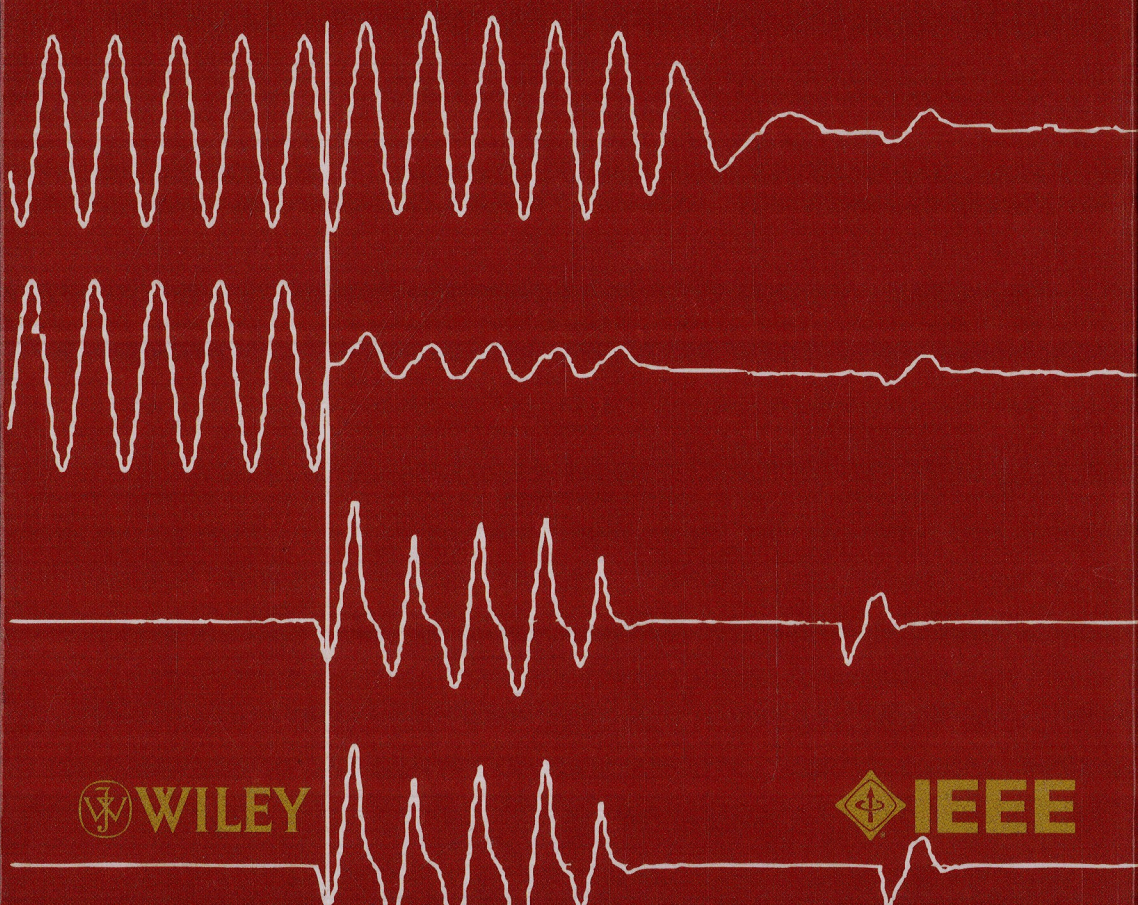


Disturbance Analysis for Power Systems

Mohamed A. Ibrahim



 **WILEY**

 **IEEE**

CONTENTS

Preface

xvii

1	POWER SYSTEM DISTURBANCE ANALYSIS FUNCTION	1
1.1	Analysis Function of Power System Disturbances	2
1.2	Objective of DFR Disturbance Analysis	4
1.3	Determination of Power System Equipment Health Through System Disturbance Analysis	5
1.4	Description of DFR Equipment	6
1.5	Information Required for the Analysis of System Disturbances	7
1.6	Signals to be Monitored by a Fault Recorder	8
1.7	DFR Trigger Settings of Monitored Voltages and Currents	10
1.8	DFR and Numerical Relay Sampling Rate and Frequency Response	11
1.9	Oscillography Fault Records Generated by Numerical Relaying	11
1.10	Integration and Coordination of Data Collected from Intelligent Electronic Devices	12
1.11	DFR Software Analysis Packages	12
1.12	Verification of DFR Accuracy in Monitoring Substation Ground Currents	21
1.13	Using DFR Records to Validate Power System Short-Circuit Study Models	24
1.14	COMTRADE Standard	31
2	PHENOMENA RELATED TO SYSTEM FAULTS AND THE PROCESS OF CLEARING FAULTS FROM A POWER SYSTEM	33
2.1	Shunt Fault Types Occurring in a Power System	33
2.2	Classification of Shunt Faults	34
2.3	Types of Series Unbalance in a Power System	39
2.4	Causes of Disturbance in a Power System	39

2.5	Fault Incident Point	40
2.6	Symmetric and Asymmetric Fault Currents	41
2.7	Arc-Over or Flashover at the Voltage Peak	44
2.8	Evolving Faults	48
2.9	Simultaneous Faults	51
2.10	Solid or Bolted ($R_F = 0$) Close-in Phase-to-Ground Faults	52
2.11	Sequential Clearing Leading to a Stub Fault that Shows a Solid ($R_F = 0$) Remote Line-to-Ground Fault	53
2.12	Sequential Clearing Leading to a Stub Fault that Shows a Resistive Remote Line-to-Ground Fault	54
2.13	High-Resistance Tree Line-to-Ground Faults	56
2.14	High-Resistance Line-to-Ground Fault Confirming the Resistive Nature of the Fault Impedance When Fed from One Side Only (Stub)	58
2.15	Phase-to-Ground Faults on an Ungrounded System	59
2.16	Current in Unfaulted Phases During Line-to-Ground Faults	60
2.17	Line-to-Ground Fault on the Grounded-Wye (GY) Side of a Delta/GY Transformer	63
2.18	Line-to-Line Fault on the Grounded-Wye Side of a Delta/GY Transformer	65
2.19	Line-to-Line Fault on the Delta Side of a Delta/GY Transformer with No Source Connected to the Delta Winding	66
2.20	Subcycle Relay Operating Time During an EHV Double-Phase-to-Ground Fault	68
2.21	Self-Clearing of a C-g Fault Inside an Oil Circuit Breaker Tank	69
2.22	Self-Clearing of a B-g Fault Caused by a Line Insulator Flashover	70
2.23	Delayed Clearing of a Pilot Scheme Due to a Delayed Communication Signal	71
2.24	Sequential Clearing of a Line-to-Ground Fault	72
2.25	Step-Distance Clearing of an L-g Fault	74
2.26	Ground Fault Clearing in Steps by an Instantaneous Ground Element at One End and a Ground Time Overcurrent Element at the Other End	76
2.27	Ground Fault Clearing by Remote Backup Following the Failures of Both Primary and Local Backup (Breaker Failure) Protection Systems	78
2.28	Breaker Failure Clearing of a Line-to-Ground Fault	79
2.29	Determination of the Fault Incident Point and Classification of Faults Using a Comparison Method	81

3	POWER SYSTEM PHENOMENA AND THEIR IMPACT ON RELAY SYSTEM PERFORMANCE	85
3.1	Power System Oscillations Leading to Simultaneous Tripping of Both Ends of a Transmission Line and the Tripping of One End Only on an Adjacent Line	86
3.2	Generator Oscillations Triggered by a Combination of L-g Fault, Loss of Generation, and Undesired Tripping of Three 138-kV Lines	91
3.3	Stable Power Swing Generated During Successful Synchronization of a 200-MW Unit	95
3.4	Major System Disturbance Leading to Different Oscillations for Different Transmission Lines Emanating from the Same Substation	96
3.5	Appearance of 120-Hz Current at a Generator Rotor During a High-Side Phase-to-Ground Fault	98
3.6	Generator Negative-Sequence Current Flow During Unbalanced Faults	101
3.7	Inadvertent (Accidental) Energization of a 170-MW Hydro Generating Unit	102
3.8	Appearance of Third-Harmonic Voltage at Generator Neutral	104
3.9	Variations of Generator Neutral Third-Harmonic Voltage Magnitude During System Faults	106
3.10	Generator Active and Reactive Power Outputs During a GSU High-Side L-g Fault	107
3.11	Loss of Excitation of a 200-MW Unit	108
3.12	Generator Trapped (Decayed) Energy	110
3.13	Nonzero Current Crossing During Faults and Mis-Synchronization Events	112
3.14	Generator Neutral Zero-Sequence Voltage Coupling Through Step-Up Transformer Interwinding Capacitance During a High-Side Ground Fault	113
3.15	Energizing a Transformer with a Fault on the High Side within the Differential Zone	115
3.16	Transformer Inrush Currents	118
3.17	Inrush Currents During Energization of the Grounded-Wye Side of a YG/Delta Transformer	120
3.18	Inrush Currents During Energization of a Transformer Delta Side	121

3.19	Two-Phase Energization of an Autotransformer with a Delta Winding Tertiary During a Simultaneous L-g Fault and an Open Phase	124
3.20	Phase Shift of 30° Across the Delta/Wye Transformer Banks	127
3.21	Zero-Sequence Current Contribution from a Remote Two-Winding Delta/YG Transformer	128
3.22	Conventional Power-Regulating Transformer Core Type Acting as a Zero-Sequence Source	129
3.23	Circuit Breaker Re-Strikes	130
3.24	Circuit Breaker Pole Disagreement During a Closing Operation	132
3.25	Circuit Breaker Opening Resistors	133
3.26	Secondary Current Backfeeding to Breaker Failure Fault Detectors	134
3.27	Magnetic Flux Cancellation	136
3.28	Current Transformer Saturation	138
3.29	Current Transformer Saturation During an Out-of-Step System Condition Initiated by Mis-Synchronization of a Generator Breaker	141
3.30	Capacitive Voltage Transformer Transient	143
3.31	Bushing Potential Device Transient During Deenergization of an EHV Line	144
3.32	Capacitor Bank Breaker Re-Strike Following Interruption of a Capacitor Normal Current	146
3.33	Capacitor Bank Closing Transient	147
3.34	Shunt Capacitor Bank Outrush into Close-in System Faults	149
3.35	SCADA Closing into a Three-Phase Fault	153
3.36	Automatic Reclosing into a Permanent Line-to-Ground Fault	154
3.37	Successful High-Speed Reclosing Following a Line-to-Ground Fault	155
3.38	Zero-Sequence Mutual Coupling-Induced Voltage	156
3.39	Mutual Coupling Phenomenon Causing False Tripping of a High-Impedance Bus Differential Relay During a Line Phase-to-Ground Fault	159
3.40	Appearance of Nonsinusoidal Neutral Current During the Clearing of Three-Phase Faults	162
3.41	Current Reversal on Parallel Lines During Faults	164
3.42	Ferranti Voltage Rise	166
3.43	Voltage Oscillation on EHV Lines Having Shunt Reactors at their Ends	168

3.44	Lightning Strike on an Adjacent Line Followed by a C-g Fault Caused by a Separate Lightning Strike on the Monitored Line	172
3.45	Spill Over of a 345-kV Surge Arrester Used to Protect a Cable Connection, Prior to its Failure	173
3.46	Scale Saturation of an A/D Converter Caused by a Calibration Setting Error	174
3.47	Appearance of Subsidence Current at the Instant of Fault Interruption	176
3.48	Energizing of a Medium Voltage Motor that has an Incorrect Formation of the Stator Winding Neutral	177
3.49	Phase Angle Change from Loading Condition to Fault Condition	179

4

CASE STUDIES RELATED TO GENERATOR SYSTEM DISTURBANCES

183

4.1	Generator Protection Basics	184
	Case Studies	186
	Case Study 4.1 Appearance of Double-Frequency (120-Hz) Current in a Hydrogenerator Rotor Due to Stator Negative-Sequence Current Flow During a 115-kV Phase-to-Ground Fault	186
	Case Study 4.2 Inadvertent (Accidental) Energization of a 170-MW Hydro Unit	193
	Case Study 4.3 Loss of Excitation for a 200-MW Generating Unit Caused by Human Error	204
	Case Study 4.4 Loss-of-Excitation Trip in an 1100-MW Unit	212
	Case Study 4.5 Mis-synchronization of a 50-MW Steam Unit for a Combined-Cycle Plant	214
	Case Study 4.6 Mis-synchronization of a 200-MW Hydro Unit	222
	Case Study 4.7 Undesired Tripping of a Numerical Differential Relay During Manual Synchronization of a Hydro Unit	231
	Case Study 4.8 Tripping of a 500-MW Combined-Cycle Plant Triggered by a High-Side 138-kV Phase-to-Ground Fault	236
	Case Study 4.9 Tripping of a 110-MW Combustion Turbine Unit in a Combined-Cycle Plant During a Power Swing	244
	Case Study 4.10 Analysis of an 800-MW Generating Plant DFR Record for a Normally Cleared 345-kV Phase-to-Ground Fault	247

Case Study 4.11 Tripping of a 150-MW Combined-Cycle Plant Due to a Failed Lead of One Generator Terminal Surge Capacitor	250
Case Study 4.12 Generator Stator Ground Fault in an 800-MW Fossil Unit	260
Case Study 4.13 Three-Phase Fault at the Terminal of an 800-MW Generator Unit	265
Case Study 4.14 Three-Phase Fault at the Terminal of a 50-MW Generator Due to a Cable Connection Failure	271
Case Study 4.15 Generator Stator Phase-to-Phase-to-Ground Fault Caused by Failure of the Rotor Fan Blade	276
Case Study 4.16 Undesired Tripping of a Pump Storage Plant During a Close-in Phase-to-Ground 345-kV Line Fault	286
Case Study 4.17 Tripping of an 800-MW Plant and the Associated EHV Lines During a 345-kV Bus Fault	293
Case Study 4.18 Tripping of a 150-MW Combined-Cycle Plant During an External 138-kV Three-Phase Fault	296
Case Study 4.19 Tripping of a 150-MW Combined-Cycle Plant During a Disturbance in the 138-kV Transmission System	303
Case Study 4.20 Undesired Tripping of a 150-MW Combined-Cycle Plant Following Successful Clearing of a 138-kV Double-Phase-to-Ground Fault	308
Case Study 4.21 Undesired Tripping of an Induction Generator by a Differential Relay Having a Capacitor Bank Within the Protection Zone	311
Case Study 4.22 Undesired Tripping of a Steam Unit Upon Its First Synchronization to the System During the Commissioning Phase of a Combined-Cycle Plant	314
Case Study 4.23 Sequential Shutdown of a Steam-Driven Generating Unit as Part of a 500-MW Combined-Cycle Plant	318
Case Study 4.24 Wiring Errors Leading to Undesired Generator Numerical Differential Relay Operation During the Commissioning Phase of a New Unit	320
Case Study 4.25 Phasing a New Generator into the System Prior to Commissioning	324
Case Study 4.26 Third-Harmonic Undervoltage Element Setting Procedure for 100% Stator Ground Fault Protection	327
Case Study 4.27 Basis for Setting the Generator Relaying Elements to Provide System Backup Protection	330

5 CASE STUDIES RELATED TO TRANSFORMER SYSTEM DISTURBANCES 335

5.1 Transformer Basics	336
5.2 Transformer Differential Protection Basics	344

5.3 Case Studies	347
Case Study 5.1 Energization of a 5-MVA 13.8/4.16-kV Station Service Transformer with a 13.8-kV Phase-to-Phase Bus Fault Within the Transformer Differential Protection Zone	347
Case Study 5.2 Lack of Protection Redundancy for a Generator Step-up Transformer Leads to Interruption of a 230-kV Area	353
Case Study 5.3 Undesired Operation of a Numerical Transformer Differential Relay Due to a Relay Setting Error in the Winding Configuration	357
Case Study 5.4 Location of a 13.8-kV Switchgear Phase-to-Phase Fault Using Transformer Differential Numerical Relay Fault Records	363
Case Study 5.5 Operation of a Unit Step-Up Transformer with an Open Phase on the 13.8-kV Delta Winding	370
Case Study 5.6 Using a Transformer Phasing Diagram, Digital Fault Recorder Record, and Relay Targets to Confirm the Damaged Phase of a Unit Auxiliary Transformer Failure	375
Case Study 5.7 Failure of a 450-MVA 345/138/13.2-kV Autotransformer	381
Case Study 5.8 Failure of a 750-kVA 13.8/0.480-kV Station Service Transformer Due to a Possible Ferroresonance Condition	387
Case Study 5.9 Undesired Tripping of a Numerical Transformer Differential Relay During an External Line-to-Ground Fault	394
Case Study 5.10 Undesired Operation of Numerical Transformer Differential Relays During Energization of Two 75-MVA 138/13.8-kV GSU Transformers	407
Case Study 5.11 Undesired Operation of a Numerical Transformer Differential Relay During Energization of a 5-MVA 13.8/4.16-kV Station Service Transformer	411
Case Study 5.12 Phase-to-Phase Fault Evolving into a Three-Phase Fault at the High Side of a 5-MVA 13.8/4.16-kV Station Service Transformer	414
Case Study 5.13 Phase-to-Phase Fault Evolving into a Three-Phase Fault at the 13.8-kV Bus Connection of a 2-MVA 13.8/0.480-kV Station Service Enclosure	420
Case Study 5.14 Phase-to-Phase Fault in a 13.8-kV Switchgear Caused by Heavy Rain Evolving into a Three-Phase Fault	426
Case Study 5.15 Undesired Operation of a Numerical Transformer Differential Relay Due to a Missing CT Cable Connection as an Input to the Relay Wiring	430
Case Study 5.16 Phase-to-Ground Fault Caused by Flashover of a Transformer 115-kV Bushing Due to a Bird Droppings	434

Case Study 5.17 Using a Transformer Numerical Relay Oscillography Record to Analyze Phase-to-Ground Faults in a 4.16-kV Low-Resistance Grounding Supply	439
Case Study 5.18 Phase-to-Phase Fault Caused by a Squirrel in a 13.8-kV Cable Bus Which Evolves into a Three-Phase Fault	447
Case Study 5.19 13.8-kV Transformer Lead Phase-to-Phase Fault Due to Animal Contact, Evolving into a 115-kV Transformer Bushing Fault	451
Case Study 5.20 Undesired Tripping of a Numerical Multifunction Transformer Relay by Assertion of a Digital Input Wired to the Buchholz Relay Trip Output	456

6 CASE STUDIES RELATED TO OVERHEAD TRANSMISSION-LINE SYSTEM DISTURBANCES	461
6.1 Line Protection Basics	463
6.2 Case Studies	466
Case Study 6.1 Using a DFR Record From One End Only to Determine Local and Remote-End Clearing Times for a Line-to-Ground Fault	466
Case Study 6.2 Analysis of Clearing Times for a Phase-to-Ground Fault from Both Ends of a 345-kV Transmission Line Using Oscillograms from One End Only	469
Case Study 6.3 Analysis of a Three-Phase Fault Caused by Lightning	471
Case Study 6.4 Analysis of a Double-Phase-to-Ground 765-kV Fault Caused by Lightning	473
Case Study 6.5 Assessment of Transmission Tower Footing Resistance by Analyzing a Three-Phase-to-Ground Fault Caused by Lightning	476
Case Study 6.6 115-kV Phase-to-Ground Fault Cleared First from a Solidly Grounded System, Then Connected and Cleared from an Ungrounded System	478
Case Study 6.7 345-kV Phase-to-Ground Fault (C-g) Caused by an Act of Vandalism	485
Case Study 6.8 345-kV Phase-to-Ground (A-g) Fault Due to an Accident Along the Line Right-of-Way	489
Case Study 6.9 False Tripping of a 138-kV Current Differential Relaying System During an External Phase-to-Ground Fault	495
Case Study 6.10 Undesired Operation of a 13.8-kV Feeder Ground Relay During a Three-Phase Fault Due to an Extra CT Circuit Ground	502

Case Study 6.11 Correction of a System Model Error from Analysis of a Failure of a Post Insulator Associated with a 115-kV Disconnect Switch	512
Case Study 6.12 Location of a 345-kV Line Fault Protected by Electromechanical Distance Relays Using Information from a DFR Record	519
Case Study 6.13 Location of an Outdoor 13.8-kV Switchgear Fault at a Cogeneration Facility Using a DFR Fault Record from a Remote Substation	524
Case Study 6.14 Breakage (Failure) of a 345-kV Subconductor Bundle During a High-Resistance Tree Fault, Due to the Heavily Loaded Line Sagging to a Tree	529
Case Study 6.15 115-kV Phase-to-Phase Fault Caused by Failure of a Circuit Switcher	536
Case Study 6.16 Undesired Tripping of a 115-kV Feeder Due to a Setting Application Error in the Time Overcurrent Element for a Numerical Line Protection Relay	539
Case Study 6.17 Mitigation of Mutual Coupling Effects on the Reach of Ground Distance Relays Protecting High- and Extrahigh-Voltage Transmission Lines	544

7 CASE STUDIES RELATED TO CABLE TRANSMISSION FEEDER SYSTEM DISTURBANCES	571
Case Studies	572
Case Study 7.1 Optimum Design of Relaying Protection Zones Leads to Quick Identification of a Faulted 345-kV Submarine Cable Section	572
Case Study 7.2 Undesired Operation of a 138-kV Cable Feeder Differential Relay During the Commissioning Phase of a 500-MW Plant	578
Case Study 7.3 Phase-to-Ground Fault Caused by Failure of a 345-kV Cable Connection Between the Generator and the Switchyard, Accompanied by Mechanical Failure of One of the Cable Pot Head Phases	588
Case Study 7.4 Troubleshooting a 345-kV Phase-to-Ground Fault Using Relay Targets Only	595
Case Study 7.5 Failure of a 345-kV Cable Connection Between a 300-MW Generator and a 345-kV Switchyard, Causing a Phase-to-Ground Fault	603
Case Study 7.6 138-kV Cable Pot Head Failure Analysis Using Numerical Current Differential Relay Oscillography and Event Records	607

8 CASE STUDIES RELATED TO BREAKER FAILURE PROTECTION SYSTEM DISTURBANCES	615
8.1 Breaker Failure Protection Basics	616
Case Studies	626
Case Study 8.1 Tripping of a Combined-Cycle 150-MW Plant by Undesired Operation of a Solid-State Breaker Failure Relaying System	626
Case Study 8.2 115-kV Dual Breaker Failures Resulting in the Loss of a 1000-MW Plant and Associated Substations	634
Case Study 8.3 230-kV Substation Outage Due to Circuit Breaker Problems During the Clearing of a Close-in Phase-to-Ground Fault	640
Case Study 8.4 Failure of a 230-kV Circuit Breaker Leading to Isolation of a 1000-MW Plant and Associated Substations	646
Case Study 8.5 Generator CB Failure During Automatic Synchronization of the Circuit Breaker	654
Case Study 8.6 Circuit Breaker Re-strikes While Clearing Simultaneous Phase-to-Ground Faults on a 230-kV Double-Circuit Tower	660
Case Study 8.7 345-kV Capacitor Bank Breaker Fault Coupled with an Additional Failure of a Dual SF6 Pressure 345-kV Breaker During the Clearing of the Fault	664
Case Study 8.8 Oil Circuit Breaker Failure Following the Clearing of a Failed 230-kV Surge Arrester	671
Case Study 8.9 Detection of a Remote Circuit Breaker Problem from Analysis of a Local Oscillogram Monitoring Line Currents and Voltages	676
Case Study 8.10 Blackout of a 138-kV Load Area Due to a Primary Relay System Failure and the Lack of DC Control Power for the Secondary Relay System Circuit	678
Case Study 8.11 Installation of Two 345-kV Breakers in Series Within a Ring Substation Configuration to Mitigate the Loss of Critical Lines During Breaker Failure Events	682
Case Study 8.12 Design of Two 138-kV Circuit Breakers in Series to Fulfill the Need of Breaker Failure Protection	682
9 PROBLEMS	685
Index	715