPTIONS

Math H.J. Bollen

Sarawac University of Technology



31051000622627



E.M. Anderson, Series Editor

Free MATLAB® Figures Available  
Via FTP! Details Inside!

# 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        |
| <b>5.4 Adjustable-Speed DC Drives</b>              | <b>300</b> |
| 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        |
| <b>5.5 Other Sensitive Load</b>                    | <b>318</b> |
| 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

|  |            |
|--|------------|
| <b>6.1 Compatibility between Equipment and Supply</b>              | <b>325</b> |
| <b>6.2 Presentation of Results: Voltage Sag Coordination Chart</b> | <b>328</b> |
| 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        |
| <b>6.3 Power Quality Monitoring</b>                                | <b>342</b> |
| 6.3.1 Power Quality Surveys  | 342        |
| 6.3.2 Individual Sites   | 357        |
| <b>6.4 The Method of Fault Positions</b>                           | <b>359</b> |
| 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        |
| <b>6.5 The Method of Critical Distances</b>                        | <b>373</b> |
| 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        |
| <b>BIBLIOGRAPHY</b>   | <b>465</b> |
| <b>APPENDIX A Overview of EMC Standards</b>                 | <b>477</b> |
| <b>APPENDIX B IEEE Standards on Power Quality</b>           | <b>481</b> |
| <b>APPENDIX C Power Quality Definitions and Terminology</b> | <b>485</b> |
| <b>APPENDIX D List of Figures</b>                           | <b>507</b> |
| <b>APPENDIX E List of Tables</b>                            | <b>525</b> |
| <b>INDEX</b>  | <b>529</b> |
| <b>ABOUT THE AUTHOR</b>                                     | <b>543</b> |