Contents

Preface *xi*
Acknowledgments *xiii*

1 Definitions: Methods of Calculations *1*
1.1 Time Behavior of the Short-Circuit Current *2*
1.2 Short-Circuit Path in the Positive-Sequence System *3*
1.3 Classification of Short-Circuit Types *5*
1.4 Methods of Short-Circuit Calculation *7*
1.4.1 Superposition Method *7*
1.4.2 Equivalent Voltage Source *10*
1.4.3 Transient Calculation *11*
1.4.4 Calculating with Reference Variables *12*
1.4.4.1 The Per-Unit Analysis *12*
1.4.4.2 The %/MVA Method *14*
1.4.5 Examples *14*
1.4.5.1 Characteristics of the Short-Circuit Current *14*
1.4.5.2 Calculation of Switching Processes *14*
1.4.5.3 Calculation with pu System *14*
1.4.5.4 Calculation with pu Magnitudes *16*
1.4.5.5 Calculation with pu System for an Industrial System *17*
1.4.5.6 Calculation with MVA System *19*

2 Fault Current Analysis *23*

3 The Significance of IEC 60909-0 *29*

4 Supply Networks *33*
4.1 Calculation Variables for Supply Networks *34*
4.2 Lines Supplied from a Single Source *35*
4.3 Radial Networks *35*
4.4 Ring Networks *35*
4.5 Meshed Networks *37*

5 Network Types for the Calculation of Short-Circuit Currents *39*
5.1 Low-Voltage Network Types *39*
5.2 Medium-Voltage Network Types *39*
5.3 High-Voltage Network Types *44*

6 Systems up to 1 kV *47*
6.1 TN Systems *48*
6.1.1 Description of the System is Carried Out by Two Letters *48*
6.2 Calculation of Fault Currents *49*
6.2.1 System Power Supplied from Generators: *50*
6.3 TT systems *52*
6.3.1 Description of the System *52*
6.4 IT Systems *53*
6.4.1 Description of the System *53*
6.5 Transformation of the Network Types Described to Equivalent Circuit Diagrams *54*
6.6 Examples *56*
6.6.1 Example 1: Automatic Disconnection for a TN System *56*
6.6.1.1 Calculation for a Receptacle *56*
6.6.1.2 For the Heater *56*
6.6.2 Example 2: Automatic Disconnection for a TT System *57*

7 Neutral Point Treatment in Three-Phase Networks *59*
7.1 Networks with Isolated Free Neutral Point *63*
7.2 Networks with Grounding Compensation *64*
7.3 Networks with Low-Impedance Neutral Point Treatment *66*
7.4 Examples *69*
7.4.1 Neutral Grounding *69*

8 Impedances of Three-Phase Operational Equipment *71*
8.1 Network Feed-Ins, Primary Service Feeder *71*
8.2 Synchronous Machines *73*
8.2.1 a.c. Component *78*
8.2.2 d.c. Component *78*
8.2.3 Peak Value *78*
8.3 Transformers *80*
8.3.1 Short-Circuit Current on the Secondary Side *81*
8.3.2 Voltage-Regulating Transformers *83*
8.4 Cables and Overhead Lines *85*
8.5 Short-Circuit Current-Limiting Choke Coils *96*
8.6 Asynchronous Machines *97*
8.7 Consideration of Capacitors and Nonrotating Loads *98*
8.8 Static Converters *98*
8.9 Wind Turbines *99*
8.9.1 Wind Power Plant with AG *100*
8.9.2 Wind Power Plant with a Doubly Fed Asynchronous Generator *101*

8.9.3 Wind Power with Full Converter *101*
8.10 Short-Circuit Calculation on Ship and Offshore Installations *102*
8.11 Examples *104*
8.11.1 Example 1: Calculate the Impedance *104*
8.11.2 Example 2: Calculation of a Transformer *104*
8.11.3 Example 3: Calculation of a Cable *105*
8.11.4 Example 4: Calculation of a Generator *105*
8.11.5 Example 5: Calculation of a Motor *106*
8.11.6 Example 6: Calculation of an LV motor *106*
8.11.7 Example 7: Design and Calculation of a Wind Farm *106*
8.11.7.1 Description of the Wind Farm *106*
8.11.7.2 Calculations of Impedances *111*
8.11.7.3 Backup Protection and Protection Equipment *116*
8.11.7.4 Thermal Stress of Cables *118*
8.11.7.5 Neutral Point Connection *119*
8.11.7.6 Neutral Point Transformer (NPT) *119*
8.11.7.7 Network with Current-Limiting Resistor *120*
8.11.7.8 Compensated Network *124*
8.11.7.9 Insulated Network *125*
8.11.7.10 Grounding System *125*

9 Impedance Corrections *127*
9.1 Correction Factor K_G for Generators *128*
9.2 Correction Factor K_{KW} for Power Plant Block *129*
9.3 Correction Factor K_T for Transformers with Two and Three Windings *130*

10 Power System Analysis *133*
10.1 The Method of Symmetrical Components *136*
10.2 Fundamentals of Symmetrical Components *137*
10.2.1 Derivation of the Transformation Equations *139*
10.3 General Description of the Calculation Method *140*
10.4 Impedances of Symmetrical Components *142*

11 Calculation of Short-Circuit Currents *147*
11.1 Three-Phase Short Circuits *147*
11.2 Two-Phase Short Circuits with Contact to Ground *148*
11.3 Two-Phase Short Circuit Without Contact to Ground *149*
11.4 Single-Phase Short Circuits to Ground *150*
11.5 Peak Short-Circuit Current, i_p *153*
11.6 Symmetrical Breaking Current, I_a *155*
11.7 Steady-State Short-Circuit Current, I_k *157*

12 Motors in Electrical Networks *161*
12.1 Short Circuits at the Terminals of Asynchronous Motors *161*
12.2 Motor Groups Supplied from Transformers with Two Windings *163*
12.3 Motor Groups Supplied from Transformers with Different Nominal Voltages *163*

13 Mechanical and Thermal Short-Circuit Strength *167*
13.1 Mechanical Short-Circuit Current Strength *167*
13.2 Thermal Short-Circuit Current Strength *173*
13.3 Limitation of Short-Circuit Currents *176*
13.4 Examples for Thermal Stress *176*
13.4.1 Feeder of a Transformer *176*
13.4.2 Mechanical Short-Circuit Strength *178*

14 Calculations for Short-Circuit Strength *185*
14.1 Short-Circuit Strength for Medium-Voltage Switchgear *185*
14.2 Short-Circuit Strength for Low-Voltage Switchgear *186*

15 Equipment for Overcurrent Protection *189*

16 Short-Circuit Currents in DC Systems *199*
16.1 Resistances of Line Sections *201*
16.2 Current Converters *202*
16.3 Batteries *203*
16.4 Capacitors *204*
16.5 Direct Current Motors *205*

17 Power Flow Analysis *207*
17.1 Systems of Linear Equations *208*
17.2 Determinants *209*
17.3 Network Matrices *212*
17.3.1 Admittance Matrix *212*
17.3.2 Impedance Matrix *213*
17.3.3 Hybrid Matrix *213*
17.3.4 Calculation of Node Voltages and Line Currents at Predetermined Load Currents *214*
17.3.5 Calculation of Node Voltages at Predetermined Node Power *215*
17.3.6 Calculation of Power Flow *215*
17.3.6.1 Type of Nodes *216*
17.3.6.2 Type of Loads and Complex Power *216*
17.3.7 Linear Load Flow Equations *218*
17.3.8 Load Flow Calculation by Newton–Raphson *219*
17.3.9 Current Iteration *223*
17.3.9.1 Jacobian Method *223*
17.3.10 Gauss–Seidel Method *224*
17.3.11 Newton–Raphson Method *224*
17.3.12 Power Flow Analysis in Low-Voltage Power Systems *226*
17.3.13 Equivalent Circuits for Power Flow Calculations *227*
17.3.14 Examples *228*
17.3.14.1 Calculation of Reactive Power *228*
17.3.14.2 Application of Newton Method *228*
17.3.14.3 Linear Equations *229*
17.3.14.4 Application of Cramer's Rule *229*
17.3.14.5 Power Flow Calculation with NEPLAN *230*

18 Examples: Calculation of Short-Circuit Currents *233*
18.1 Example 1: Radial Network *233*
18.2 Example 2: Proof of Protective Measures *235*
18.3 Example 3: Connection Box to Service Panel *237*
18.4 Example 4: Transformers in Parallel *238*
18.5 Example 5: Connection of a Motor *240*
18.6 Example 6: Calculation for a Load Circuit *241*
18.7 Example 7: Calculation for an Industrial System *243*
18.8 Example 8: Calculation of Three-Pole Short-Circuit Current and Peak Short-Circuit Current *244*
18.9 Example 9: Meshed Network *246*
18.10 Example 10: Supply to a Factory *249*
18.11 Example 11: Calculation with Impedance Corrections *250*
18.12 Example 12: Connection of a Transformer Through an External Network and a Generator *253*
18.13 Example 13: Motors in Parallel and their Contributions to the Short-Circuit Current *255*
18.14 Example 14: Proof of the Stability of Low-Voltage Systems *257*
18.15 Example 15: Proof of the Stability of Medium-Voltage and High-Voltage Systems *259*
18.16 Example 16: Calculation for Short-Circuit Currents with Impedance Corrections *269*

Bibliography *273*
Standards *277*
Explanations of Symbols *281*
Symbols and Indices *283*
Indices *286*
Secondary Symbols, Upper Right, Left *287*
American Cable Assembly (AWG) *287*

Index *289*