

CONTENTS

| | |
|--|-------------|
| Preface | xvii |
| 1 Introduction | 1 |
| 1.1 Risk in Power Systems | 1 |
| 1.2 Basic Concepts of Power System Risk Assessment | 3 |
| 1.2.1 System Risk Evaluation | 3 |
| 1.2.2 Data in Risk Evaluation | 5 |
| 1.2.3 Unit Interruption Cost | 6 |
| 1.3 Outline of the Book | 8 |
| 2 Outage Models of System Components | 13 |
| 2.1 Introduction | 13 |
| 2.2 Models of Independent Outages | 14 |
| 2.2.1 Repairable Forced Failure | 14 |
| 2.2.2 Aging Failure | 16 |
| 2.2.2.1 Probability of Transition to Aging Failure | 16 |
| 2.2.2.2 Unavailability Due to Aging Failure | 18 |
| 2.2.2.3 Explicit Expression of Equation 2.10 | 20 |
| 2.2.3 Nonrepairable Chance Failure | 21 |
| 2.2.4 Planned Outage | 22 |
| 2.2.5 Semiforced Outage | 25 |
| 2.2.6 Partial Failure Mode | 26 |
| 2.2.7 Multiple Failure Mode | 28 |
| 2.3 Models of Dependent Outages | 28 |
| 2.3.1 Common-Cause Outage | 29 |
| 2.3.1.1 Composite Model | 29 |
| 2.3.1.2 Individual Model | 30 |
| 2.3.1.3 Comparison between Composite and Individual Models | 32 |

| | | |
|----------|--|-----------|
| 2.3.2 | Component-Group Outage | 34 |
| 2.3.3 | Station-Originated Outage | 36 |
| 2.3.4 | Cascading Outage | 37 |
| 2.3.5 | Environment-Dependent Failure | 38 |
| 2.4 | Conclusions | 40 |
| 3 | Parameter Estimation in Outage Models | 43 |
| 3.1 | Introduction | 43 |
| 3.2 | Point Estimation of Mean and Variance of Failure Data | 44 |
| 3.2.1 | Sample Mean | 44 |
| 3.2.2 | Sample Variance | 46 |
| 3.3 | Interval Estimation of Mean and Variance of Failure Data | 46 |
| 3.3.1 | General Concept of Confidence Interval | 47 |
| 3.3.2 | Confidence Interval of Mean | 48 |
| 3.3.3 | Confidence Interval of Variance | 51 |
| 3.4 | Estimating Failure Frequency of Individual Components | 51 |
| 3.4.1 | Point Estimation | 52 |
| 3.4.2 | Interval Estimation | 52 |
| 3.5 | Estimating Probability from a Binomial Distribution | 54 |
| 3.6 | Experimental Distribution of Failure Data and Its Test | 55 |
| 3.6.1 | Experimental Distribution of Failure Data | 55 |
| 3.6.2 | Test of Experimental Distribution | 56 |
| 3.7 | Estimating Parameters in Aging Failure Models | 58 |
| 3.7.1 | Mean Life and Its Standard Deviation in the Normal Model | 59 |
| 3.7.2 | Shape and Scale Parameters in the Weibull Model | 61 |
| 3.7.3 | Example | 64 |
| 3.8 | Conclusions | 68 |
| 4 | Elements of Risk Evaluation Methods | 69 |
| 4.1 | Introduction | 69 |
| 4.2 | Methods for Simple Systems | 70 |
| 4.2.1 | Probability Convolution | 70 |
| 4.2.2 | Series and Parallel Networks | 71 |
| 4.2.2.1 | Series Network | 72 |
| 4.2.2.2 | Parallel Network | 73 |
| 4.2.3 | Markov Equations | 74 |
| 4.2.4 | Frequency-Duration Approaches | 76 |
| 4.2.4.1 | Frequency of Encountering a State | 77 |
| 4.2.4.2 | Frequency of Transition between Two States | 77 |
| 4.2.4.3 | Frequency of Encountering a State Set | 77 |
| 4.2.4.4 | Mean Duration of Residing in Each System State | 78 |
| 4.2.4.5 | Mean Duration of Residing in a State Set | 78 |
| 4.3 | Methods for Complex Systems | 79 |

| | | |
|----------|--|------------|
| 4.3.1 | State Enumeration | 79 |
| 4.3.2 | Nonsequential Monte Carlo Simulation | 82 |
| 4.3.3 | Sequential Monte Carlo Simulation | 84 |
| 4.4. | Conclusions | 87 |
| 5 | Risk Evaluation Techniques for Power Systems | 89 |
| 5.1 | Introduction | 89 |
| 5.2 | Techniques Used in Generation-Demand Systems | 90 |
| 5.2.1 | Convolution Technique | 90 |
| 5.2.1.1 | Discrete Generation Probability Distribution | 90 |
| 5.2.1.2 | Discrete Load Probability Distribution | 91 |
| 5.2.1.3 | Index Calculation | 92 |
| 5.2.2 | State Sampling Method | 94 |
| 5.2.3 | State Duration Sampling Method | 96 |
| 5.3 | Techniques Used in Radial Distribution Systems | 98 |
| 5.3.1 | Analytical Technique | 99 |
| 5.3.2 | State Duration Sampling Method | 101 |
| 5.4 | Techniques Used in Substation Configurations | 102 |
| 5.4.1 | Failure Modes and Modeling | 103 |
| 5.4.2 | Connectivity Identification | 105 |
| 5.4.3 | Stratified State Enumeration Method | 107 |
| 5.4.4 | State Duration Sampling Method | 111 |
| 5.5 | Techniques Used in Composite Generation and Transmission Systems | 113 |
| 5.5.1 | Basic Procedure | 114 |
| 5.5.2 | Component Failure Models | 114 |
| 5.5.3 | Load Curve Models | 116 |
| 5.5.4 | Contingency Analysis | 117 |
| 5.5.4.1 | AC Power-Flow-Based Sensitivity Technique | 117 |
| 5.5.4.2 | DC Power-Flow-Based Contingency Analysis | 118 |
| 5.5.5 | Optimization Models for Load Curtailments | 119 |
| 5.5.5.1 | AC Power-Flow-Based OPF Model | 119 |
| 5.5.5.2 | DC Power-Flow-Based OPF Model | 120 |
| 5.5.6 | State Enumeration Method | 121 |
| 5.5.7 | State Sampling Method | 123 |
| 5.6 | Conclusions | 125 |
| 6 | Application of Risk Evaluation to Transmission Development Planning | 127 |
| 6.1 | Introduction | 127 |
| 6.2 | Concept of Probabilistic Planning | 128 |
| 6.2.1 | Basic Procedure | 128 |
| 6.2.2 | Cost Analysis | 129 |
| 6.2.3 | Present Value | 130 |

| | | |
|----------|--|------------|
| 6.3 | Risk Evaluation Approach | 130 |
| 6.3.1 | Risk Evaluation Procedure | 131 |
| 6.3.2 | Risk Cost Model | 131 |
| 6.4 | Example 1: Selecting the Lowest-Cost Planning Alternative | 133 |
| 6.4.1 | System Description | 133 |
| 6.4.2 | Planning Alternatives | 134 |
| 6.4.3 | Risk Evaluation | 135 |
| 6.4.4 | Overall Economic Analysis | 137 |
| 6.4.4.1 | Approach | 137 |
| 6.4.4.2 | Data | 139 |
| 6.4.4.3 | Results | 140 |
| 6.4.5 | Summary | 141 |
| 6.5 | Example 2: Applying Different Planning Criteria | 141 |
| 6.5.1 | System and Planning Alternatives | 141 |
| 6.5.2 | Study Conditions and Data | 143 |
| 6.5.2.1 | Study Conditions | 143 |
| 6.5.2.1 | Data | 143 |
| 6.5.3 | Risk and Risk Cost Evaluation | 144 |
| 6.5.4 | Overall Economic Analysis | 146 |
| 6.5.4.1 | Cash Flows in Multiple Stage Investments | 147 |
| 6.5.4.2 | Performance-Based Cost Efficiency Criterion | 147 |
| 6.5.4.3 | Combined Criterion of Single Contingency and Cost Efficiency | 148 |
| 6.5.5 | Summary | 149 |
| 6.6 | Conclusions | 150 |
| 7 | Application of Risk Evaluation to Transmission Operation Planning | 151 |
| 7.1 | Introduction | 151 |
| 7.2 | Concept of Risk Evaluation in Operation Planning | 152 |
| 7.3 | Risk Evaluation Method | 155 |
| 7.4 | Example 1: Determining the Lowest-Risk Operation Mode | 157 |
| 7.4.1 | System and Study Conditions | 157 |
| 7.4.2 | Assessing Impacts of Load Transfer | 158 |
| 7.4.3 | Comparing Different Reconfigurations | 159 |
| 7.4.4 | Selecting Operation Mode Under the $N-2$ Condition | 161 |
| 7.4.5 | Summary | 162 |
| 7.5 | Example 2: A Simple Case by Hand Calculations | 163 |
| 7.5.1 | Basic Concept | 163 |
| 7.5.2 | Case Description | 163 |
| 7.5.3 | Study Conditions and Data | 164 |
| 7.5.4 | Risk Evaluation | 166 |
| 7.5.4.1 | Calculating the Failure State Probability | 166 |
| 7.5.4.2 | Evaluating EENS by Assuming One-Hour Switching Time | 167 |

| | | |
|----------|---|------------|
| 7.5.4.3 | Evaluating EENS by Assuming Two-Hour Switching Time | 168 |
| 7.5.5 | Summary | 170 |
| 7.6 | Conclusions | 170 |
| 8 | Application of Risk Evaluation to Generation Source Planning | 173 |
| 8.1 | Introduction | 173 |
| 8.2 | Procedure for Reliability Planning | 174 |
| 8.3 | Simulation of Generation and Risk Costs | 175 |
| 8.3.1 | Simulation Approach | 175 |
| 8.3.2 | Minimization Cost Model | 176 |
| 8.3.3 | Expected Generation and Risk Costs | 177 |
| 8.4 | Example 1: Selecting Location and Size of Cogenerators | 178 |
| 8.4.1 | Basic Concept | 178 |
| 8.4.2 | System and Cogeneration Candidates | 179 |
| 8.4.3 | Risk Sensitivity Analysis | 181 |
| 8.4.4 | Maximum Benefit Analysis | 183 |
| 8.4.5 | Summary | 187 |
| 8.5 | Example 2: Making a Decision to Retire a Local Generation Plant | 187 |
| 8.5.1 | Case Description | 187 |
| 8.5.2 | Risk Evaluation | 188 |
| 8.5.3 | Total Cost Analysis | 189 |
| 8.5.3.1 | Investment Cost | 190 |
| 8.5.3.2 | Operation Cost | 190 |
| 8.5.3.3 | Risk Cost | 190 |
| 8.5.4 | Summary | 191 |
| 8.6 | Conclusions | 192 |
| 9 | Selection of Substation Configurations | 193 |
| 9.1 | Introduction | 193 |
| 9.2 | Load Curtailment Model | 194 |
| 9.3 | Risk Evaluation Approach | 197 |
| 9.3.1 | Component Failure Models | 197 |
| 9.3.2 | Procedure of Risk Evaluation | 197 |
| 9.3.3 | Economic Analysis Method | 198 |
| 9.4 | Example 1: Selecting Substation Configuration | 198 |
| 9.4.1 | Two Substation Configurations | 198 |
| 9.4.2 | Risk Evaluation | 199 |
| 9.4.2.1 | Study Condition Data | 199 |
| 9.4.2.2 | Results | 200 |
| 9.4.3 | Economic Analysis | 203 |
| 9.4.4 | Summary | 204 |

| | | |
|-----------|--|------------|
| 9.5 | Example 2: Selecting Transmission Line Arrangement Associated with Substations | 205 |
| 9.5.1 | Description of Two Options | 205 |
| 9.5.2 | Risk Evaluation and Economic Analysis | 206 |
| 9.5.2.1 | Study Conditions and Data | 206 |
| 9.5.2.2 | Results | 207 |
| 9.5.2.3 | Economic Analysis | 209 |
| 9.5.3 | Summary | 209 |
| 9.6 | Conclusions | 209 |
| 10 | Reliability-Centered Maintenance | 211 |
| 10.1 | Introduction | 211 |
| 10.2 | Basic Tasks in RCM | 212 |
| 10.2.1 | Comparison between Maintenance Alternatives | 212 |
| 10.2.2 | Lowest-Risk Maintenance Scheduling | 213 |
| 10.2.3 | Predictive Maintenance Versus Corrective Maintenance | 213 |
| 10.2.4 | Ranking the Importance of Components | 214 |
| 10.3 | Example 1: Transmission Maintenance Scheduling | 215 |
| 10.3.1 | Procedure of Transmission Reliability-Centered Maintenance | 215 |
| 10.3.2 | Description of the System and Maintenance Outage | 217 |
| 10.3.3 | The Lowest-Risk Schedule of the Cable Replacement | 218 |
| 10.3.4 | Summary | 218 |
| 10.4 | Example 2: Workforce Planning in Maintenance | 219 |
| 10.4.1 | Problem Description | 220 |
| 10.4.2 | Procedure | 220 |
| 10.4.3 | Case Study and Results | 221 |
| 10.4.4 | Summary | 222 |
| 10.5 | Example 3: A Simple Case Performed by Hand Calculations | 223 |
| 10.5.1 | Case Description | 223 |
| 10.5.2 | Study Conditions and Data | 224 |
| 10.5.3 | EENS Evaluation | 224 |
| 10.5.4 | Summary | 226 |
| 10.6 | Conclusions | 226 |
| 11 | Probabilistic Spare-Equipment Analysis | 229 |
| 11.1 | Introduction | 229 |
| 11.2 | Spare-Equipment Analysis Based on Reliability Criteria | 230 |
| 11.2.1 | Unavailability of Components | 230 |
| 11.2.1.1 | Unavailability Due to Repairable Failures | 230 |
| 11.2.1.2 | Unavailability Due to Aging Failures | 231 |
| 11.2.1.3 | Total Unavailability | 231 |
| 11.2.2 | Group Reliability and Spare-Equipment Analysis | 231 |
| 11.3 | Spare-Equipment Analysis Using the Probabilistic Cost Method | 233 |

| | | |
|-----------|--|------------|
| 11.3.1 | Failure Cost Model | 233 |
| 11.3.2 | Unit failure Cost Estimation | 234 |
| 11.3.3 | Annual Investment Cost Model | 235 |
| 11.3.4 | Present-Value Approach | 235 |
| 11.3.5 | Procedure for Spare-Equipment Analysis | 235 |
| 11.4 | Example 1: Determining Number and Timing of Spare Transformers | 236 |
| 11.4.1 | Transformer Group and Data | 236 |
| 11.4.2 | Spare-Transformer Analysis Based on Group Failure Probability | 236 |
| 11.4.3 | Spare-Transformer Plans Based on the Probabilistic Cost Model | 238 |
| 11.4.3.1 | Evaluating Failure Cost Deductions Due to Spares | 238 |
| 11.4.3.2 | Benefit/Cost Analysis | 238 |
| 11.4.4 | Summary | 240 |
| 11.5 | Example 2: Determining Redundancy Level of 500 kV Reactors | 240 |
| 11.5.1 | Problem Description | 241 |
| 11.5.2 | Study Condition and Data | 242 |
| 11.5.3 | Redundancy Analysis | 244 |
| 11.5.4 | Summary | 245 |
| 11.6 | Conclusions | 246 |
| 12 | Reliability-Based Transmission-Service Pricing | 249 |
| 12.1 | Introduction | 249 |
| 12.2 | Basic Concept | 250 |
| 12.2.1 | Incremental Reliability Value | 250 |
| 12.2.2 | Impacts of Customers on System Reliability | 252 |
| 12.2.3 | Reliability Component in Price Design | 253 |
| 12.3 | Calculation Methods | 254 |
| 12.3.1 | Unit Incremental Reliability Value (UIRV) | 254 |
| 12.3.2 | Generation Credit for Reliability Improvement (GCRI) | 255 |
| 12.3.3 | Load Charge for Reliability Degradation (LCRD) | 255 |
| 12.3.4 | Load Charge Rate Due to Generation Credit (LCRGC) | 255 |
| 12.4 | Rate Design | 256 |
| 12.4.1 | Charge Rate for Wheeling Customers | 256 |
| 12.4.2 | Charge Rate for Native Customers | 256 |
| 12.4.3 | Credit to Generation Customers | 257 |
| 12.5 | Application Example | 257 |
| 12.5.1 | Calculation of the UIRV | 258 |
| 12.5.2 | Calculation of the GCRI | 258 |
| 12.5.3 | Calculation of the LCRD | 259 |
| 12.5.4 | Calculation of the LCRGC | 260 |
| 12.5.5 | Calculations of Charge Rates | 260 |
| 12.6 | Conclusions | 261 |

| | |
|---|------------|
| 13 Probabilistic Transient Stability Assessment | 263 |
| 13.1 Introduction | 263 |
| 13.2 Probabilistic Modeling and Simulation Methods | 264 |
| 13.2.1 Selection of Prefault System States | 264 |
| 13.2.2 Fault Models | 264 |
| 13.2.2.1 Probability of Fault Occurrence | 264 |
| 13.2.2.2 Probability of Fault Location | 265 |
| 13.2.2.3 Probability of Fault Type | 265 |
| 13.2.2.4 Probability of Unsuccessful Automatic Reclosure | 266 |
| 13.2.2.5 Probability Model of Fault-Clearing Time | 266 |
| 13.2.3 Monte Carlo Simulation of Fault Events | 267 |
| 13.2.4 Transient Stability Simulation | 268 |
| 13.3 Procedure | 268 |
| 13.3.1 Procedure for the First Type of Study | 268 |
| 13.3.2 Procedure for the Second Type of Study | 270 |
| 13.4 Examples | 270 |
| 13.4.1 System Description and Data | 270 |
| 13.4.1.1 System Load Data | 272 |
| 13.4.1.2 Fault Model Data | 272 |
| 13.4.2 Transfer Limit Calculation in the Columbia River System | 273 |
| 13.4.3 Generation Rejection Requirement in the Peace River System | 275 |
| 13.4.4 Summary | 278 |
| 13.5 Conclusions | 279 |
| | |
| Appendix A Basic Probability Concepts | 281 |
| A.1 Probability Calculation Rules | 281 |
| A.1.1 Intersection | 281 |
| A.1.2 Union | 281 |
| A.1.3 Full Conditional Probability | 282 |
| A.2 Random Variable and its Distribution | 282 |
| A.3 Important Distributions in Risk Evaluation | 283 |
| A.3.1 Exponential Distribution | 283 |
| A.3.2 Normal Distribution | 283 |
| A.3.3 Log-Normal Distribution | 284 |
| A.3.4 Weibull Distribution | 285 |
| A.4 Numerical Characteristics | 286 |
| A.4.1 Mathematical Expectation | 287 |
| A.4.2 Variance and Standard Deviation | 287 |
| A.4.3 Covariance and Correlation Coefficients | 287 |
| | |
| Appendix B Elements of Monte Carlo Simulation | 289 |
| B.1 General Concept | 289 |

| | | |
|---|---|------------|
| B.2 | Random Number Generators | 290 |
| B.2.1 | Multiplicative Congruent Generator | 290 |
| B.2.1 | Mixed Congruent Generator | 291 |
| B.3 | Inverse Transform Method of Generating Random Variates | 292 |
| B.4 | Important Random Variates in Risk Evaluation | 292 |
| B.4.1 | Exponential Distribution Random Variate | 292 |
| B.4.2 | Normal Distribution Random Variate | 293 |
| B.4.3 | Log-Normal Distribution Random Variate | 294 |
| B.4.4 | Weibull Distribution Random Variate | 294 |
| Appendix C Power-Flow Models | | 297 |
| C.1 | AC Power-Flow Models | 297 |
| C.1.1 | Power-Flow Equations | 297 |
| C.1.2 | Newton–Raphson Method | 298 |
| C.1.3 | Fast Decoupled Method | 298 |
| C.2 | DC Power-Flow Models | 299 |
| C.2.1 | Basic Equation | 299 |
| C.2.2 | Line-Flow Equation | 300 |
| Appendix D Optimization Algorithms | | 303 |
| D.1 | Simplex Methods for Linear Programming | 303 |
| D.1.1 | Primal Simplex Method | 303 |
| D.1.2 | Dual Simplex Method | 305 |
| D.2 | Interior Point Method for Nonlinear Programming | 306 |
| D.2.1 | Optimality and Feasibility Conditions | 306 |
| D.2.2 | Procedure for Algorithms | 308 |
| Appendix E Three Probability Distribution Tables | | 311 |
| Table 1: | Relationship between area Q and z under the standard normal distribution | 312 |
| Table 2: | Relationship between area α and $t_\alpha(n)$ under the t -distribution | 313 |
| Table 3: | Relationship between area α and $\chi_\alpha^2(n)$ under the χ^2 distribution | 314 |
| References | | 315 |
| Index | | 321 |
| About the Author | | 325 |