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A Practical Guide to IEC 60 909

Ismail Kasikci

 **WILEY-VCH**

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Foreword

This book is the result of many years of professional activity in the area of power supply, teaching at the VDE, as well as at the Technical academy in Esslingen and at the Master Trade School in Heidelberg. Every planner of electrical systems is obligated today to calculate the single-pole or three-pole short circuit current before and after the project management phase. IEC 60 909 is internationally recognized and used. This standard will be discussed in the present book on the basis of fundamental principles and technical references, thus permitting a summary of the standard in the *simplest* and *most understandable* way possible. The rapid development in all areas of technology is also reflected in the improvement and elaboration of the regulations, in particular in regard to IEC 60 909. Every system installed must not only be suitable for normal operation, but must also be designed in consideration of fault conditions and must remain undamaged following operation under normal conditions and also following a fault condition. Electrical systems must therefore be designed so that neither persons nor equipment are endangered. The dimensioning, cost effectiveness and safety of these systems depends to a great extent on being able to control short circuit currents. With increasing power of the installation, the importance of calculating short circuit currents has also increased accordingly. Short circuit current calculation is a prerequisite for the correct dimensioning of operational electrical equipment, controlling protective measures and stability against short circuits in the selection of equipment. Solutions to the problems of selectivity, back-up protection, protective equipment and voltage drops in electrical systems will not be dealt with in this book. The reduction factors, such as frequency, temperatures other than the normal operating temperature, type of wiring etc. and the resulting current carrying capacity of conductors and cables will also not be dealt with here.

This book is comprised of the following sections:

Part 1 describes the most important terms and definitions, together with relevant processes and types of short circuits.

Part 2 is an overview of the IEC 60 909 standards, including recent changes to these.

Part 3 explains the significance, purpose and creation of IEC 60 909.

Part 4 deals with the network design of supply networks.

Part 5 gives an overview of the network types for low and medium voltage.

Part 6 describes the systems (network types) in the low voltage network IEC 60354 Part 30 with the cut-off conditions.

Part 7 illustrates the types of neutral point treatment in three-phase networks.

Part 8 discusses the impedances of three-phase operational equipment along with relevant data, tables, diagrams and characteristic curves.

Part 9 presents the impedance corrections for generators, power substation transformers and distribution transformers.

Part 10 is concerned with the method of symmetrical components. With the exception of the three-pole short circuit current, all other fault currents are unsymmetrical. The calculation of these currents is not possible in the positive-sequence system. The method of symmetrical components is therefore described here.

Part 11 is devoted to the calculation of short circuit types.

Part 12 discusses the contribution of high and low voltage motors to the short circuit current.

Part 13 deals with the subject of mechanical and thermal stresses in operational equipment as the result of short circuit currents.

Part 14 gives an overview of the design values for short circuit current strength.

Part 15 is devoted to the most important overcurrent protection devices, with time-current characteristics.

Part 16 gives a brief overview of the procedure for calculating short circuit currents in DC systems.

Part 17 gives a list of programs for the calculation of short circuit currents.

Part 18 represents a large number of examples taken from practice which enhance the understanding of the theoretical foundations. A large number of diagrams and tables required for calculation simplify the application of the IEC 60909 standard as well as the calculation of short circuit currents and therefore shorten the time necessary to carry out the planning of electrical systems.

In the appendices two software programs are introduced to carry out simplified short circuit calculations (appended to this book as a CD ROM).

I am especially indebted to Professor B. Müller of the University of Applied Sciences for Technique and Economics Berlin for critically reviewing the manuscript and for valuable suggestions.

I also wish to thank Siemens AG for their friendly support in the compilation of data and diagrams for switchgear, as well as for permission to include the program KUBS plus, developed by Siemens as an aid in the calculation of short circuit currents and in the selection of circuit breakers, and Elektra Soft for the calculation tools for electrical engineering, with this book.

At this point I would also like to express my gratitude to all those colleagues who supported me with their ideas, criticism, suggestions and corrections. My heartiest appreciation is due to Eva E. Wille, Anette Eckerle, Maike Petersen, Hans-Jochen Schnitt and Michael Baer for their excellent cooperation and their support in the publication of this book. Furthermore, I welcome every suggestion, criticism and idea regarding the use of this book from those who read the book.

Finally, without the support of my wife this book could never have been written. In recognition of all the weekends and evenings I sat at the computer, I dedicate this book to my family.

Ismail Kasikci

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Symbols and Indices

| | |
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| A | Initial value of DC aperiodic component |
| A | Cross-section of conductor |
| a | Center-to-center distance between conductors |
| $\underline{a}, \underline{a}^2$ | Rotational operators |
| \underline{b} | Width of rectangular conductor |
| c | Voltage factor |
| C | Capacitance |
| E | Internal voltage of voltage source; source voltage |
| E_B | No-load voltage of battery |
| E'' | Subtransient voltage of synchronous machine |
| f | Frequency |
| h | Height of conductor |
| L' | Distributed inductance |
| I_a | Cut-off current |
| I_{an} | Starting current |
| I_b | Operating current |
| I_k | Steady state short circuit current |
| I''_k | Initial symmetrical short circuit current |
| I''_{k1} | Single-pole short circuit current |
| I''_{k2} | Two-pole short circuit current |
| I''_{k3} | Three-pole short circuit current |
| I''_{k2E} | Two-pole short circuit with contact to ground |
| I''_{kEE} | Double ground fault |
| I_{ma} | Rated short circuit making current |
| I_n | Nominal current of protective equipment |
| i_p | Peak short circuit current |
| I_r | Rated current |
| I_{rM} | Magnetic setting current |
| I_{sc} | Rated short circuit breaking current |
| I_{cm} | Rated short circuit making current |
| I_{cu} | Rated short circuit breaking current |
| I_{th} | Rated short-time current |
| K | Correction factor |

| | |
|-----------|--|
| L_B | Inductance of battery |
| L_{BBr} | Total inductance of battery |
| L_{BL} | Inductance of a battery conductor |
| L_C | Inductance of capacitor |
| L_{CBr} | Total inductance of capacitor |
| L_{CL} | Inductance of a capacitor conductor |
| L_{CY} | Inductance of coupling branch for capacitor |
| L_{DL} | Inductance of conductor in converter arm |
| L_M | Inductance of DC motor |
| L_{MBr} | Total inductance of DC motor |
| L_{ML} | Inductance of a DC motor conductor |
| L_s | Inductance of saturated choke coil |
| L_Y | Inductance of coupling branch |
| m | Decaying DC aperiodic component |
| M_r | Rated-load torque of motor |
| n | Decaying AC component |
| p | Pole-pair of asynchronous motor |
| p | Ratio I_k/I_p |
| P | Effective power |
| P_{kT} | Transformer winding losses |
| P_T | Transformation ratio of transformer |
| Q | Idle power |
| r | Resistance, conductor radius, absolute or relative value |
| R | Resistance |
| R_l | Resistance of conductor |
| R' | Resistance per unit length |
| R_{BL} | Resistance of battery conductor |
| R_s | Resistance of saturated choke coil |
| R_Y | Resistance of coupling branch |
| R_{BY} | Resistance of battery coupling branch |
| R_C | Resistance of capacitor |
| R_{CBr} | Total resistance of capacitor |
| R_{CL} | Resistance of a capacitor conductor |
| R_{DL} | Resistance of conductor in converter arm |
| R_M | Resistance of DC motor |
| R_{ML} | Resistance of DC motor conductor |
| R_{MY} | Resistance of DC motor coupling branch |
| S | Apparent power, cross-section |
| S''_k | Initial symmetrical short circuit power |
| t | Time |
| T_k | Duration of short circuit |
| t_p | Time until onset of peak short circuit current |
| U_{NB} | Nominal voltage of battery |
| U_{rM} | Rated voltage of DC motor |
| u_{Rr} | Rated value for resistive voltage drop in % |

| | |
|-------------------|--|
| u_{kr} | Rated value for short circuit voltage in % |
| \underline{Z}_k | Short circuit impedance of network |
| X | Reactance |
| x_d'' | Subtransient reactance of synchronous motor |
| Z | Impedance |
| Z_1 | Positive-sequence impedance |
| Z_2 | Negative-sequence impedance |
| Z_0 | Zero-sequence impedance |
| φ | Phase angle |
| ε | Coefficient of grounding |
| μ | Factor for calculation of symmetrical breaking current |
| λ | Factor for calculation of steady state short circuit current |
| μ_0 | Absolute permeability in vacuum |
| κ | Withstand ratio |
| η | Efficiency of AC motor |
| ρ | Specific resistance |
| δ | Decay coefficient, ground fault factor |
| Ψ | Angular velocity |

Indices

| | |
|-------------|---|
| a | Cut-off |
| A, B, C | Description of position, e.g. bus bar |
| B | Battery |
| B_r | Battery branch |
| $a.c. : AC$ | AC current |
| AMZ | Maximum current-dependent time relay |
| ASM | Asynchronous machine |
| C | Capacitor |
| D | Converter |
| $d.c. : DC$ | DC current |
| E | Ground |
| F | Short circuit position |
| G | Generator |
| HV | High voltage |
| i | Internal |
| K | Cable |
| k | Short circuit |
| $k1$ | Single-pole short circuit current |
| $k2$ | Two-pole short circuit current |
| $k2E$ | Two-pole short circuit with contact to ground |
| $k3$ | Three-pole short circuit current |
| kEE | Double ground fault |

| | |
|--|--|
| <i>l</i> | Length |
| <i>L</i> | Conductor |
| <i>L₁, L₂, L₃</i> | External conductor |
| <i>LV</i> | Low voltage |
| <i>M</i> | Motor |
| <i>max</i> | Maximum |
| <i>min</i> | Minimum |
| <i>MV</i> | Medium voltage |
| <i>n</i> | Nominal value |
| <i>N</i> | Neutral conductor, network |
| <i>OPE</i> | Overcurrent protective equipment |
| <i>OV</i> | Overvoltage |
| <i>pS</i> | Limiting dynamic value |
| <i>PE</i> | Protective ground conductor |
| <i>Q</i> | Network connection point |
| <i>r</i> | Rated value |
| <i>S</i> | Smoothing choke |
| <i>SP</i> | Connection box to on-site power |
| <i>T</i> | Transformer |
| <i>UMZ</i> | Maximum current-independent time relay |
| <i>UV</i> | Undervoltage |
| <i>1</i> | Component of positive-phase system |
| <i>2</i> | Component of negative-phase system |
| <i>0</i> | Component of zero-phase system |

Secondary symbols, upper right, left

| | |
|-----------|---|
| <i>''</i> | Subtransient value |
| <i>'</i> | Transient value |
| <i>'</i> | Resistance or reactance per unit length |
| <i>*</i> | Relative magnitude |

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1

Terms and Definitions

The following terms and definitions correspond largely to those defined in IEC 60 909. Refer to this standard for all terms not used in this book.

The terms short circuit and ground fault describe faults in the isolation of operational equipment which occur when live parts are shunted out as a result.

- Causes:
 1. Overtemperatures due to excessively high overcurrents.
 2. Disruptive discharges due to overvoltages.
 3. Arcing due to moisture together with impure air, especially on insulators.
- Effects:
 1. Interruption of power supply.
 2. Destruction of system components.
 3. Development of unacceptable mechanical and thermal stresses in electrical operational equipment.
- Short circuit:

According to IEC 60 909, a short circuit is the accidental or intentional conductive connection through a relatively low resistance or impedance between two or more points of a circuit which are normally at different potentials.
- Short circuit current:

According to IEC 60 909, a short circuit current results from a short circuit in an electrical network.

It is necessary to differentiate here between the short circuit current at the position of the short circuit and the transferred short circuit currents in the network branches.
- Initial symmetrical short circuit current:

This is the effective value of the symmetrical short circuit current at the moment at which the short circuit arises, when the short circuit impedance has its value from the time zero.
- Initial symmetrical short circuit apparent power:

The short circuit power represents a fictitious parameter. During the planning of networks, the short circuit power is a suitable characteristic number.

- Peak short circuit current:
The largest possible momentary value of the short circuit occurring.
- Steady state short circuit current:
Effective value of the initial symmetrical short circuit current remaining after the decay of all transient phenomena.
- DC aperiodic component:
Average value of the upper and lower envelope curve of the short circuit current, which slowly decays to zero.
- Symmetrical breaking current:
Effective value of the short circuit current which flows through the contact switch at the time of the first contact separation.
- Equivalent voltage source:
The voltage at the position of the short circuit, which is transferred to the positive-sequence system as the only effective voltage and is used for the calculation of the short circuit currents.
- Superposition method:
The superposition method considers the previous load of the network before the occurrence of the short circuit. It is necessary to know the load flow and the setting of the transformer step switch.
- Voltage factor:
Ratio between the equivalent voltage source and the network voltage U_n , divided by $\sqrt{3}$.
- Equivalent electrical circuit:
Model for the description of the network by an equivalent circuit.
- Far-from-generator short circuit:
The value of the symmetrical AC periodic component remains essentially constant.
- Near-to-generator short circuit:
The value of the symmetrical AC periodic component does not remain constant. The synchronous machine first delivers an initial symmetrical short circuit current which is larger than twice the rated current of the synchronous machine.
- Positive-sequence short circuit impedance:
The impedance of the positive-sequence system as seen from the position of the short circuit.
- Negative-sequence short circuit impedance:
The impedance of the negative-sequence system as seen from the position of the short circuit.
- Zero-sequence short circuit impedance
The impedance of the zero-sequence system as seen from the position of the short circuit. Three times the value of the neutral point to ground impedance occurs here.
- Short circuit impedance:
Impedance required for calculation of the short circuit currents at the position of the short circuit.

1.1

Time behavior of the short circuit current

Figure 1.1 shows the time behavior of the short circuit current for the occurrence of far-from-generator and near-to-generator short circuits.

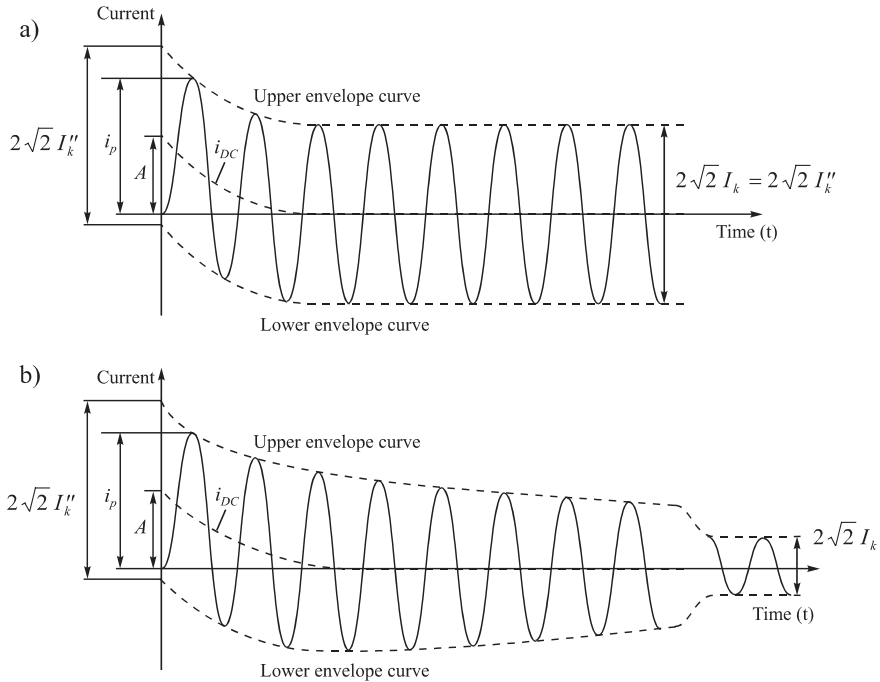


Fig. 1.1: Time behavior of the short circuit current [1], [35]
 a) far-from-generator short circuit, b) near-to-generator short circuit

I_k'' : Initial symmetrical short circuit current

i_p : Peak short circuit current

i_{DC} : Decaying DC aperiodic component

A : Initial value of DC aperiodic component

The DC aperiodic component depends on the point in time at which the short circuit occurs. For a near-to-generator short circuit, the subtransient and the transient behavior of the synchronous machines is important. Following the decay of all transient phenomena, the steady state sets in.

1.2

Short circuit path in the positive-sequence system

For the same external conductor voltages, a three-pole short circuit allows three currents of the same magnitude to develop between the three conductors. It is therefore only necessary to consider one conductor in further calculations. Depending on the distance from the position of the short circuit from the generator, here it is necessary to consider near-to-generator and far-from-generator short circuits separately. For far-from-generator and near-to-generator short circuits, the short circuit path can be represented by a mesh diagram with AC voltage source, reactances X and resistances R (Figure 1.2). Here, X and R replace all components such as cables, conductors, transformers, generators and motors.

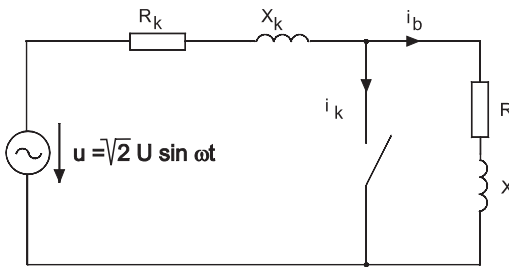


Fig. 1.2: Equivalent circuit of the short circuit current path in the positive-sequence system

The following differential equation can be used to describe the short circuit process:

$$i_k \cdot R_k + L_k \frac{di_k}{dt} = \hat{u} \cdot \sin(\omega t + \psi), \quad (1.1)$$

where ψ is the phase angle at the point in time of the short circuit. This assumes that the current before S closes (short circuit) is zero. The inhomogeneous first order differential equation can be solved by determining the homogeneous solution i_k and a particular solution i_k'' .

$$i_k = i_{k\sim}'' + i_{k-} \quad (1.2)$$

The homogeneous solution, with the time constant $g = L/R$, solution yields:

$$i_k = \frac{-\hat{u}}{\sqrt{(R^2 + X^2)}} e^{\frac{t}{g}} \sin(\psi - \varphi_k). \quad (1.3)$$

For the particular solution, we obtain:

$$i_k'' = \frac{-\hat{u}}{\sqrt{(R^2 + X^2)}} \sin(\omega t + \psi - \varphi_k). \quad (1.4)$$

The total short circuit current is composed of both components:

$$i_k = \frac{-\hat{u}}{\sqrt{(R^2 + X^2)}} [\sin(\omega t + \psi - \varphi_k) - e^{\frac{t}{\tau_g}} \sin(\psi - \varphi_k)]. \quad (1.5)$$

The phase angle of the short circuit current (short circuit angle) is then, in accordance with the above equation,

$$\varphi_k = \psi - \nu = \arctan \frac{X}{R}. \quad (1.6)$$

For the far-from-generator short circuit, the short circuit current is therefore made up of a constant AC periodic component and the decaying DC aperiodic component. From the simplified calculations, we can now reach the following conclusions:

- The short circuit current always has a decaying DC aperiodic component in addition to the stationary AC periodic component.
- The magnitude of the short circuit current depends on the operating angle of the current. It reaches a maximum at $\gamma = 90^\circ$ (purely inductive load). This case serves as the basis for further calculations.
- The short circuit current is always inductive.

1.3

Classification of short circuit types

For a three-pole short circuit, three voltages at the position of the short circuit are zero. The conductors are loaded symmetrically. It is therefore sufficient to calculate only in the positive-sequence system. The two-pole short circuit current is less than that of the three-pole short circuit, but larger close to synchronous machines. The single-pole short circuit current occurs most frequently in low voltage networks with solid grounding. The double ground connection occurs in networks with a free neutral point or with a ground fault neutralizer grounded system.

For the calculation of short circuit currents, it is necessary to differentiate between the far-from-generator and the near-to-generator cases.

- Far-from-generator short circuit
When double the rated current is not exceeded in any machine, we speak of a far-from-generator short circuit.

$$I_k'' < 2 \cdot I_{rG} \quad (1.7)$$

or also when

$$I_k'' = I_a = I_k. \quad (1.8)$$

- Near-to-generator short circuit
When the value of the initial symmetrical short circuit current I''_k exceeds double the rated current in at least one synchronous or asynchronous machine at the time at which the short circuit occurs, we speak of a near-to-generator short circuit.

$$I''_k > 2 \cdot I_{rG} \quad (1.9)$$

or also when

$$I''_k > I_a > I_k. \quad (1.10)$$

Figure 1.3 schematically illustrates the most important types of short circuits in three-phase networks.

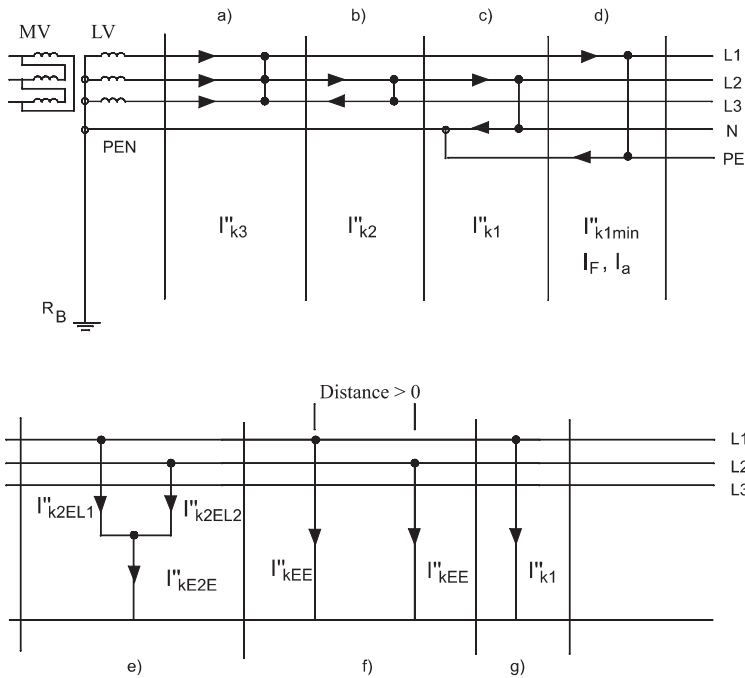


Fig. 1.3: Types of faults

a) three-pole short circuit, b) two-pole short circuit without contact to ground, c) single-pole short circuit between conductors L2-N,

d) single-pole short circuit between L1-PE, e) two-pole short circuit with contact to ground, f) double ground connection, g) single-pole short circuit to ground

1. Three-pole short circuits:
 - Connection of all conductors with or without simultaneous contact to ground
 - Symmetrical loading of the three external conductors
 - Calculation only according to single pole.
2. Two-pole short circuits:
 - Unsymmetrical loading
 - All voltages non-zero
 - Coupling between external conductors
 - For a near-to-generator short circuit $I''_{k2} > I''_{k3}$.
3. Single-pole short circuits:
 - Very frequent occurrence in low voltage networks.
4. Two-pole short circuits:
 - In networks with free neutral point or with ground fault neutralizer grounded system $I''_{kEE} < I''_{k2E}$
 - The leakage current flowing to ground is a capacitive ground fault current and is called I_C
 - With a ground fault neutralizer grounded system a residual ground fault current I_{Rest} occurs
 - I_C and I_{Rest} are special cases of I''_{k1} .

1.4

Methods of short circuit calculation

The short circuit currents in three-phase systems can be determined by three different calculational procedures:

1. Calculating with the equivalent voltage source $\frac{c \cdot U_n}{\sqrt{3}}$ at the fault location
2. Superposition method for a defined load flow case
3. Transient calculation.

1.4.1

Equivalent voltage source

The equivalent voltage source will be introduced here as the only effective voltage of the generators or network inputs for the calculation of short circuit currents. The internal voltages of generators or network inputs are short circuited, and at the position of the short circuit (fault position) the value (is used as the only effective voltage (Figure 1.4).

- The voltage factor c [5] considers (Table 1.1):
- The different voltage values, depending on time and position
- The step changes of the transformer switch

- That the loads and capacitances in the calculation of the equivalent voltage source can be neglected
- The subtransient behavior of generators and motors

This method assumes the following conditions:

- The passive loads and conductor capacitances can be neglected
- The step setting of the transformers do not have to be considered
- The excitation of the generators do not have to be considered
- The time and position dependence of the previous load (loading state) of the network does not have to be considered

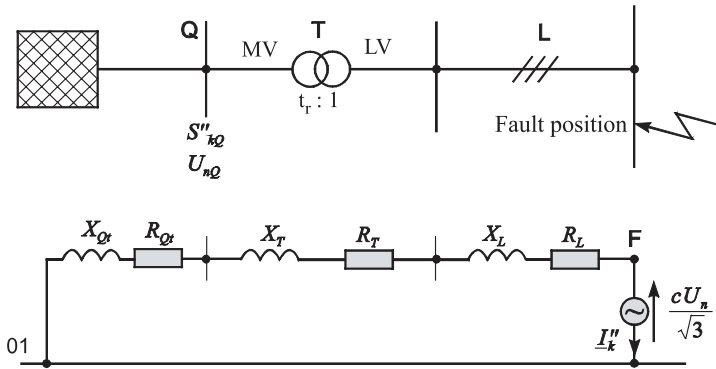


Fig. 1.4: Network circuit with equivalent voltage source
 a) three-phase network, b) equivalent circuit in positive-sequence system

Table 1.1: Voltage factor c according to E DIN IEC 73/89/CDV (VDE 0102, Part 100):1997-08

| Network voltage U_n | Voltage factor c for calculation of | |
|---|---|---|
| | the largest short circuit current ¹ c_{max} | the smallest short circuit current c_{min} |
| Low voltage 100 V to 1000 V (IEC 38, Table 1) | 1.05^2 | 0.95 |
| Medium voltage > 1 kV to 35 kV | 1.10^3 | 1.00 |
| High voltage > 35 kV | | |

1) $c_{max} \cdot U_n$ must not exceed the highest voltage U_m for operational equipment in the network

2) for low voltage networks with a tolerance of +6%

3) for low voltage networks with a tolerance of +10%

1.4.2

Superposition method

The superposition method is an exact method for the calculation of the short circuit currents. The method consists of three steps. The voltage ratios and the loading condition of the network must be known before the occurrence of the short circuit. In the first step the currents, voltages and the internal voltages for steady-state operation before onset of the short circuit are calculated (Figure 1.5b). The calculation considers the impedances, power supply feeders and node loads of the active elements. In the second step the voltage applied to the fault location before the occurrence of the short circuit and the current distribution at the fault location are determined with a negative sign (Figure 1.5c). This voltage source is the only voltage source in the network. The internal voltages are short-circuited. In the third step both conditions are superimposed. We then obtain zero voltage at the fault location. The superposition of the currents also leads to the value zero. The disadvantage of this method is that the steady-state condition must be specified. The data for the network (effective and reactive power, node voltages and the step settings of the transformers) are often difficult to determine. The question also arises, which operating state leads to the greatest short circuit current. Figure 1.5 illustrates the procedure for the superposition method.

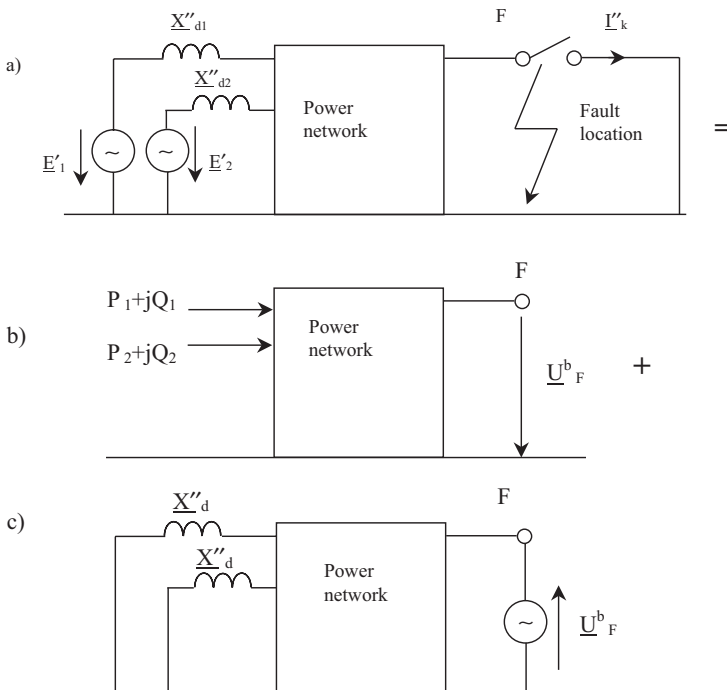


Fig. 1.5: Principle of the superposition method
a) undisturbed operation, b) operating voltage at the fault location, c) superposition of a) and b)

1.4.3

Transient calculation

With the transient method the individual operating equipment and, as a result, the entire network are represented by a system of differential equations. The calculation is very tedious. The method with the equivalent voltage source is a simplification relative to the other methods. Since 1988, it has been standardized internationally in IEC 60 909. The calculation is independent of a current operational state. In this book, we will therefore deal with and discuss the method with the equivalent voltage source.

1.5

Calculating with reference variables

There are several methods for performing short circuit calculations with absolute and reference impedance values. A few are summarized here and examples are calculated for comparison. To define the relative values, there are two possible reference variables.

For the characterization of electrotechnical relationships we require the four parameters:

- Voltage U in V
- Current I in A
- Impedance Z in Ω
- Apparent power S in VA.

Three methods can be used to calculate the short circuit current:

1. The Ohm system: Units: kV , kA , V , MVA
2. The pu system:
This method is used predominantly for electrical machines; all four parameters u , i , z and s are given as per unit (unit = 1). The reference value is 100 MVA. The two reference variables for this system are U_B and S_B .
Example: The reactances of a synchronous machine X_d , X'_d , X''_d are given in pu or in % pu , multiplied by 100 %.
3. The %/MVA system:
This system is especially well suited for the fast determination of short circuit impedances. As formal unit only the % symbol is added.

2

General Information About IEC 60 909

IEC 60 909 includes a standard procedure for the calculation of short circuit currents in low and high voltage networks up to 380 kV at 50 Hz or 60 Hz [1]. The purpose of this procedure is to define a brief, general and easy to handle calculation procedure, which is intended to lead with sufficient accuracy to results on the safe side. For this purpose, we calculate with an equivalent voltage source at the position of the short circuit. It is also possible to use the superposition method here.

A complete calculation of the time behavior for far-from-generator and near-to-generator short circuits is not required here. In most cases, it is sufficient to calculate the three-pole and the single-pole short circuit currents, assuming that for the duration of the short circuit no change takes place in the type of short circuit, the step switch of the variable-ratio transformers is set to the principal tapping and arc resistances can be neglected.

The short circuit currents and short circuit impedances can always be determined by the following methods:

- Calculation by hand
- Calculation using a PC
- Using field tests
- Measurements on network models.

The short circuit currents and short circuit impedances can be measured in low voltage networks with measuring instruments directly at the assumed position of the short circuit.

For the dimensioning and the choice of operational equipment and overcurrent protective equipment, the calculation of short circuit currents in three-phase networks is of great importance, since the electrical systems must be designed not only for the normal operating state but also to withstand fault situations.

IEC 60 909 describes the basis for calculation, which consists of three parts:

1. Main part I: Networks with short circuit currents without decaying AC periodic component (far-from-generator short circuits).
2. Main part II: Networks with short circuit currents with decaying AC periodic component (near-to-generator short circuits).

3. Main part III: Double ground connection, Transferred short circuit currents via ground.

Summary of IEC 60 909

- Restructuring of calculations.
- The supplementary pages with examples and conversion factors supplement the theoretical part.
- The high and low voltage networks are treated in the same way.
- The rules for calculating the smallest and largest short circuits are equally valid for high and low voltage networks.
- The corrections to the impedances of generators and power plant blocks do not depend on the time behavior of the short circuit current.
- In low voltage networks a temperature rise of 20 °C to 80 °C is assumed for the single-pole short circuit. This increases the resistance of the cable or conductor by a factor of 1.24.
- The indices for symmetrical components (0,1,2) are internationally standardized.
- The short circuit currents are determined with the equivalent voltage source method, in accordance with IEC 60 909. For this, the internal voltages in the network are short circuited. The only effective voltage at the position of the short circuit is then $\frac{c \cdot U_n}{\sqrt{3}}$, where c is the voltage factor.
- The superposition method is the more accurate method. However, this requires knowing the network conditions before the occurrence of the short circuit.

The draft standard IEC 73/89/CDV:1997-08 is structured as follows:

- Main part 1: describes the scope of application and the terms used.
- Main part 2: explains the properties of short circuit currents and the conditions which must be satisfied for calculation with the equivalent voltage source method.
- Main part 3: deals with the short circuit impedances of generators, power transformers and power plant blocks.
- Main part 4: describes the calculation of the individual short circuit currents for far-from-generator and near-to-generator short circuits.

3

The Significance of IEC 60 909

The short circuit is an undesired network operating state. This state can cause overloading of the operational equipment (transformers, transmission lines, cables, generators) as well as damage to the insulation. The transition from normal operation to operation under fault conditions takes place through electromagnetic and electromechanical transient phenomena, which influence the magnitude and temporal behavior of the short circuit currents. These processes depend on the current sources, the position of the short circuit, the time from the onset of the short circuit until it decays, etc.

The most common type of short circuit is the “dead” short circuit, i.e. the impedance at the faulty location is negligibly small. Short circuit currents are as a rule much larger than load currents. The thermal and dynamic stresses resulting from these short circuits can destroy the operational equipment and endanger persons. During the planning and project management of electrical systems, the smallest short circuit current I''_{k1min} must therefore be determined and taken into account for configuring the overcurrent protection equipment, and the largest short circuit current I''_{k3max} for dimensioning the operational equipment. Only in this way can electrical systems be correctly dimensioned and protected, allowing their safe and economic operation. Otherwise, unpleasant consequences can be expected. A few of these are listed here:

- impairment of safety and reliability of the power supply,
- interruption of the power supply,
- destruction of system components,
- emergence of mechanical and thermal stresses in the operational electrical equipment,
- emergence of overvoltages.

Until 1962, VDE 0670 switchgear regulations were the standard for short circuit calculations. VDE 0102 was released in 1971 and revised in 1975, so that in Germany the calculations for low and high voltage networks were made uniform. In the meantime, further developments in electrical power systems have taken place and various software has appeared on the market. In order to meet the requirements and developments, in 1985 both parts, Calculation of Three-phase Networks in accordance with DIN VDE 0102, were extended to include the newly summarized information about operational equipment.

In 1988, on the basis of this draft version the IEC publication “Short Circuit Current Calculation in three-Phase ac Systems” appeared. In 1990, the present standard IEC 60 909 “Calculation of Short Circuit Currents in Three-phase Networks” was released.

The method of symmetrical components is used for symmetrical and asymmetrical short circuits. The capacitances of conductors and shunt admittances of passive loads are neglected here. With this method, motors are treated as generators in high voltage networks and are neglected in low voltage networks. For a double ground connection, only the voltage of the short circuit current source is used as the effective voltage.

For the assessment of electrical systems, such as breaking conditions, protective measures, thermal and mechanical short circuit strengths, selectivity and voltage drop, etc. comprehensive calculations are performed.

For the calculation of short circuits, the following are important:

- power draw and documentation of result,
- short circuit currents,
- transferred short circuit currents,
- impedance protection, maximum current-dependent and current-independent time relays,
- examination of breaking conditions,
- proof of stability of switchgear, switching devices, cables and conductors against short circuits.

Figure 3.1 makes clear the importance and the range of applicability of short circuit current calculations and additional calculations relating to other regulations.

In medium voltage networks, the type of the smallest fault current which must be considered depends on the type of neutral point design. This is decisive for the type of network protection required.

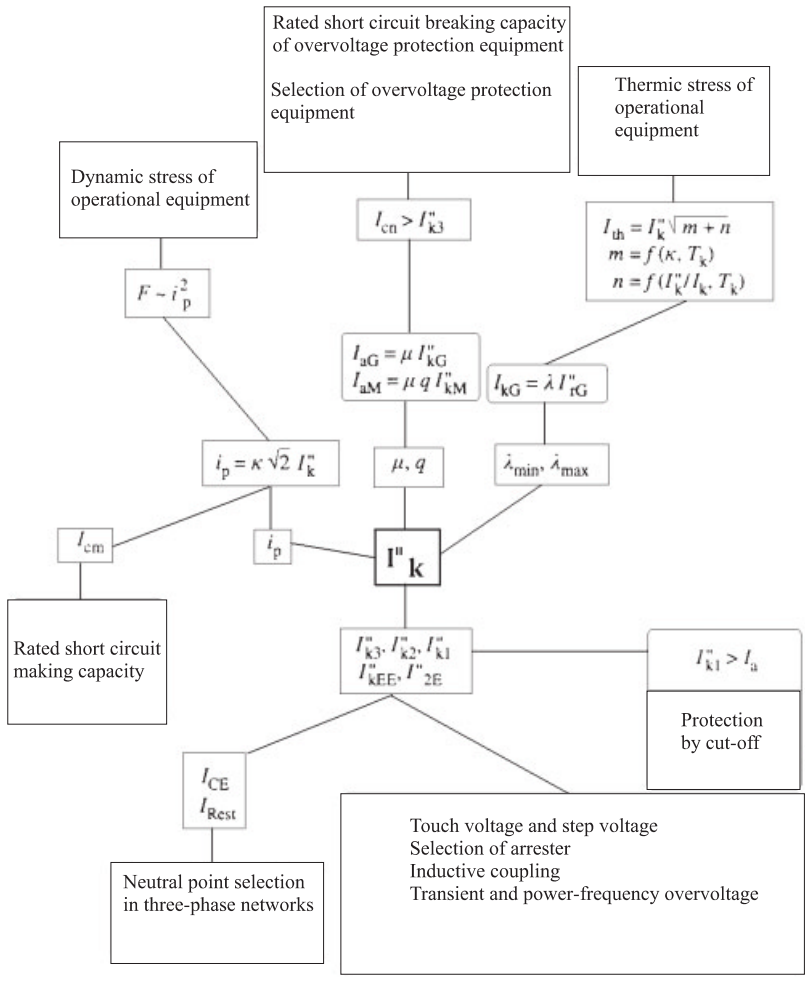


Fig. 3.1: Range of applicability of short circuit calculations [1, 16, 17, 35]

4 Supply Networks

Electrical supply networks such as can be found in practice will be briefly explained here.

4.1 Calculation variables for supply networks

- Short circuit currents in accordance with IEC 60 909
- Ground loop impedance
- Peak short circuit current
- Initial symmetrical short circuit power
- Load flow
- Load distribution for the network

4.2 Lines supplied from a single source

A feed-in supplies any number of distributed loads along the line (Example: bus distributor), Figure 4.1.

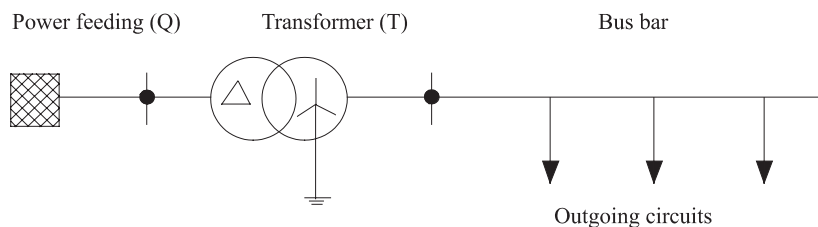


Fig. 4.1: Line supplied from a single source

Characteristics of this input:

- No security of supply
- High network losses

4.3

Radial networks

A feed-in supplies a large number of branched lines (Example: industrial network), Figure 4.2.

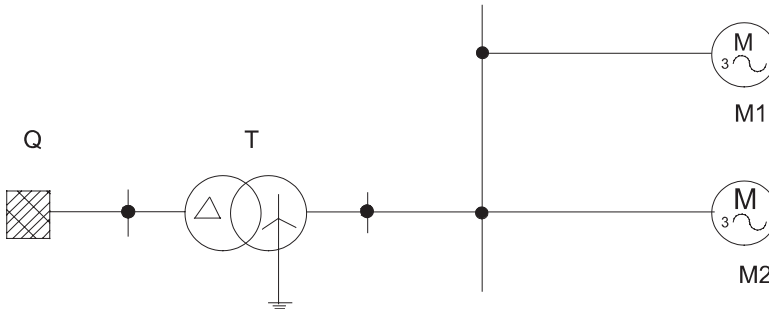


Fig. 4.2: Radial network

Characteristics of this input:

- Advantages
 1. Very clearly arranged
 2. Simple network protection
 3. Easily calculated
- Disadvantages
 1. Single source supply
 2. Low security of supply
 3. Poor voltage stabilization

4.4

Ring networks

The ring network is usually fed from two sources (Example: industrial network), Figure 4.3.

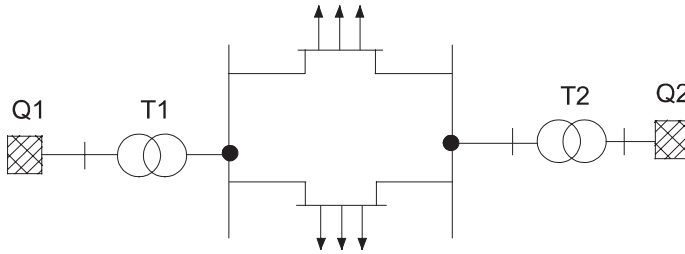


Fig. 4.3: Ring network

Characteristics of this input

- Advantages
 1. Increased voltage security
 2. Better load balancing
 3. Better voltage stability
- Disadvantages
 1. Network protection difficult

4.5

Meshed networks

The supply of each load is ensured by the linking of several supply lines and in part by several feed-ins. The failure of one line or one feed-in can normally be compensated by the remaining part of the network (Example: computer centers, chemical industry), Figure 4.4.

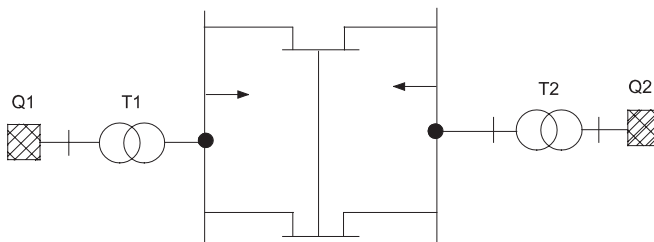


Fig. 4.4: Meshed network

Characteristics of this input:

- Advantages
 1. High security of supply
 2. Good voltage stability

3. Good load balancing
 4. Low network losses
- Disadvantages
 1. Selectivity
 2. Impedance protection
 3. High short circuit currents
 4. Extensive short circuit and load flow calculations

5 Network Types for the Calculation of Short Circuit Currents

5.1 Low voltage network types

In this section other types of networks are shown which are sometimes encountered in practice and in which the short circuit currents are fed from different sources. The most frequently found network types in the public and the industrial sectors are radial networks. For these networks the calculation of short circuit currents is very simple. The medium and low voltage side can be configured arbitrarily, according to the requirements for supplying power (Figure 5.1).

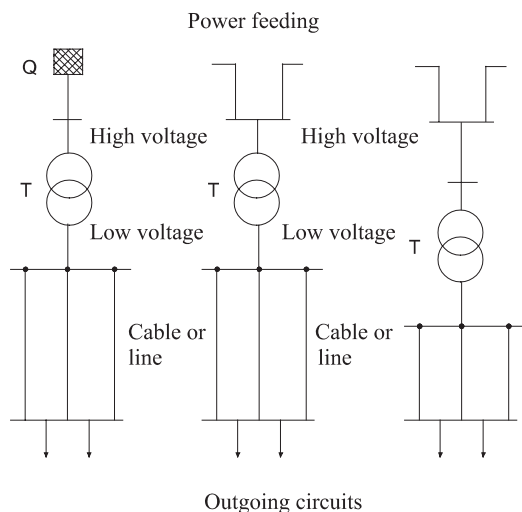


Fig. 5.1: Simple radial networks with different centers of load distribution

In industrial networks, power supply to the systems must not fail. In the event of a malfunction, switchover can take place from another transformer (Figure 5.2).

Radial networks with redundant inputs have a higher security of supply and a high voltage quality (Figure 5.3). The transformers can be loaded uniformly.

The meshed network with different inputs is the most widely used network type for electrical distribution in industry (Figure 5.4). The disadvantages of such networks are high costs of investment and an arrangement which is difficult to oversee.

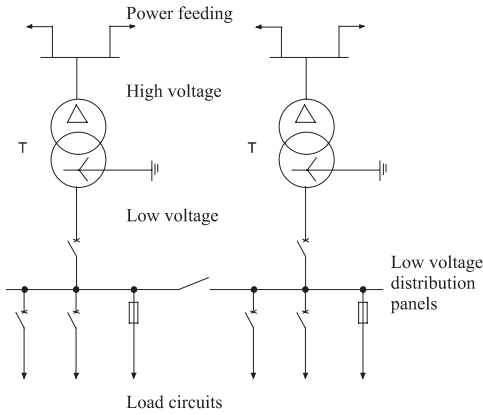


Fig. 5.2: Simple radial networks with individual load circuits

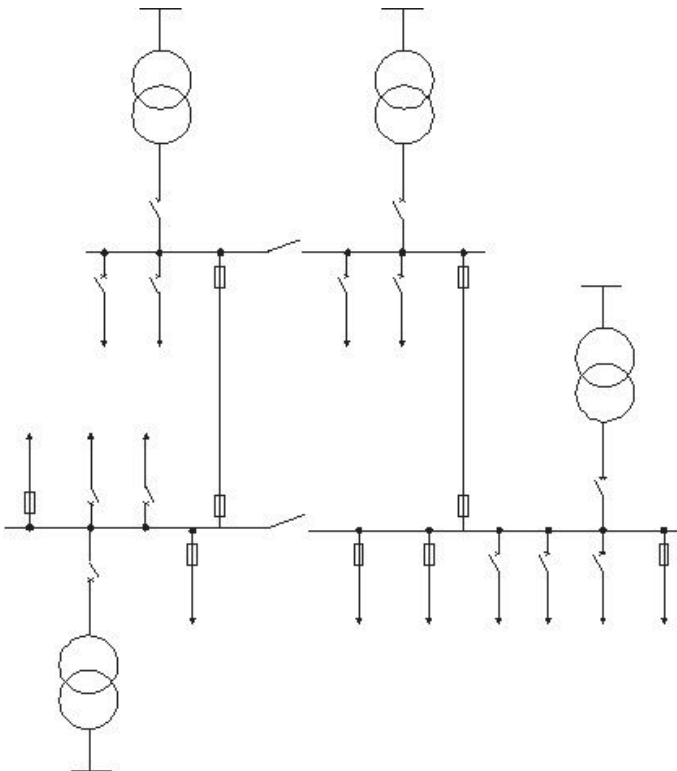


Fig. 5.3: Simple radial networks with redundant inputs

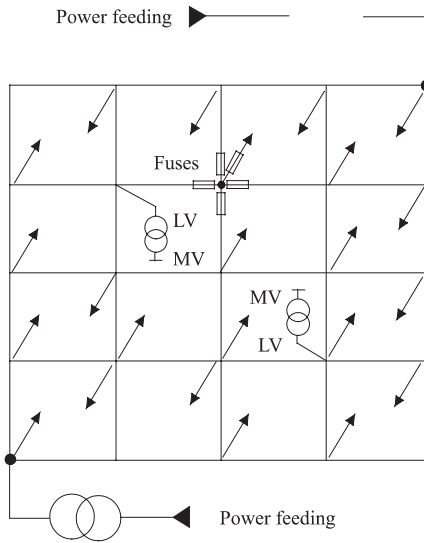


Fig. 5.4: Meshed network with different inputs, network nodes with fuses

5.2

Medium voltage network types

For optimum design of medium voltage systems the following points, which are not explained in further detail, are of great importance:

- Network losses
- Complexity of maintenance
- Investment costs
- Power requirement coverage
- Security of supply
- Ease of operation
- Environmental compatibility.

Figure 5.5 illustrates an industrial load center network which supplies individual large scale loads and Figure 5.6 a ring network, in which the supply of power is ensured.

The following Figures 5.5 to 5.8 depict medium voltage network types with different possible structures. The network with open rings (Figure 5.5a) is connected through circuit breakers to the bus bar. The ring can be opened and closed by the load switch disconnecter. The network with remote station (Figure 5.5b and 5.5c) with network supporting structure is connected through several input cables to the bus bar of the transformer substation. An industrial area can also be supplied from several transformer stations (Figure 5.8). The short circuit current can also be fed from different sources, as Figures 5.9 and 5.10 show.

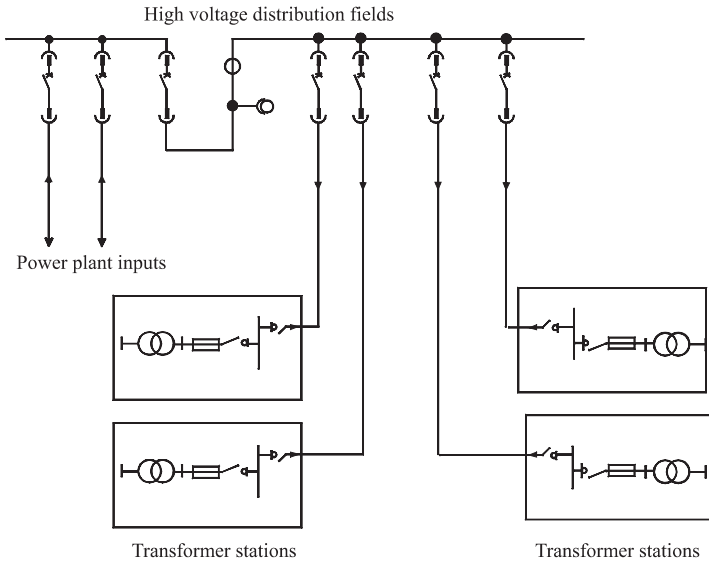


Fig. 5.5: Industrial load center network

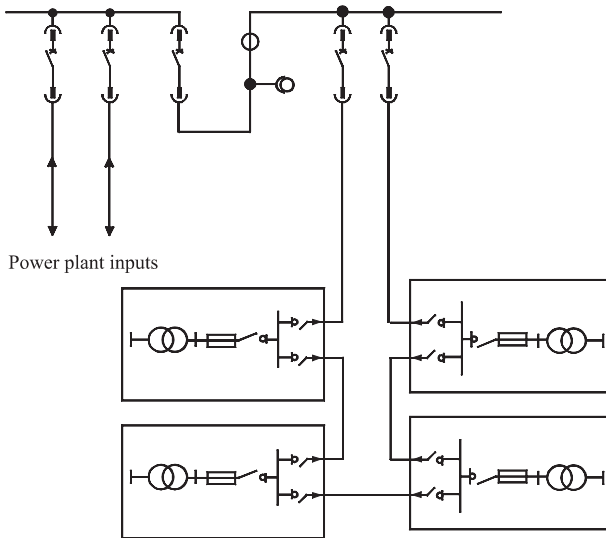


Fig. 5.6: Industrial ring network

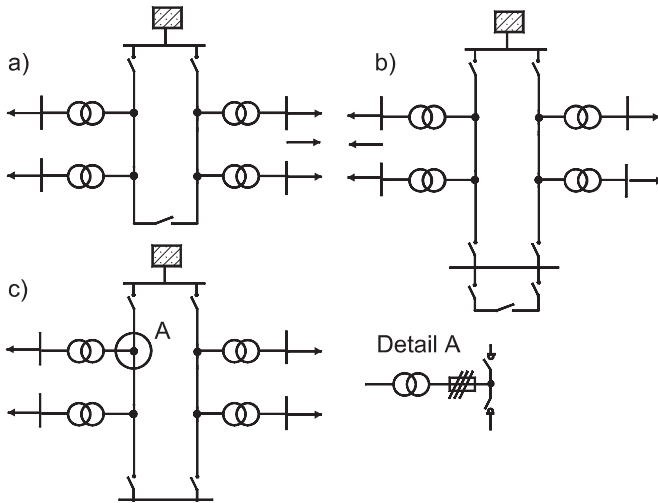


Fig. 5.7: a) ring network, b) network with remote station, c) network supporting structure

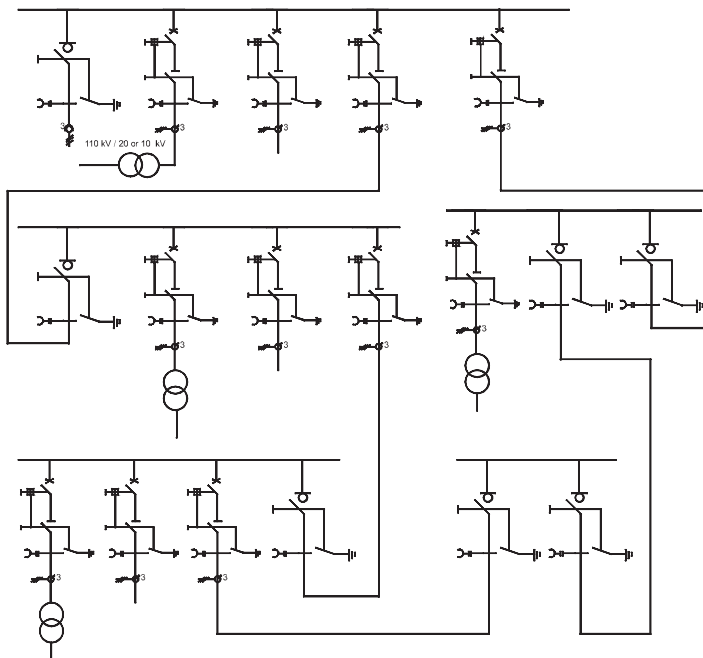


Fig. 5.8: Network configuration for medium voltage systems

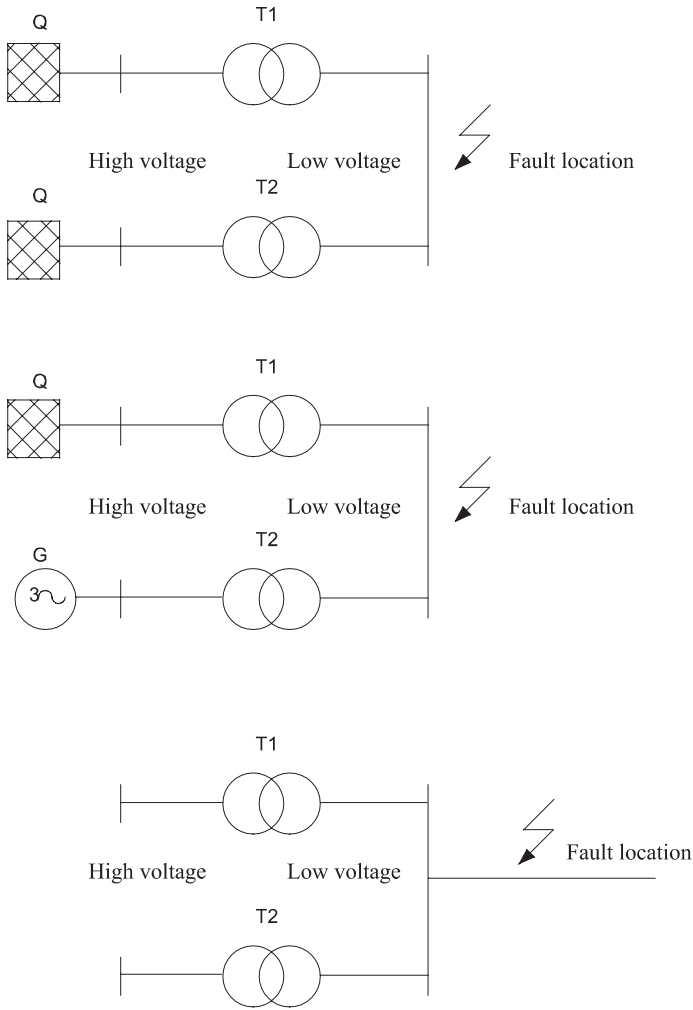


Fig. 5.9: Short circuit with simple inputs

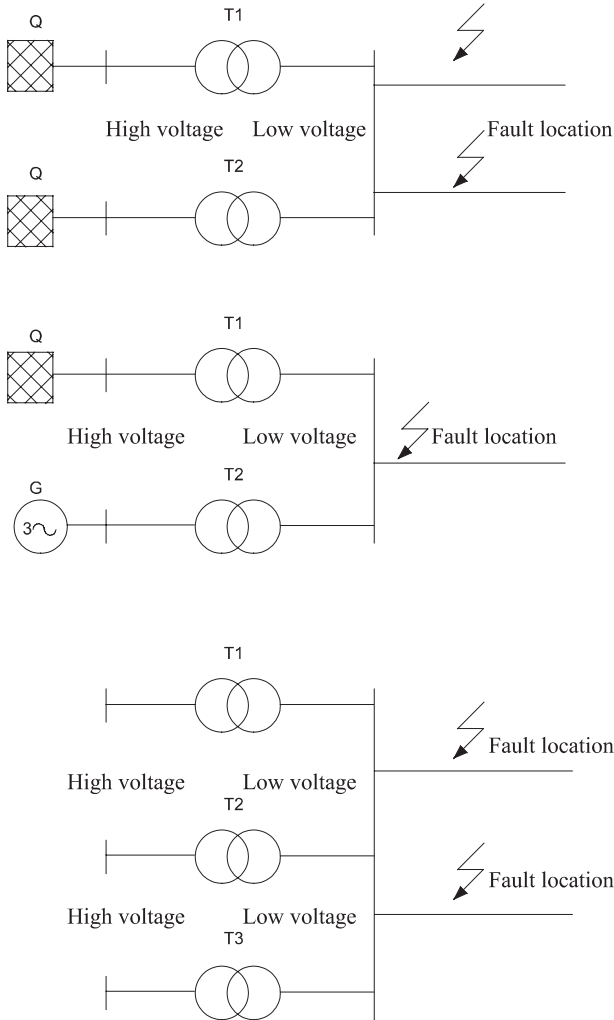


Fig. 5.10: Short circuit with several simple inputs

6 Systems up to 1 kV

Systems are classified according to the type of ground connection of the power source (input type) and the type of exposed conductive parts of the electrical system (IEC 60 364 part 41). In this chapter, the three different types of systems and protective measures are briefly described.

6.1 TN systems

According to IEC 364 the TN system is preferred in the area of public low voltage networks and also in the industrial sector. In TN systems, the grounding of the operational equipment is implemented by connection to the PEN conductor or for small cross-sections to the protective ground conductor (PE) (Figure 6.1).

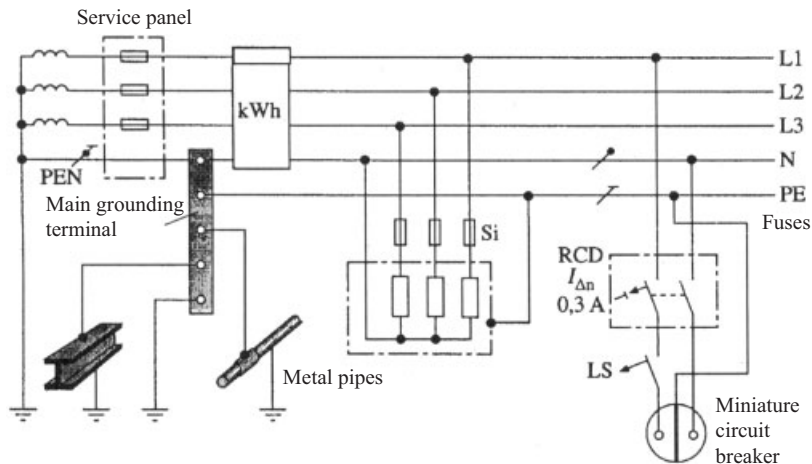


Fig. 6.1: Circuitry of the TN-C-S system, LS = Circuit breaker

Description of the system:

1st letter: describes the grounding conditions of the power source

T: direct grounding of a point

2nd letter: describes the grounding conditions of the exposed conductive parts of the electrical system

N: direct connection of exposed conductive parts through PEN or PE to system grounding, continuing in TN system

S: neutral conductor (N) and protective ground conductor (PE), as separate and separated conductors

C: neutral conductor and protective ground conductor combined in a single conductor (PEN)

Permissible overcurrent protective equipment:

- Fuses
- Line-protection circuit breakers
- Circuit breakers
- RCDs (Residual Current Protective Devices)

The following conditions must be satisfied for the ground loop impedance:

$$Z_s \leq \frac{U_0}{I_a} \quad (6.1)$$

where:

Z_s is the ground loop impedance

U_0 is the conductor-to-ground voltage and

I_a is the breaking current of the overcurrent protective equipment

The ground loop impedance (loop resistance) of the TN system is required in order to calculate the minimum required fault current at the position of the short circuit (Figure 6.2).

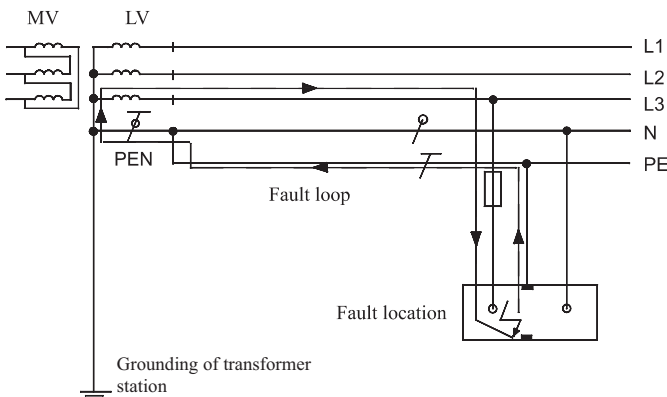


Fig. 6.2: Ground loop impedance

6.2

Calculation of fault currents

This section presents and explains simple fundamental considerations for the calculation of the fault current.

In TN systems, the fault current is calculated in order to ensure protection in case of indirect contact and to guarantee that the protective equipment switches off within the specified time. Figure 6.3 gives an overview of the calculations carried out here.

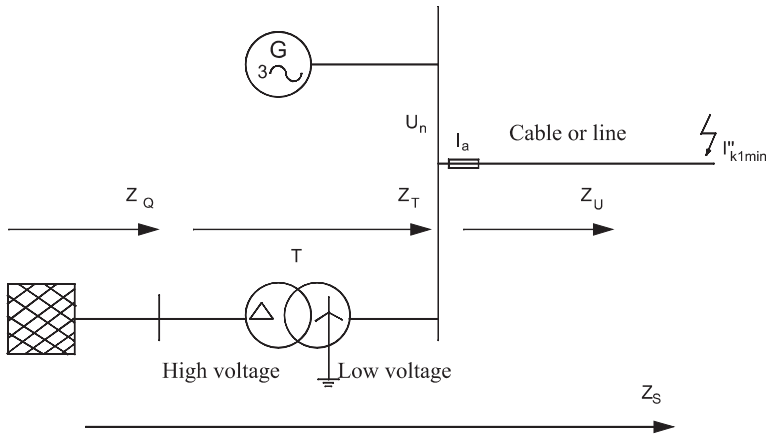


Fig. 6.3: Overview of the power supply

The impedance upstream from the power source is given by:

$$Z_Q = \sqrt{R_Q^2 + X_Q^2} \quad (6.2)$$

and with the short circuit power of the high voltage network:

$$Z_Q = \frac{cU_n^2}{S''_{kQ}} \quad (6.3)$$

If exact data are not available for the reactance and resistance, we can then use the following values [11]:

$$R_Q = 0.100 \cdot X_Q \quad (6.4)$$

$$X_Q = 0.995 \cdot Z_Q \quad (6.5)$$

Impedance of the transformer:

$$Z_T = \frac{(U_n)^2}{S_{rT}} \cdot \frac{u_{kr} \%}{100} \quad (6.6)$$

If exact data are not available for the reactance and resistance, we can then use the following values [11]:

$$R_T = 0.31 \cdot Z_T \quad (6.7)$$

$$X_T = 0.95 \cdot Z_T \quad (6.8)$$

$$Z_T = \sqrt{R_T^2 + X_T^2} \quad (6.9)$$

Impedance of the power source:

$$Z_S = Z_Q + Z_T \quad (6.10)$$

System power supplied from generators:

Transient reactance of generator:

$$X'_d = \frac{U_n^2}{S_{rG}} \cdot \frac{x'_d}{100} \quad (6.11)$$

Zero-sequence reactance

$$X_0 = \frac{U_n^2}{S_{rG}} \cdot \frac{x_0}{100} \quad (6.12)$$

If exact data are not available for the reactance and resistance, we can then use the following values [11]:

$$X'_d = 30\% \cdot x'_d \quad (6.13)$$

$$X'_d = 6\% \cdot x_0 \quad (6.14)$$

Calculation of the fault current I''_{k1min} (external conductor – protective ground conductor):

In accordance with IEC 60 364, protection for indirect contact is ensured if the following equation is satisfied:

$$I''_{k1min} = \frac{\sqrt{3} \cdot c_{min} \cdot U_n}{3 \cdot \sqrt{(2 \cdot l \cdot l' + R_v)^2 + (2 \cdot l \cdot X'_L + X_v)^2}} \quad (6.15)$$

For cables and conductors with reduced PEN or protective ground conductor cross-sections, equation 6.15 can be used provided that we substitute

$$R'_L = \frac{R'_{L1} + R'_{L2}}{2} \quad (6.16).$$

This protective measure requires coordinating the type of ground connection and the characteristics of the protective ground conductors and protective equipment. An immediate and automatic cut-off of the faulty circuit is ensured when the following condition is met:

$$I''_{k1min} \geq I_a \quad (6.17)$$

Calculation of the resistance at a temperature of 80 °C in accordance with IEC 60 909 for a minimum single-pole short circuit current:

$$R_{L80^\circ} = R_{L20^\circ} \cdot [1 + 0.004 \frac{1}{^\circ\text{C}} (\theta_e - 20^\circ\text{C})] \quad (6.18)$$

The meanings of the symbols are:

| | |
|---------------|--|
| c | Voltage factor |
| S''_{kQ} | Short circuit power of the high voltage network |
| X_Q | Reactance upstream from power source |
| X_T | Reactance of power source |
| Z_Q | Impedance upstream from power source |
| R_Q | Resistance upstream from power source |
| R_T | Resistance of power source |
| Z_T | Impedance of power source |
| I''_{k1min} | Smallest single-pole short circuit current |
| I_a | Breaking current of overcurrent protective equipment |
| l | Length of conductor (half the loop length) |
| R'_L | Resistance per unit length of cable or conductor |
| X'_L | Reactance per unit length of cable or conductor |
| R_v | Ground loop resistance of main network |
| X_v | Ground loop reactance of main network |
| R'_{L1} | Resistance per unit length of external conductor |
| R'_{L2} | Resistance per unit length of PEN or protective ground conductor |
| Z_S | Sum of impedances of network feed-ins and power source |

6.3 TT systems

In TT systems the neutral conductor does not serve a protective ground conductor function. The connection of the operational equipment take place through the protective ground conductor to a common grounding system (Figure 6.4). TT systems are of no importance in the industrial sector.

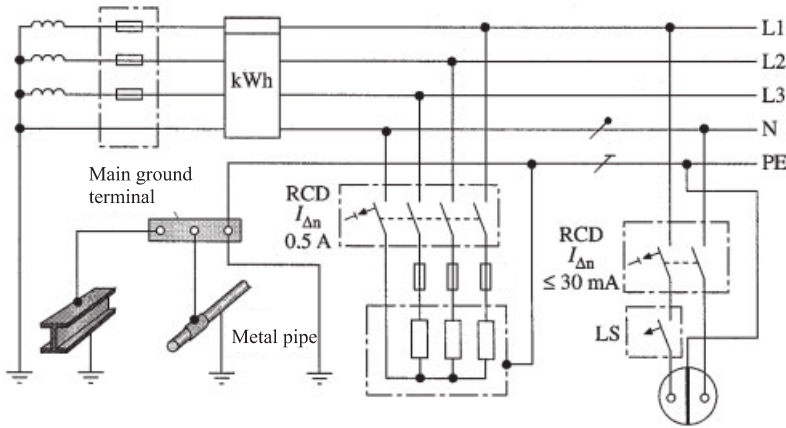


Fig. 6.4: Circuitry of the TT system

Description of system:

1st letter: describes the grounding conditions of the power source

T: direct grounding of a point

2nd letter: describes the grounding conditions of the exposed conductive parts of the electrical system

T: exposed conductive parts, grounded directly and independently of power source

1. Permissible overcurrent protective equipment:

- RCDs (Residual Current Protective Devices)
- Line-protection circuit breakers, e.g. with A, B, C and D characteristic
- Circuit breakers
- Fuses

The following condition must be satisfied for the ground resistance of the exposed conductive parts:

$$R_A \leq \frac{U_L}{I_{\Delta n}}, \quad (6.19)$$

$$R_A \leq \frac{U_L}{I_{\Delta n}}, \quad (6.20)$$

where:

R_A is the sum of the resistances of the ground electrode and the protective ground conductor

U_L is the touch voltage and

$I_{\Delta n}$ is the rated differential current of the RCD

6.4 IT systems

The power source for IT systems is isolated. Its application is primarily in the industrial sector and in the operation rooms of hospitals (Figure 6.5).

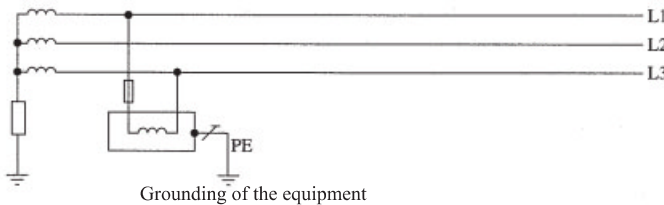


Fig. 6.5: Circuitry of the IT system

Description of system:

1st letter: describes the grounding conditions of the power source

I: isolation of active parts from ground or connection of active parts to ground through an impedance (indirect grounding)

2nd letter: describes the grounding conditions of the exposed conductive parts of the electrical system

T: exposed conductive parts, grounded directly and independently of power source

The protection for indirect contact is implemented by messages generated in the isolation monitoring, with equipotential bonding or cut-off in addition in the case of a double fault.

- Permissible overcurrent protective equipment:
- Insulation monitoring
- RCDs (Residual Current Protective Devices)
- Line-protection circuit breakers
- Circuit breakers
- Fuses.

The ground resistance of the exposed conductive parts must be sufficiently low to allow the following condition to be satisfied:

$$R_E \leq \frac{U_L}{I_d}. \quad (6.21)$$

where:

R_E is the grounding resistance

U_L is the touch voltage and

I_d is the leakage current

6.5

Transformation of the network types described to equivalent circuit diagrams

There are many possible arrangements of networks. In order to calculate the total impedance at the position of the short circuit, the network topologies in multiple and meshed networks are simplified and transformed in a star-delta or delta-star transformation (Figure 6.6).

With this approach, the network is reduced to a network with simple inputs. The entire short circuit path is represented by resistances and reactances and the impedance at the position of the short circuit calculated from these. The following relationships then apply:

The impedance is generally:

$$\underline{Z} = R + j \cdot X. \quad (6.22)$$

The magnitude of the impedance is:

$$Z = \sqrt{R^2 + X^2}. \quad (6.23)$$

Series circuit (Figure 6.6a):

$$\underline{Z}_G = \underline{Z}_1 + \underline{Z}_2. \quad (6.24)$$

Parallel circuit (Figure 6.6b):

$$\underline{Z}_G = \frac{\underline{Z}_1 \cdot \underline{Z}_2}{\underline{Z}_1 + \underline{Z}_2}. \quad (6.25)$$

Delta-star transformation (Figure 6.6c):

$$\underline{Z}_1 = \frac{\underline{Z}_a \cdot \underline{Z}_c}{\underline{Z}_a + \underline{Z}_b + \underline{Z}_c}, \quad (6.26)$$

$$Z_2 = \frac{Z_a \cdot Z_b}{Z_a + Z_b + Z_c},$$

$$Z_3 = \frac{Z_b \cdot Z_c}{Z_a + Z_b + Z_c}.$$

Star-delta transformation (Figure 6.6d):

$$Z_a = \frac{Z_1 \cdot Z_2 + Z_1 \cdot Z_3 + Z_2 \cdot Z_3}{Z_3}, \tag{6.27}$$

$$Z_b = \frac{Z_1 \cdot Z_2 + Z_1 \cdot Z_3 + Z_2 \cdot Z_3}{Z_1},$$

$$Z_c = \frac{Z_1 \cdot Z_2 + Z_1 \cdot Z_3 + Z_2 \cdot Z_3}{Z_2}.$$

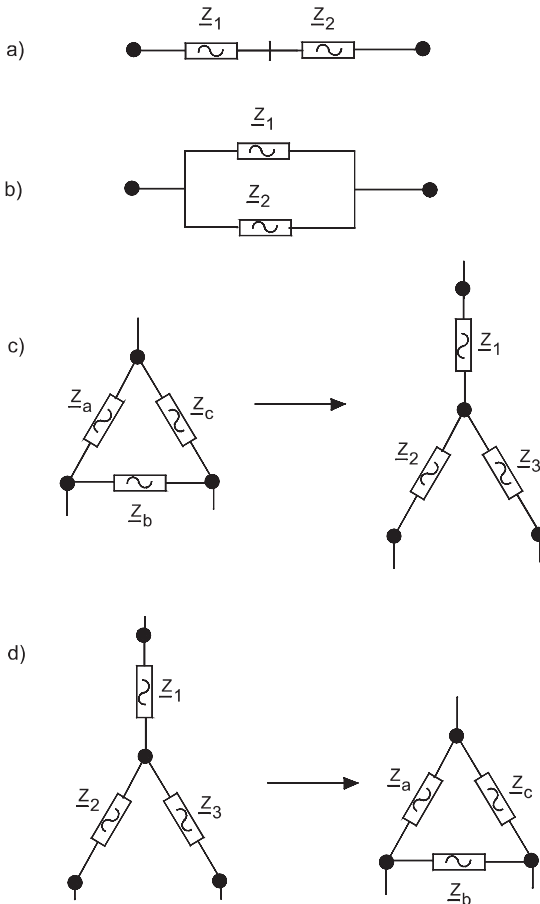


Fig. 6.6: Network transformations

7

Neutral Point Treatment in Three-phase Networks

The main faults are the single-pole short circuit and the short circuit to ground. The short circuit to ground is a conductive connection between a point in the network belonging to the operational circuit and ground. Between 80 and 90 % of all faults in grounded networks are short circuits to ground. If the short circuit currents are identical in all three conductors with a three-pole short circuit, the fault is then symmetrical. In all other cases, the fault currents in the three conductors are different and these faults are then asymmetrical. In addition, in three-phase networks various so-called transverse faults are possible. Along with these transverse faults, line interruptions can also occur. This results in longitudinal faults, which are however of no importance for short circuit current calculations. For ground faults and short circuits to ground, the magnitude of the short circuit current depends primarily on how the neutral point of the network is connected to ground. The short circuit currents are determined by the voltage sources present in the network (generators and motors) and by the network impedances. The requirement of an optimum and inexpensive network can lead to different neutral point treatments. The expense for grounding systems, network protection, network design, operating mode and size of the network is the determining factor in the choice of neutral point treatment. The neutral point treatment also affects the following parameters:

- Touch, step and grounding electrode voltages
- Single-pole short circuit currents
- Voltage stress

For the construction and operation of electrical systems, a knowledge of the grounding measures is indispensable. The most important measure is protection in the event of indirect touching. That is, the safety of human beings and of objects must be ensured. For this, the calculation of the ground potential rise is important. This value characterizes the maximum touch voltage. Thus, in terms of danger to human beings the touch voltage at which a fault current can flow through the body and the heart is especially critical. The touch voltage is part of the ground potential rise in the event of a fault which can be picked up by human beings. The highest touch voltage which may remain without any limit in time in low voltage systems is 50 V for AC voltages and 120 V for DC voltages. As stated in HD 637 S1, the highest touch voltage for times greater than 5 seconds in high voltage systems is 75 V. The

magnitude of the permissible touch voltage depends on the duration of the fault and is given in Table C.3 of HD 637 S1. If the ground potential rise remains below 150 V, the condition is satisfied and no further measures are required. Otherwise, additional measures must be undertaken. For a fault with contact to ground, the type of neutral point grounding determines the magnitude of the line-to-ground voltage and the magnitude of the currents flowing to ground. This section will briefly discuss the principles of grounding systems and then deal with the different methods of neutral point grounding in high voltage networks.

The project planner has to determine and observe the following parameters for the dimensioning of grounding systems:

1. Magnitude of the fault current (this parameter depends on the neutral point grounding of the high voltage network. See Table 7.1).
2. Duration of the fault (this parameter depends on the neutral point grounding of the high voltage network).
3. Characteristics of ground (measurement of the ground resistivity).
4. Ground resistance.
5. Correct choice and dimensioning of materials.

The design of grounding systems must satisfy four requirements:

1. The mechanical strength and resistance to corrosion of the grounding electrode and protective conductor, as well as their connections, must be ensured. These determine the minimum dimensions for the grounding electrodes.
2. The greatest fault current must be calculated and held under control from the thermal point of view.
3. Damage to objects and operational equipment (especially information technology) must be avoided.
4. The safety of persons with respect to voltages on grounding systems (touch voltages, parasitic voltages) which occur at the time of the greatest ground fault current must be ensured.

The ground potential rises and touch voltages of a grounding system can be calculated from known data. The fault current frequently divides in the system. For the calculation of the grounding system parameters, it is necessary to consider all grounding electrodes and other grounding systems. In accordance with HD 637 S1, for step voltages it is not necessary to define permissible values. When a system satisfies the requirements with regard to the touch voltages, then no dangerous step voltages can occur.

Table 7.1: Decisive currents for the dimensioning of grounding systems metal shielding of grounding cables are involved in leading away fault currents which flow to ground. They

| Type of high voltage network | | Decisive for thermal loading | | Decisive for ground potential rise and touch voltage |
|--|---|---|----------------------|---|
| | | Ground electrodes | Ground conductor | |
| Networks with isolated neutral point | | – | I''_{kEE} | $I_E = r \cdot I_C$ |
| Networks with ground-fault-neutralizer-grounded system | In systems with ground-fault-neutralizer-grounded system | – | I''_{kEE} | $I_E = r \cdot \sqrt{I_L^2 + I_{Res}^2}$ |
| | In systems without ground-fault-neutralizer-grounded system | | | $I_E = r \cdot I_{Res}$ |
| Networks with low resistance neutral point grounding | | I''_{k1} | I''_{k1} | I_E |
| Networks with ground-fault-neutralizer-grounded and temporary low resistance neutral point grounding | In systems in which temporary grounding takes place | I''_{k1} | I''_{k1} | I_E |
| | In all other systems | With ground fault coil Without ground fault coil | – I''_{kEE} | $I_E = r \cdot \sqrt{I_L^2 + I_{Res}^2}$ $I_E = r \cdot I_{Res}$ |

I_C Calculated or measured capacitive ground fault current.

I_{Res} Residual ground fault current. When the exact value is not known, you can assume 10 % of I_C .

I_L Sum of the rated currents of parallel ground fault coils for the system under discussion.

I''_{k1} Initial symmetrical short circuit current for a single-pole ground fault, calculated in accordance with IEC 60909.

I''_{kEE} Double-line-to-ground fault, calculated in accordance with IEC 60909 or HD533 (for I''_{kEE} 85 % of the three-pole initial symmetrical short circuit current can be used as the greatest value).

I_E Grounding current.

r Reduction factor.

assume a part of the ground fault current from the particular circuit. This effect gives rise to the effective relieving of a high voltage grounding system affected by a ground fault. The extent of this relief is described by the reduction factor.

The reduction factor r for an overhead ground wire in a three-phase current conductor is:

$$r = \frac{I_E}{3 I_0} = \frac{3 I_0 - I_{FW}}{3 I_0}$$

The ground potential rise is

$$\underline{U}_E = \underline{Z}_E \cdot \underline{I}_E$$

In the event of a fault, the ground potential rise is

$$\underline{I}_E = r \cdot \sum 3 \cdot \underline{I}_0$$

The meanings of the symbols are:

\underline{I}_{EW} : Current in the overhead ground wire in A

\underline{U}_E : Ground potential rise in V

\underline{I}_E : Grounding current in A

$3\underline{I}_0$: Sum of the zero-sequence currents in A

\underline{Z}_E : Grounding impedance in Ω

We can differentiate between three types of neutral point treatment:

7.1

Networks with isolated free neutral point

The short circuit current to ground flows through the capacitances to ground C_E of the uninterrupted conductors (Figure 7.1). The short circuit currents to ground are small in this case and in small networks are usually self-quenching, although large transient overvoltages can occur. The potential of the neutral point relative to ground is determined by the capacitances C_E . The short circuit current to ground I_{CE} at the position of the short circuit is given by:

$$I_{CE} = 3 \cdot w \cdot C_E \frac{c \cdot U_n}{\sqrt{3}}. \quad (7.1)$$

The short circuit current to ground increases with the length of the conductor, so that the operation of this type of network is restricted to smaller networks (up to 30 kV). The limiting value of the short circuit current to ground is around 35 A, since otherwise the arcing is no longer self-quenching.

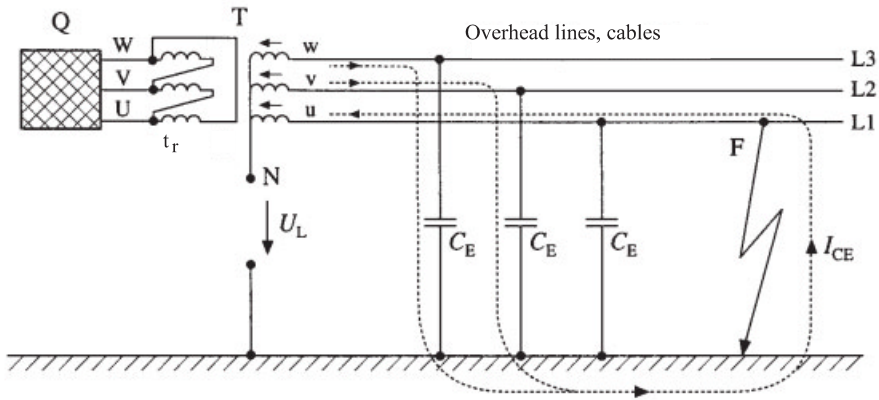


Fig. 7.1: Isolated network

7.2
Networks with grounding compensation

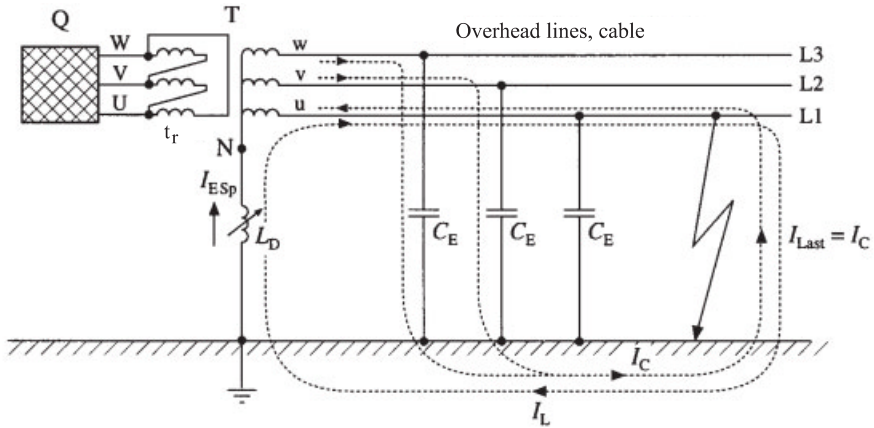


Fig. 7.2: Ground fault neutralizer grounded system

A network with grounding compensation is present when the neutral point is grounded through ground fault coils in such a way that their inductance is matched to the capacitance to ground (Figure 7.2). For the matching condition $I_C = I_L$:

$$I_C = 3 \cdot w \cdot C_E \frac{c \cdot U_n}{\sqrt{3}}, \text{ und } I_L = \frac{c \cdot U_n}{\sqrt{3} \cdot w \cdot L} \quad (7.2)$$

Here, we refer to the ground fault current I_F as the unbalanced residual current. The capacitive short circuit to ground I_C is compensated by the inductive coil current I_L of the ground fault quenching coils apart from a residual current. If the short circuit current to ground exceeds 35 A, the network must be operated with grounding compensation. The residual current should not exceed 60 A for medium voltage networks and 130 A for high voltage networks, in order to ensure the self-quenching of the arcing and to keep the thermal stress under control. If this is not the case, low impedance neutral point grounding must be used. Here too, overvoltages occur as for networks with an isolated free neutral point.

7.3 Networks with low impedance neutral point treatment

In accordance with HD 63751, a network with low impedance neutral point grounding (Figure 7.3) is present only when the neutral point of one or more transformers is directly grounded and the network protection is designed so that in the event of a short circuit to ground at any arbitrary fault position automatic cut-off must take place (protection by cut-off).

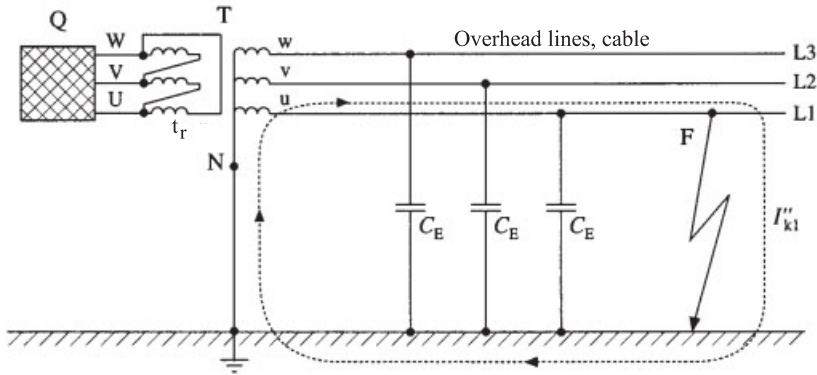


Fig. 7.3: Low-resistance grounded network

The fault to ground is described as a short circuit to ground and the fault current as short circuit current to ground or single-pole short circuit current. The short circuit currents to ground are however limited by the neutral point impedance ($Z_S = 20 \dots 60 \Omega$) to values below 5 kA. The ground fault factor $\delta = \frac{U_{LE}}{U/\sqrt{3}}$ will be introduced here to describe the voltage conditions for the neutral point treatment, where U_{LE} is the conductor-to-ground voltage for a fault and U the operating voltage before the fault occurs. For a single-pole short circuit current, then:

$$I''_{k1} = \frac{\sqrt{3} \cdot c_{min} \cdot U_n}{Z_1 + Z_2 + Z_0} \tag{7.3}$$

Table 7.2 gives an overview of neutral point arrangement on fault behavior in three-phase high-voltage networks.

Table 7.2: Arrangement of neutral point

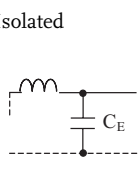
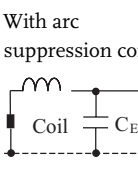
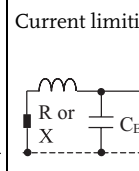
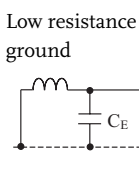
| Arrangement of neutral point (only one-phase shown) | Isolated | With arc suppression coil | Current limiting | Low resistance ground |
|--|---|---|--|--------------------------------|
|  |  |  |  | |
| Examples of use | Power plant auxiliaries | Overhead line | Cable network | High voltage |
| Fault current | $I_E < 40 \text{ A}$ | $I_{\text{Rest}} < 60\text{--}120 \text{ A}$ | e.g. $I''_{k1} = 2 \text{ kA}$ | high |
| Fault duration | $t > 2 \text{ h}$ | $t < 2\text{--}3 \text{ h}$ | $t \leq 1\text{--}3 \text{ s}$ | $t \leq 1\text{--}3 \text{ s}$ |
| Ground fault factor $\delta = U_{LE} / (U_{LL}/\sqrt{3})$ | $\delta \sim \sqrt{3}$ | $\delta \sim \sqrt{3}$ | $\delta \sim 1.4\text{--}1.8$ | $\delta \leq 1.4$ |
| Over-voltage | $k \sim 2.5$ | $k \sim 3.0$ | $k < 2.5$ | $k < 2.5$ |
| Voltage rise | yes | yes | no | no |
| Ground fault arc | self-quenching up to several A | self-quenching | usually sustained | sustained |
| Detection of fault | location by disconnection | location by disconnection | selective disconnection | short circuit protection |
| Where δ : Ground fault factor U_{LE} : Conductor – ground voltage at fault occurrence U_{LL} : Operating voltage before fault occurrence I_E : Ground fault current I_{Rest} : Residual current C_E : Ground capacitance I''_{KEE} : Double ground fault I'_{KEE} : Two phase to ground fault I'_{KEE} : Phase to ground fault | | | | |

Table 7.3 shows an overview of application of neutral point arrangements.

Table 7.3: Application of neutral point arrangements

| <i>Neutral point selection</i> | <i>Ground fault factor δ</i> | <i>Application</i> | <i>Results</i> |
|---------------------------------------|--|--|---|
| Direct grounding | ≤ 1.4 | in low voltage power systems < 1 kV | short circuit protection selective disconnection |
| Low resistance ground | 0.87 to 1.4 | in high voltage power systems > 110 kV medium voltage power systems for cable networks 10–30 kV | saving of insulation short circuit protection selective disconnection |
| With arc suppression coil | > 1.4 | overhead and cable networks up to 110 kV | location by disconnection |
| Short circuited with suppression coil | first > 1.4 after short grounding < 1.4 | cable network 10–110 kV | first location by disconnection then disconnection |

8

Impedances of Three-phase Operational Equipment

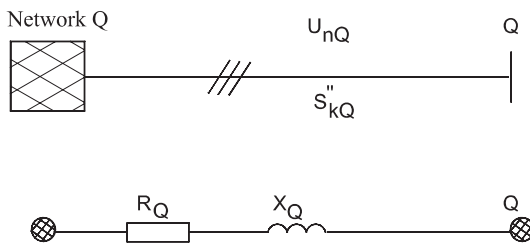
For the calculation of short circuit currents it is necessary to know conductor-specific equivalent data and impedances of electrical operational equipment, which are usually given by the respective manufacturer.

The calculation of short circuit currents is based on the use of equivalent circuits for the operational equipment. In principle, the equivalent resistances and reactances must be determined for all equipment. The impedances of generators, network transformers and power plant blocks should take account of the impedance corrections for calculating the short circuit currents. For generators, transformers and choke coils, the impedances and reactances are given in the *p.u.* or in the %/MVA system. Cables and lines are however assigned Ohm/km values.

The impedances of operational equipment are described in detail in the following:

8.1

Network feed-ins



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Fig. 8.1: Network feed-in and equivalent circuit

The input is from a network, usually designated "Q" for source and not from a generator (Figure 8.1). The calculation of this network is performed with the initial symmetrical short circuit power S''_{kQ} or the initial symmetrical short circuit current I''_{kQ} at the interface S.

The internal impedance of a high or medium voltage network can then be determined according to:

$$\begin{aligned}\underline{Z}_Q &= R_Q + j X_Q, \\ Z_Q &= \frac{c \cdot U_{nQ}}{\sqrt{3} I''_{kQ}}, \\ Z_Q &= \frac{c \cdot U_{nQ}^2}{S''_{kQ}}.\end{aligned}\tag{8.1}$$

If the short circuit is fed through transformers, it is possible to further extend the above relationships:

$$\begin{aligned}Z_{Qt} &= \frac{c \cdot U_{nQ}}{\sqrt{3} \cdot I''_{kQ}} \cdot \frac{1}{\dot{u}_r^2}, \\ Z_{Qt} &= \frac{c \cdot U_{nQ}^2}{S''_{kQ}} \cdot \frac{1}{\dot{u}_r^2},\end{aligned}\tag{8.2}$$

$$I''_{kQ} = \frac{c \cdot U_{nQt}}{\sqrt{3} \cdot Z_{Qt}}.\tag{8.3}$$

It is sufficient to calculate only with reactances in high voltage networks with a voltage of greater than 35 kV, i.e. $Z = 0 + jX_Q$. In all other cases, the calculation proceeds as follows:

$$\begin{aligned}X_Q &= 0.995 \cdot Z_Q, \\ R_Q &= 0.1 \cdot X_Q, \\ S''_{kQ} &= \sqrt{3} \cdot U_{nQ} \cdot I''_{kQ}.\end{aligned}\tag{8.4}$$

The meanings of the symbols are:

| | |
|------------|---|
| U_{nQ} | Nominal voltage of the network at the interface Q |
| S''_{kQ} | Initial symmetrical short circuit power |
| I''_{kQ} | Initial symmetrical short circuit current |
| c | Voltage factor |
| \dot{u} | Rated value of transformation ratio for transformer with step switch set to principal tapping |
| Z_Q | Positive-sequence impedance of short circuit |
| Z_{Qt} | Positive-sequence impedance relative to low voltage side of transformer |
| R_Q | Resistance of power supply feeder |
| X_Q | Reactance of power supply feeder |

8.2 Synchronous machines

Figure 8.2 illustrates the equivalent circuit for a synchronous machine. For a three-pole terminal short circuit, only the two inductive reactances X_h and X_s occur. The magnitude of the short circuit current therefore depends only on these reactances. Initially, the large peak short circuit current occurs, which then decays to the steady state short circuit current. The DC aperiodic component occurs here unchanged and decays in accordance with the decay constant. The changed magnetic fields in different rotors induce voltages which in turn affect the stators. The currents in the damper winding decay very quickly, because the equivalent resistances are very large. We refer to these processes as subtransient (transpired quickly).

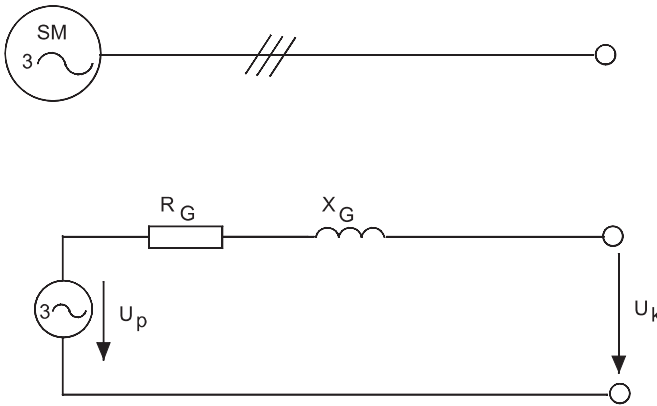


Fig. 8.2: Synchronous machine and equivalent circuit

The initial symmetrical short circuit current is determined from the initial reactance:

$$I_k'' = \frac{U_{qE}}{X_d''}. \quad (8.5)$$

The currents in the field winding decay slower due to the small resistance. We refer to this process as transient (temporary) and determine this from the transient reactance:

$$I_k'' = \frac{U_{qE}}{X_d}, \quad (8.6)$$

Finally, the continuous component resulting from the reactance of the main field is given here:

$$I_k = \frac{U_{gE}}{X_d''}. \quad (8.7)$$

The initial reactance X_d'' of a synchronous machine determines the magnitude of the initial symmetrical short circuit current.

For low voltage generators:

$$\underline{Z}_G = R_G + j X_d'', \quad (8.8)$$

$$R_G = 0.12 \cdot X_d''. \quad (8.9)$$

For high voltage generators $U_{RG} > 1$ kV:

For $S_{rG} \geq 100 \cdot$ MV A:

$$R_G = 0.05 \cdot j X_d'' \quad (8.10)$$

For $S_{rG} < 100 \cdot$ MV A:

$$R_G = 0.7 \cdot j X_d''. \quad (8.11)$$

The meanings of the symbols are:

| | |
|----------|----------------------------|
| X_d'' | Initial reactance |
| X_d' | Transient reactance |
| X_d | Synchronous reactance |
| X_0 | Zero-sequence reactance |
| Z_G | Impedance of generator |
| S_{rG} | Rated power of generator |
| R_G | Resistance of generator |
| U_{rG} | Rated voltage of generator |

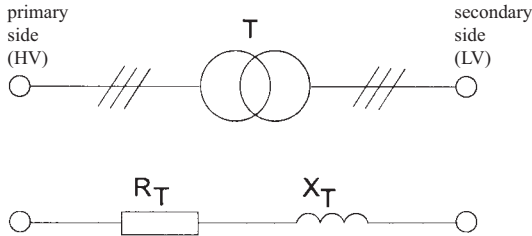
Table 8.1 below gives various values for the calculation of reactances.

Table 8.1: Relative characteristic values of synchronous generators

| <i>Machine type</i> | <i>Turbogenerator</i> | <i>Salient pole with damper winding</i> | <i>Salient pole without damper winding</i> |
|-----------------------------------|-----------------------|---|--|
| Synchronous reactance (x_d) | 110 % to 280 % | 70 % to 170 % | 70 % to 170 % |
| Transient reactance (x_d') | 14 % to 35 % | 20 % to 45 % | 20 % to 40 % |
| Initial reactance (x_d'') | 9 % to 22 % | 12 % to 30 % | 20 to 40 % |
| Zero-sequence reactance (x_0) | 3 % to 10 % | 5 % to 20 % | 5 % to 25 % |

8.3 Transformers

At this point, it is useful to explain the transformer and its equivalent circuit for the case of a short circuit (Fig. 8.3).



01

Fig. 8.3: Transformer and equivalent circuit

The short circuit voltage U_k is the primary voltage at which a transformer with short-circuited secondary winding already takes up its primary rated current. U_k is usually expressed as a relative short circuit voltage in percent of the primary voltage. It is a measure for the loading of the voltage change occurring. The following condition applies:

$$u_k = \frac{U_k \cdot 100\%}{U_{nHV}}, \quad (8.12)$$

When a short circuit occurs during operation of a transformer on the secondary side the peak short circuit current i_p first flows, which then gradually decays to the steady state short circuit current. The magnitude of i_p depends on the momentary value of the voltage and the magnetic state of the iron core. The value of the steady state short circuit current I_k depends on the short circuit voltage U_k and the internal resistance Z .

$$I_{kd} = \frac{U_{nHV}}{Z}, \quad (8.13)$$

$$Z = \frac{U_k}{I_{nLV}}, \quad (8.14)$$

$$U_{nHV} = \frac{U_k \cdot 100\%}{u_k}, \quad (8.15)$$

$$I_k = \frac{I_{nLV} \cdot 100\%}{u_k}. \quad (8.16)$$

8.3.1

Short circuit current on the secondary side

The equivalent circuit of the positive-sequence, negative-sequence and zero-sequence system is given by the number and the circuitry of the windings. The negative-sequence impedance is, due to the phase angle, identical with the positive-sequence impedance. The positive-sequence impedance of the transformer is calculated as follows:

$$Z_T = \frac{u_{kr}}{100\%} \frac{U_{rT}^2}{S_{rT}}, \quad (8.17)$$

$$R_T = \frac{U_{Rr}}{100\%} \frac{U_{rT}^2}{S_{rT}} = \frac{P_{krT}}{3 \cdot I_{rT}^2}, \quad (8.18)$$

$$X_T = \sqrt{Z_T^2 - R_T^2}. \quad (8.19)$$

For low voltage transformers, the equivalent resistances and the inductive reactances in the zero-sequence and positive-sequence systems are (Figure 8.4):

for the connection symbol Dyn5:

$$Z_{2T} = Z_{1T} \quad (8.20)$$

$$R_{0T} = R_T \quad (8.21)$$

$$X_{0T} = 0.95 \cdot X_T \quad (8.22)$$

for the connection symbols Dzn0 and Yzn11:

$$R_{0T} = 0.4 \cdot R_T \quad (8.23)$$

$$X_{0T} = 0.1 \cdot X_T \quad (8.24)$$

for the connection symbol YYn6:

$$R_{0T} = R_T \quad (8.25)$$

$$X_{0T} = 7 \dots 100 X_T \quad (8.26)$$

Transformers with three windings are employed in auxiliary service for the internal requirements of power stations, in the industrial sector or as network transformers. The short circuit impedances of transformers with three windings in the positive-sequence system can be calculated as follows, in accordance with Figure 8.5:

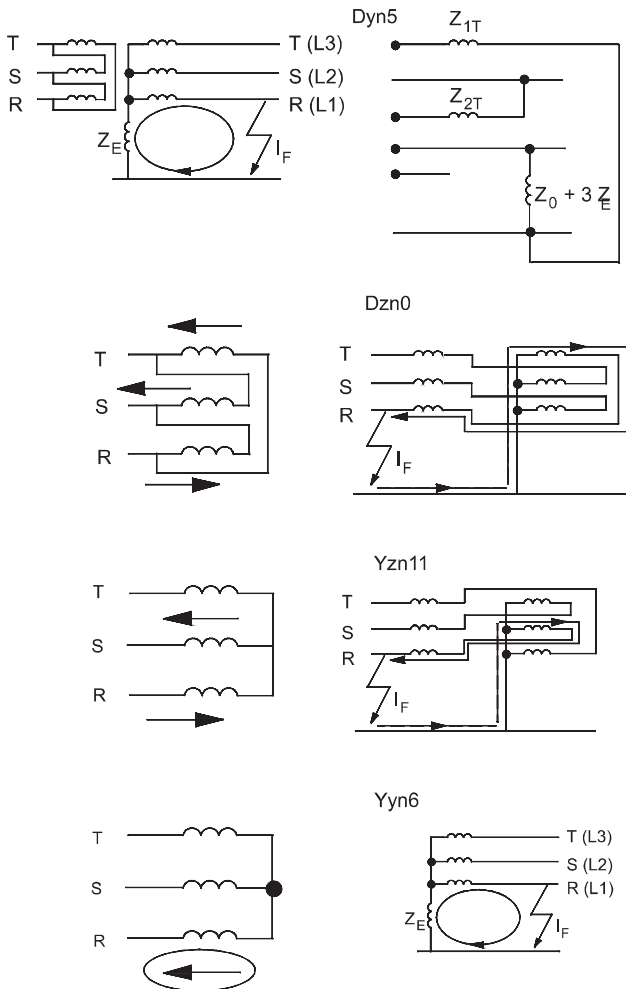
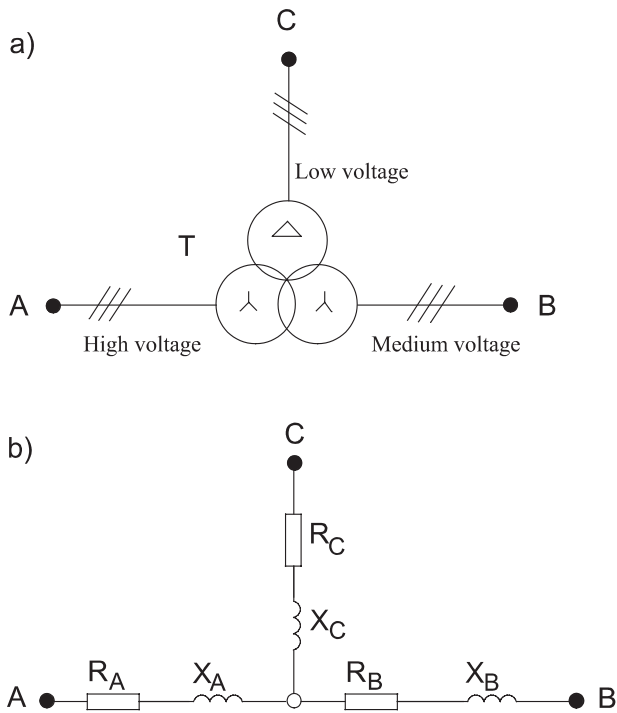


Fig. 8.4: Equivalent resistances and reactances in the zero-sequence and positive-sequence system for low voltage transformers



01

Fig. 8.5: a) Circuit diagram for transformer with three windings and b) equivalent circuit

with side C open:

$$Z_{AB} = \frac{u_{krAB}}{100\%} \frac{U_{rTA}^2}{S_{rTAB}}, \quad (8.27)$$

with side B open:

$$Z_{AC} = \frac{u_{krAC}}{100\%} \frac{U_{rTA}^2}{S_{rTAC}}, \quad (8.28)$$

with side A open:

$$Z_{BC} = \frac{u_{krBC}}{100\%} \frac{U_{rTA}^2}{S_{rTBC}}. \quad (8.29)$$

With the positive-sequence short circuit impedances, it follows that:

$$Z_A = \frac{1}{2} \cdot (Z_{AB} + Z_{AC} - Z_{BC}), \quad (8.30)$$

$$Z_B = \frac{1}{2} \cdot (Z_{BC} + Z_{AB} - Z_{AC}), \quad (8.31)$$

$$Z_C = \frac{1}{2} \cdot (Z_{AC} + Z_{BC} - Z_{AB}). \quad (8.32)$$

The meanings of the symbols are:

| | |
|-----------|--|
| U_{rT} | Rated voltage of transformer on higher or lower voltage side |
| I_{rT} | Rated current of transformer on higher or lower voltage side |
| U_{nHV} | Nominal voltage on higher voltage side |
| U_{nLV} | Nominal voltage on lower voltage side |
| U_k | Short circuit voltage |
| S_{rT} | Rated apparent power of transformer |
| P_{krT} | Total winding losses of transformer at rated current |
| u_{kr} | Rated value of short circuit voltage in % |
| u_{Rr} | Rated value of resistive voltage drop in % |
| R_{0T} | Zero-phase equivalent resistance of transformer |
| R_T | Equivalent resistance of transformer |
| X_{0T} | Inductive zero-sequence resistance of transformer |
| X_T | Inductive resistance of transformer. |

The equivalent resistances and reactances of transformers can also be taken from Figure 8.6.

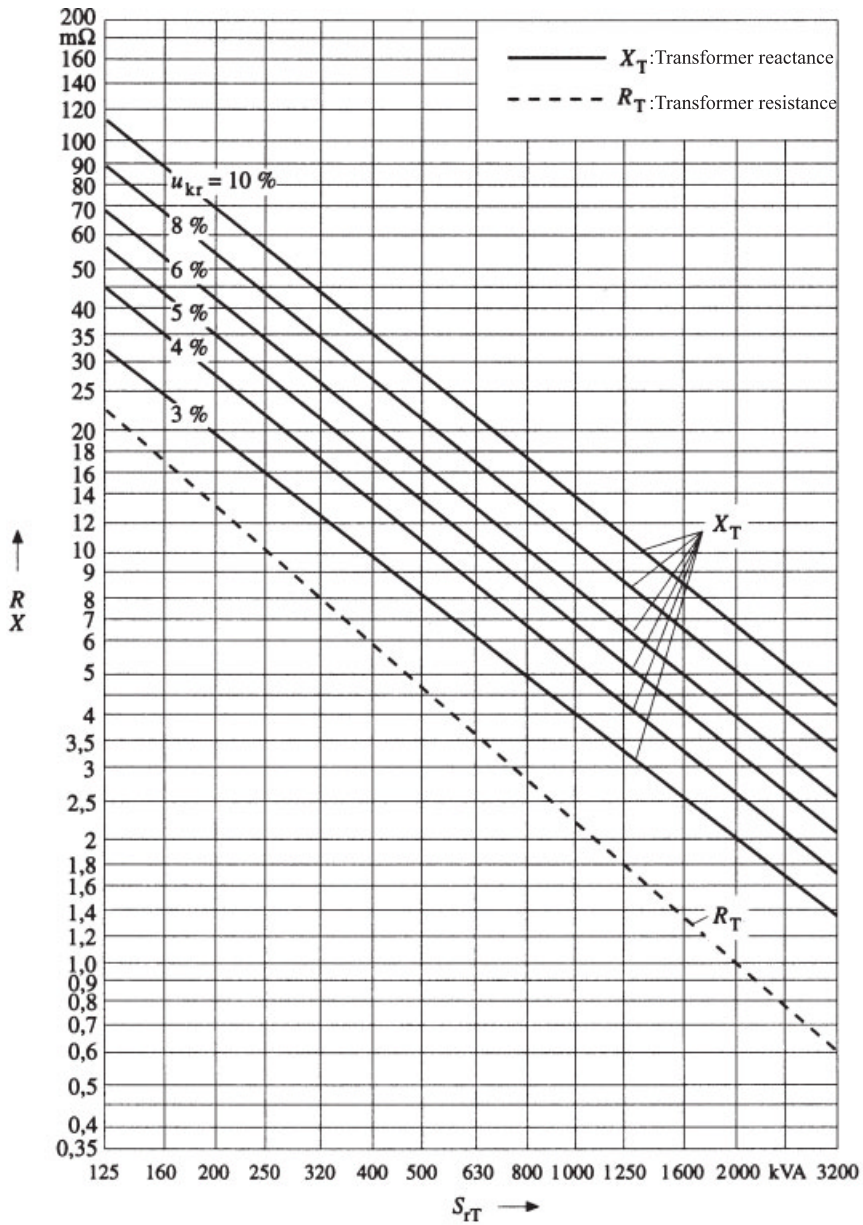


Fig. 8.6: Equivalent resistances and reactances of transformers for low and medium voltage networks [19]

8.3.2

Voltage regulating transformers

For the compensation of voltage fluctuations in networks, the windings of transformers are provided with a tap so that the transformation ratios can be adjusted in order to keep the voltage for certain sections constant. Voltage regulating transformers can be divided into two groups: controllable power transformers and series regulating transformers. Controllable transformers have several taps on the voltage side to be regulated, with which the transformation ratio can be increased or decreased in the same proportions, usually in steps of one or two percent. This is also known as in-phase voltage control, since only the magnitude of the voltage is regulated. Voltage regulation takes place step-wise with a switching device which can be described as a stepping switch or stepping switch device. Switchover between the steps must take place under load, since load-dependent voltage fluctuations are regulated during operation. The transformation ratio of the transformers is determined from the rated voltages. With stepping switches it is possible to match the transformation ratio to the load. The transformation ratio can be calculated, taking into account the step setting:

$$t = (1 + p_T) \cdot t_r$$

where, for t_r :

$$t_r = \frac{U_{rTHV}}{U_{rTLV}}$$

Regulating transformers are used, in addition to maintaining constant voltage levels, for controlling the load flow. They too can be switched under load. These can be divided into quadrature control transformers and phase-angle control transformers. For quadrature control transformers, an additional voltage is generated which is phase shifted by 90° from the voltage of a conductor. The additional voltage is added to the side on which the voltage is regulated. Phase-angle control transformers are a combination of quadrature control transformers and in-phase control transformers. Stepping regulators are implemented via power electronics components, which are fast and require little maintenance.

The most important features of high voltage transformers can be taken from Table 8.2.

Table 8.2: Characteristic values of high voltage transformers

| Rated voltage U_r (kV) | Rated power S_{rT} (MVA) | Short circuit voltage u_{kr} (%) | Impedance losses P_{krT} (%) | No-load losses P_{0rT} (%) | No-load current i_{0rT} (%) |
|-----------------------------|-------------------------------|--|--------------------------------------|------------------------------------|-------------------------------------|
| ≤ 30 | 2–4 | 6 | 0.9–0.8 | 0.17–0.14 | 1.3–1.1 |
| | 5–10 | 7 | 0.8–0.7 | 0.13–0.11 | 1.0–0.8 |
| | 12.5–40 | 10 | 0.6–0.4 | 0.08–0.06 | 0.8–0.5 |
| $30 < U_{rTHV} \leq 110$ | 6.3–10 | 10 | 0.9–0.8 | 0.18–0.14 | 0.9–0.8 |
| | 12.5–40 | 12 | 0.8–0.5 | 0.10–0.07 | 0.8–0.5 |
| | 50, 60 | 13 | 0.4 | 0.06 | 0.5–0.05 |
| | 80 | 14 | 0.5 | 0.05 | 0.45–0.05 |
| 110 | 100–350 | 12–16 | 0.31–0.19 | 0.05–0.03 | 0.45–0.05 |
| $110 < U_{rTHV} \leq 220$ | 100–1000 | 10–20 | 0.32–0.19 | 0.065–0.035 | 0.47–0.04 |
| $220 < U_{rTHV} \leq 380$ | 100–1000 | 11–20 | 0.4–0.2 | 0.07–0.04 | 0.48–0.04 |

8.4
Cables and overhead lines

The short circuit impedances for low voltage networks can be taken from the tables of IEC 60 909 that the cross-section is known.

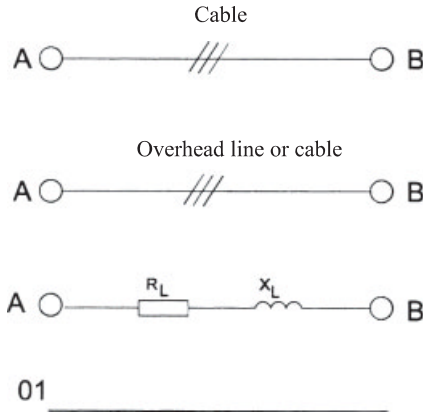


Fig. 8.7: Cables and lines in the positive-sequence system

For cables and line (Figures 8.7 and 8.8), we can then calculate the determining values as follows:

$$\underline{Z}_L = R_L + jX_L, \tag{8.33}$$

$$R_L = l \cdot R'_L, \tag{8.34}$$

$$X_L = l \cdot X'_L. \tag{8.35}$$

Length-specific values for overhead lines:

Resistance in Ω/km :

$$R_L = \frac{l}{\kappa \cdot S}, \quad (8.36)$$

The zero-sequence resistances of lines can be calculated from:

$$R_{0L} = \frac{R_{0L}}{R_L} \cdot R_L, \quad (8.37)$$

$$X_{0L} = \frac{R_{0L}}{R_L} \cdot X_L. \quad (8.38)$$

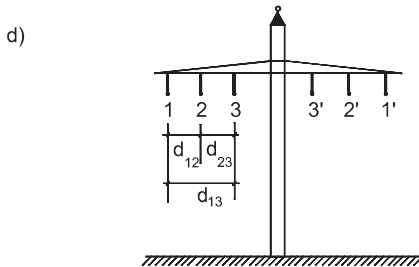
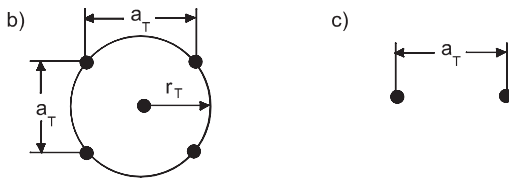
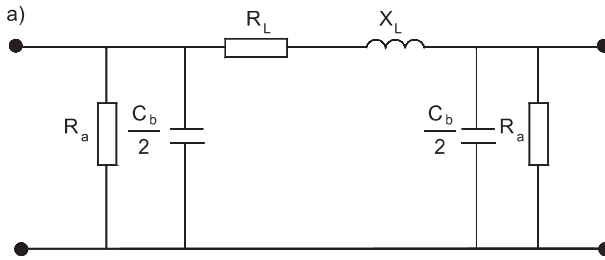


Fig. 8.8: Basis of calculation for overhead lines a) equivalent circuit of an overhead line, b) 4x conductor bundle line, c) 2x conductor bundle line, d) mast diagram

Inductive load reactance in Ω/km :

$$X_L = \omega \cdot L_b = \frac{\omega \cdot \mu_0}{2 \cdot \pi} \left(\ln \frac{d}{r} + \frac{l}{4 \cdot n} \right). \quad (8.39)$$

Double line:

$$X_L = \omega \cdot L_b = \frac{\omega \cdot \mu_0}{2 \cdot \pi} \left(\ln \frac{d \cdot d'}{r_e \cdot d''} + \frac{l}{4 \cdot n} \right). \quad (8.40)$$

Permeability:

$$\mu_0 = 4 \cdot \pi \cdot 10^{-4} \text{ Vs}/(\text{A} \cdot \text{m}). \quad (8.41)$$

Equivalent radius:

$$r_e = \sqrt[n]{n \cdot r \cdot R^{n-1}}. \quad (8.42)$$

Average geometrical distance between conductors:

$$d = \sqrt[3]{d_{12} \cdot d_{23} \cdot d_{31}}, \quad (8.43)$$

$$d' = \sqrt[3]{d'_{12} \cdot d'_{23} \cdot d'_{31}}, \quad (8.44)$$

$$d'' = \sqrt[3]{d''_{11} \cdot d''_{22} \cdot d''_{33}}. \quad (8.45)$$

Equivalent capacitive reactance in Ω/km :

$$C_b = \frac{2 \cdot \pi \cdot \varepsilon_0}{\ln \frac{d \cdot d'}{r \cdot d''}}, \quad (8.46)$$

$$X_b = \frac{1}{\omega \cdot C_B} \quad (8.47)$$

The meanings of the symbols are:

| | |
|---------|---|
| a_T | Distance of conductor elements |
| C_b | Load capacitance |
| d | Average geometrical distance between three conductors or between center points of conductor bundles |
| L_b | Load inductance |
| n | Number of conductor elements |
| r | Conductor radius |
| r_e | Equivalent radius |
| R | Radius of conductor element |
| R_L | Effective resistance of a conductor |
| S | Cross-section |
| X_L | Inductive load reactance |
| μ_0 | Permeability. |

The impedance values for overhead lines, cables and conductors are generally available from the respective manufacturers. If no information is available, the following tables 8.2 to 8.18 can be used.

Table 8.3: Impedances for PVC-insulated three-phase NYY cables [20]

| Cross-section of conductor S | 3 ₂ ¹ and 4 ₂ ¹ - Conductive cable | 4/5-Conductive cable | 1-Conductive cable with PE, separated | 1-Conductive cable with PE, bundled |
|------------------------------------|---|-------------------------|--|--|
| Cu conductor | | | | |
| mm ² | mΩ/m | mΩ/m | mΩ/m | mΩ/m |
| 0.5 | – | 107.2 | – | – |
| 0.75 | – | 71.5 | – | – |
| 1 | – | 53.6 | – | – |
| 1.5 | – | 35.7 | – | – |
| 2.5 | – | 21.44 | – | – |
| 4 | – | 13.4 | – | – |
| 6 | – | 8.93 | – | – |
| 10 | – | 5.36 | – | – |
| 16 | – | 3.35 | – | – |
| 25 | 3.11 | 2.15 | 3.13 | 3.12 |
| 35 | 2.23 | 1.54 | 2.25 | 2.24 |
| 50 | 1.56 | 1.08 | 1.60 | 1.59 |
| 70 | 1.12 | 0.78 | 1.17 | 1.16 |
| 95 | 0.84 | 0.59 | 0.89 | 0.88 |
| 120 | 0.67 | 0.47 | 0.74 | 0.72 |
| 150 | 0.55 | 0.39 | 0.63 | 0.61 |
| 185 | 0.45 | 0.33 | 0.56 | 0.53 |
| 240 | 0.37 | 0.27 | 0.49 | 0.46 |
| 300 | 0.31 | 0.24 | 0.45 | 0.42 |
| Al-Leiter = Al conductor | | | | |
| 16 | – | 5.70 | – | – |
| 25 | – | 3.64 | – | – |
| 35 | – | 2.60 | – | – |
| 50 | – | 1.83 | – | – |
| 70 | – | 1.31 | – | – |
| 95 | – | 0.97 | – | – |
| 120 | – | 0.77 | – | – |
| 150 | 0.90 | 0.63 | 0.96 | 0.94 |
| 185 | 0.74 | 0.52 | 0.80 | 0.79 |
| 240 | 0.58 | – | 0.66 | 0.64 |
| 300 | – | – | 0.57 | 0.55 |

Table 8.4: Resistance values for PVC-insulated four-conductor and five-conductor cables with Cu conductor at 55 °C conductor temperature [20]

| Cross-section of conductor S mm² | Resistance r mΩ/m | Reactance x mΩ/m | Impedance z mΩ/m |
|--|--|---|---|
| 4 × 0.5 | 81.90 | 0.23 | 81.90 |
| 4 × 0.75 | 55.74 | 0.23 | 55.74 |
| 4 × 1 | 41.18 | 0.23 | 41.18 |
| 4 × 1.5 | 27.53 | 0.23 | 27.53 |
| 4 × 2.5 | 16.86 | 0.22 | 16.96 |
| 4 × 4 | 10.49 | 0.21 | 10.49 |
| 4 × 6 | 7.01 | 0.20 | 7.01 |
| 4 × 10 | 4.16 | 0.19 | 4.16 |
| 4 × 16 | 2.62 | 0.18 | 2.63 |
| 4 × 25 | 1.654 | 0.176 | 1.663 |
| 4 × 35 | 1.192 | 0.160 | 1.203 |
| 4 × 50 | 0.880 | 0.159 | 0.894 |
| 4 × 70 | 0.610 | 0.155 | 0.629 |
| 4 × 95 | 0.440 | 0.154 | 0.466 |
| 4 × 120 | 0.348 | 0.151 | 0.379 |
| 4 × 150 | 0.282 | 0.151 | 0.320 |
| 4 × 185 | 0.226 | 0.151 | 0.272 |
| 4 × 240 | 0.172 | 0.149 | 0.228 |
| 4 × 300 | 0.136 | 0.149 | 0.202 |

For PVC-insulated cables with aluminum conductors, multiply the resistance value R' by the factor 1.7.

Table 8.5: Resistance values for PVC-insulated 3½ and 4½ conductor three-phase cables with Cu conductors at 55 °C conductor temperature [20]

| Cross-section of conductor S mm² | Resistance r mΩ/m | Reactance x mΩ/m | Impedance z mΩ/m |
|--|--|---|---|
| 3 × 25/16 | 2.135 | 0.182 | 2.143 |
| 3 × 35/16 | 1.904 | 0.183 | 1.913 |
| 3 × 50/25 | 1.267 | 0.179 | 1.279 |
| 3 × 70/35 | 0.901 | 0.174 | 0.918 |
| 3 × 95/50 | 0.660 | 0.168 | 0.681 |
| 3 × 120/70 | 0.479 | 0.160 | 0.505 |
| 3 × 150/70 | 0.446 | 0.167 | 0.476 |
| 3 × 185/95 | 0.333 | 0.163 | 0.371 |
| 3 × 240/120 | 0.260 | 0.164 | 0.307 |
| 3 × 300/150 | 0.209 | 0.162 | 0.264 |

For PVC-insulated cables with aluminum conductors, multiply the resistance value R' by the factor 1.7.

Table 8.6: Resistance values for PVC-insulated single-conductor three-phase cables with PE or PEN, next to each other, with Cu conductors at 55 °C conductor temperature [20]

| Cross-section of conductor S mm² | Resistance r mΩ/m | Reactance x mΩ/m | Impedance z mΩ/m |
|--|--|---|---|
| 1 × 25/16 | 2.1350 | 0.390 | 2.170 |
| 1 × 35/16 | 1.904 | 0.377 | 1.941 |
| 1 × 50/25 | 1.267 | 0.373 | 1.321 |
| 1 × 70/35 | 0.901 | 0.366 | 0.973 |
| 1 × 95/50 | 0.660 | 0.333 | 0.739 |
| 1 × 120/70 | 0.479 | 0.330 | 0.582 |
| 1 × 150/70 | 0.446 | 0.327 | 0.553 |
| 1 × 185/95 | 0.333 | 0.326 | 0.466 |
| 1 × 240/120 | 0.260 | 0.320 | 0.412 |
| 1 × 300/150 | 0.209 | 0.328 | 0.381 |

For PVC-insulated cables with aluminum conductors, multiply the resistance value R' by the factor 1.7.

Table 8.7: Resistance values for PVC-insulated single-conductor three-phase cables with PE or PEN, at distance d from each other, with Cu conductors at 55 °C conductor temperature [20]

| Cross-section of conductor S mm² | Resistance r mΩ/m | Reactance x mΩ/m | Impedance z mΩ/m |
|--|--|---|---|
| 1 × 25/16 | 2.135 | 0.390 | 2.170 |
| 1 × 35/16 | 1.904 | 0.377 | 1.941 |
| 1 × 50/25 | 1.267 | 0.373 | 1.321 |
| 1 × 70/35 | 0.901 | 0.366 | 0.973 |
| 1 × 95/50 | 0.660 | 0.362 | 0.753 |
| 1 × 120/70 | 0.479 | 0.359 | 0.599 |
| 1 × 150/70 | 0.446 | 0.356 | 0.571 |
| 1 × 185/95 | 0.333 | 0.354 | 0.486 |
| 1 × 240/120 | 0.260 | 0.349 | 0.435 |
| 1 × 300/150 | 0.209 | 0.347 | 0.405 |

For PVC-insulated cables with aluminum conductors, multiply the resistance value R' by the factor 1.7.

Table 8.8: Resistance values at 80 °C for Cu cables and conductors [24]

| Cross-section of conductor <i>S</i> in mm ² | Copper | | | Aluminum | | |
|--|---------------------------------|--------------------------------|--------------------------------|---------------------------------|--------------------------------|--------------------------------|
| | Resistance <i>r</i> mΩ/km | Reactance <i>x</i> mΩ/km | Impedance <i>z</i> mΩ/km | Resistance <i>r</i> mΩ/km | Reactance <i>x</i> mΩ/km | Impedance <i>z</i> mΩ/km |
| 4 × 1.5 | 15 | 0.115 | 15 | – | – | – |
| 4 × 2.5 | 9.02 | 0.110 | 9.02 | – | – | – |
| 4 × 4 | 5.654 | 0.106 | 5.654 | – | – | – |
| 4 × 6 | 3.757 | 0.100 | 3.758 | – | – | – |
| 4 × 10 | 2.244 | 0.094 | 2.264 | – | – | – |
| 4 × 16 | 1.413 | 0.090 | 1.415 | – | – | – |
| 4 × 25 | 0.895 | 0.086 | 0.899 | 1.68 | 0.086 | 1.682 |
| 4 × 35 | 0.649 | 0.083 | 0.654 | 1.226 | 0.083 | 1.228 |
| 4 × 50 | 0.479 | 0.083 | 0.486 | 0.794 | 0.083 | 0.798 |
| 4 × 70 | 0.332 | 0.082 | 0.341 | 0.551 | 0.082 | 0.557 |
| 4 × 95 | 0.239 | 0.082 | 0.252 | 0.396 | 0.082 | 0.404 |
| 4 × 120 | 0.192 | 0.080 | 0.208 | 0.316 | 0.080 | 0.325 |
| 4 × 150 | 0.153 | 0.080 | 0.172 | 0.257 | 0.080 | 0.270 |
| 4 × 185 | 0.122 | 0.080 | 0.146 | 0.203 | 0.080 | 0.221 |
| 4 × 240 | 0.093 | 0.079 | 0.122 | 0.155 | 0.079 | 0.173 |
| 4 × 300 | 0.074 | 0.079 | 0.108 | 0.124 | 0.079 | 0.147 |

Table 8.9: Resistance values at 20 °C for Cu cables and conductors [24]

| Cross-section of conductor <i>S</i> in mm ² | Copper | | | Aluminum | | |
|--|---------------------------------|--------------------------------|--------------------------------|---------------------------------|--------------------------------|--------------------------------|
| | Resistance <i>r</i> mΩ/km | Reactance <i>x</i> mΩ/km | Impedance <i>z</i> mΩ/km | Resistance <i>r</i> mΩ/km | Reactance <i>x</i> mΩ/km | Impedance <i>z</i> mΩ/km |
| 4 × 1.5 | 12.1 | 0.114 | 12.1 | – | – | – |
| 4 × 2.5 | 7.28 | 0.110 | 7.28 | – | – | – |
| 4 × 4 | 4.56 | 0.106 | 4.56 | – | – | – |
| 4 × 6 | 3.03 | 0.100 | 3.03 | – | – | – |
| 4 × 10 | 1.81 | 0.0945 | 1.812 | – | – | – |
| 4 × 16 | 1.14 | 0.0895 | 1.143 | – | – | – |
| 4 × 25 | 0.722 | 0.0879 | 0.729 | 1.20 | 0.088 | 1.203 |
| 4 × 35 | 0.524 | 0.0851 | 0.530 | 0.876 | 0.086 | 0.880 |
| 4 × 50 | 0.387 | 0.0848 | 0.396 | 0.641 | 0.084 | 0.646 |
| 4 × 70 | 0.268 | 0.0819 | 0.280 | 0.443 | 0.082 | 0.450 |
| 4 × 95 | 0.193 | 0.0819 | 0.209 | 0.320 | 0.082 | 0.330 |
| 4 × 120 | 0.155 | 0.0804 | 0.174 | 0.253 | 0.080 | 0.265 |
| 4 × 150 | 0.124 | 0.0804 | 0.147 | 0.206 | 0.080 | 0.220 |
| 4 × 185 | 0.0991 | 0.0804 | 0.127 | 0.164 | 0.080 | 0.182 |
| 4 × 240 | 0.0754 | 0.0797 | 0.109 | 0.125 | 0.079 | 0.147 |
| 4 × 300 | 0.0601 | 0.0797 | 0.998 | 0.100 | 0.079 | 0.127 |

Table 8.10: Resistances per unit length r in positive-sequence system for overland line conductors manufactured in accordance with DIN 48 201 and $f = 50$ Hz at 20°C [7]

| Cross-section of conductor S in mm^2 | Nominal cross-section S in mm^2 | Copper r in Ω/km | Aluminum r in Ω/km |
|--|---|---|---|
| 10 | 10 | 1.804 | 2.855 |
| 16 | 15.9 | 1.134 | 1.795 |
| 25 | 24.2 | 0.745 | 1.18 |
| 35 | 34.4 | 0.524 | 0.83 |
| 50 | 49.5 | 0.364 | 0.577 |
| 70 | 65.8 | 0.276 | 0.436 |
| 95 | 93.2 | 0.195 | 0.308 |
| 120 | 117 | 0.155 | 0.246 |

Table 8.11: Inductive reactances per unit length x in Ω/km in positive-sequence system for overland line conductors at $f = 50$ Hz [7]

| Cross-section of conductor S in mm^2 | Average distance d between conductors in cm | | | | | |
|--|---|-----------|-----------|-----------|-----------|------------|
| | 50 | 60 | 70 | 80 | 90 | 100 |
| 10 | 0.37 | 0.38 | 0.40 | 0.40 | 0.41 | 0.42 |
| 16 | 0.36 | 0.37 | 0.38 | 0.38 | 0.40 | 0.40 |
| 25 | 0.34 | 0.35 | 0.37 | 0.37 | 0.38 | 0.39 |
| 35 | 0.33 | 0.33 | 0.35 | 0.36 | 0.37 | 0.38 |
| 50 | 0.32 | 0.32 | 0.34 | 0.35 | 0.36 | 0.37 |
| 70 | 0.31 | 0.32 | 0.33 | 0.34 | 0.35 | 0.35 |
| 95 | 0.29 | 0.31 | 0.32 | 0.33 | 0.34 | 0.34 |
| 120 | 0.29 | 0.30 | 0.31 | 0.32 | 0.33 | 0.34 |

Table 8.12: Quotients of effective resistances and inductive reactances in the zero-sequence and positive-sequence systems for NAYY and NYY cables as a function of the ground return system at $f = 50$ Hz [7]

| S in mm^2 | $\frac{R_{OL}}{R_L}$ | | | | $\frac{X_{OL}}{X_L}$ | | | |
|-------------------------|----------------------|------|----------|------|----------------------|-------|----------|-------|
| | Copper | | Aluminum | | Copper | | Aluminum | |
| | a | c | a | c | a | c | a | c |
| 4×1.5 | 4.0 | 1.03 | – | – | 3.99 | 21.28 | – | – |
| 4×2.5 | 4.0 | 1.05 | – | – | 4.01 | 21.62 | – | – |
| 4×4 | 4.0 | 1.11 | – | – | 3.98 | 21.36 | – | – |
| 4×6 | 4.0 | 1.21 | – | – | 4.03 | 21.62 | – | – |
| 4×10 | 4.0 | 1.47 | – | – | 4.02 | 20.22 | – | – |
| 4×16 | 4.0 | 1.86 | – | – | 3.98 | 17.09 | – | – |
| 4×25 | 4.0 | 1.35 | – | – | 4.13 | 12.97 | – | – |
| 4×35 | 4.0 | 2.71 | 4.0 | 2.12 | 3.78 | 10.02 | 4.13 | 15.47 |
| 4×50 | 4.0 | 2.95 | 4.0 | 2.48 | 3.76 | 7.61 | 3.76 | 11.99 |
| 4×70 | 4.0 | 3.18 | 4.0 | 2.84 | 3.66 | 5.68 | 3.66 | 8.63 |
| 4×95 | 4.0 | 3.29 | 4.0 | 3.07 | 3.65 | 4.63 | 3.65 | 6.51 |
| 4×120 | 4.0 | 3.35 | 4.0 | 3.19 | 3.65 | 4.21 | 3.65 | 5.53 |
| 4×150 | 4.0 | 3.38 | 4.0 | 3.26 | 3.65 | 3.94 | 3.65 | 4.86 |
| 4×185 | 4.0 | 3.41 | 4.0 | 3.32 | 3.65 | 3.74 | 3.65 | 4.35 |
| 4×240 | 4.0 | 3.42 | – | – | 3.67 | 3.62 | – | – |
| 4×300 | 4.0 | 3.44 | – | – | 3.66 | 3.52 | – | – |

- a Ground return system through fourth conductor
c Ground return system through fourth conductor and ground

Table 8.13: Resistances r per unit length of conductors for copper conductors

| Cross-section of conductor S in mm^2 | 20 °C Ω/km | 30 °C Ω/km |
|--|-----------------------------|-----------------------------|
| 1.5 | 12.1 | 12.57 |
| 2.5 | 7.41 | 7.56 |
| 4 | 4.61 | 4.73 |
| 6 | 3.08 | 3.15 |
| 10 | 1.83 | 1.88 |
| 16 | 1.15 | 1.18 |
| 25 | 0.727 | 0.75 |
| 35 | 0.524 | 0.54 |
| 50 | 0.387 | 0.40 |
| 70 | 0.268 | 0.28 |
| 95 | 0.193 | 0.20 |
| 120 | 0.153 | 0.16 |
| 150 | 0.124 | 0.13 |
| 185 | 0.0991 | 0.10 |

Table 8.14: Impedance z for main outgoing and return lines of power supply companies

| <i>Impedance</i> | |
|--|--------------------|
| <i>Cross-section of conductor (NYM or NYY) S in mm²</i> | <i>z m Ω/m</i> |
| 1.5 | 0.03001 |
| 2.5 | 0.01838 |
| 4 | 0.01131 |
| 6 | 0.00752 |
| 10 | 0.00449 |
| 16 | 0.00284 |
| 25 | 0.00180 |
| 35 | 0.00131 |
| 50 | 0.00098 |
| 70 | 0.00069 |
| 95 | 0.00052 |

Table 8.15: Resistances of conductors in XLPE-insulated cables (6 to 30 kV) at 20 °C [26]

| <i>Cross-section of conductor S in mm²</i> | <i>Copper conductor Ω/km</i> | <i>Aluminum conductor Ω/km</i> |
|---|----------------------------------|------------------------------------|
| 25 | 0.727 | 1.20 |
| 35 | 0.524 | 0.868 |
| 50 | 0.387 | 0.641 |
| 70 | 0.268 | 0.443 |
| 95 | 0.193 | 0.320 |
| 120 | 0.153 | 0.253 |
| 150 | 0.124 | 0.206 |
| 185 | 0.0991 | 0.164 |
| 240 | 0.0754 | 0.125 |
| 300 | 0.0601 | 0.100 |
| 400 | 0.0470 | 0.0778 |
| 500 | 0.0366 | 0.0605 |

Table 8.16: Resistances per unit length of XLPE-insulated copper cables (6 to 20 kV) for $f = 50$ Hz [26]

| Cross-section of conductor S in mm^2 | 6/10 kV | | 12/20 kV | |
|--|--|--|--|--|
| | single-conductors on top of each other | single-conductors next to each other | single-conductors on top of each other | single-conductors next to each other |
| 35 | 0.671 | 0.673 | 0.671 | 0.672 |
| 50 | 0.497 | 0.498 | 0.496 | 0.498 |
| 70 | 0.345 | 0.346 | 0.345 | 0.346 |
| 95 | 0.249 | 0.251 | 0.249 | 0.250 |
| 120 | 0.198 | 0.200 | 0.198 | 0.200 |
| 150 | 0.163 | 0.165 | 0.163 | 0.165 |
| 185 | 0.132 | 0.134 | 0.131 | 0.133 |
| 240 | 0.102 | 0.104 | 0.101 | 0.103 |
| 300 | 0.082 | 0.085 | 0.082 | 0.084 |
| 400 | 0.068 | 0.071 | 0.067 | 0.070 |
| 500 | 0.055 | 0.058 | 0.055 | 0.058 |

Table 8.17: Inductances of XLPE-insulated copper cables (6 to 30 kV) for $f = 50$ Hz [26]

| Cross-section of conductor S in mm^2 | 6/10 kV | | 12/20 kV | | 18/30 kV | |
|---|----------------|----------------|----------------|----------------|----------------|----------------|
| | mh/km | mh/km | mh/km | mh/km | mh/km | mh/km |
| 35 | 0.45 | 0.76 | 0.48 | 0.76 | – | – |
| 50 | 0.42 | 0.73 | 0.45 | 0.74 | 0.48 | 0.75 |
| 70 | 0.39 | 0.70 | 0.43 | 0.70 | 0.45 | 0.71 |
| 95 | 0.38 | 0.67 | 0.41 | 0.68 | 0.43 | 0.68 |
| 120 | 0.36 | 0.65 | 0.39 | 0.65 | 0.42 | 0.66 |
| 150 | 0.35 | 0.63 | 0.38 | 0.63 | 0.41 | 0.64 |
| 185 | 0.34 | 0.61 | 0.36 | 0.62 | 0.39 | 0.63 |
| 240 | 0.32 | 0.59 | 0.35 | 0.59 | 0.37 | 0.60 |
| 300 | 0.31 | 0.57 | 0.33 | 0.58 | 0.36 | 0.59 |
| 400 | 0.30 | 0.55 | 0.33 | 0.55 | 0.34 | 0.56 |
| 500 | 0.29 | 0.53 | 0.31 | 0.53 | 0.33 | 0.54 |

Table 8.18: Effective capacitances of XLPE-insulated copper cables [26]

| <i>Nominal voltage</i> | <i>6/10 kV</i> | <i>12/20 kV</i> | <i>18/30 kV</i> |
|---|----------------|-----------------|-----------------|
| <i>Cross-section of conductor S in mm²</i> | <i>μF/km</i> | <i>μF/km</i> | <i>μF/km</i> |
| 35 | 0.22 | 0.16 | – |
| 50 | 0.25 | 0.18 | 0.14 |
| 70 | 0.28 | 0.20 | 0.15 |
| 95 | 0.31 | 0.22 | 0.17 |
| 120 | 0.34 | 0.23 | 0.18 |
| 150 | 0.37 | 0.25 | 0.19 |
| 185 | 0.40 | 0.27 | 0.20 |
| 240 | 0.44 | 0.30 | 0.22 |
| 300 | 0.48 | 0.32 | 0.24 |
| 400 | 0.55 | 0.36 | 0.27 |
| 500 | 0.60 | 0.40 | 0.29 |

Table 8.19: Ground fault currents of XLPE-insulated copper cables [26]

| <i>Nominal voltage</i> | <i>6/10 kV</i> | <i>12/20 kV</i> | <i>18/30 kV</i> |
|---|----------------|-----------------|-----------------|
| <i>Cross-section of conductor S in mm²</i> | <i>A/km</i> | <i>AF/km</i> | <i>A/km</i> |
| 35 | 1.2 | 1.7 | – |
| 50 | 1.4 | 1.9 | 2.3 |
| 70 | 1.5 | 2.1 | 2.5 |
| 95 | 1.7 | 2.4 | 2.7 |
| 120 | 1.9 | 2.6 | 2.9 |
| 150 | 2.0 | 2.7 | 3.1 |
| 185 | 2.2 | 3.0 | 3.3 |
| 240 | 2.4 | 3.3 | 3.7 |
| 300 | 2.6 | 3.5 | 4.0 |
| 400 | 3.0 | 4.0 | 4.4 |
| 500 | 3.3 | 4.3 | 4.8 |

8.5

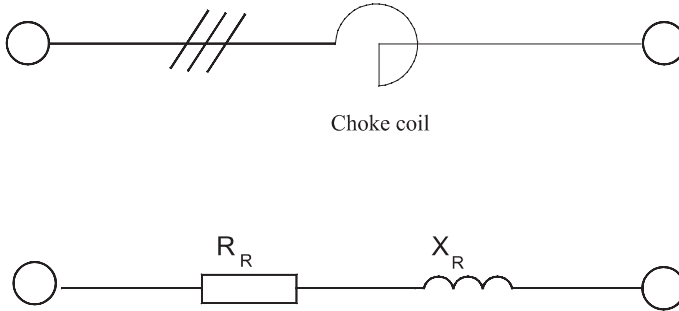
Short circuit current limiting

The short circuit current limiting choke coils (Figure 8.9) are used to limit the current flowing as a result of a fault condition in series systems with insufficient stability against short circuits. They are used in order to reduce the breaking capacity of the circuit breakers to a permissible value.

The following conditions apply here:

$$X_R = \frac{u_{kR}}{100\%} \cdot \frac{U_n}{\sqrt{3} \cdot I_{rR}}, \quad (8.48)$$

$$R_R \ll X_R. \quad (8.49)$$



01

Fig. 8.9: Short circuit current limiting choke coil and equivalent circuit

The meanings of the symbols are:

- X_R Reactance of choke coil
- U_n Nominal power line voltage
- R_R Resistance of choke coil
- u_{kR} Rated voltage drop of choke coil (given on nameplate)
- I_{rR} Rated current of choke coil (given on nameplate)

8.6 Asynchronous machines

Asynchronous motors (Fig. 8.10) have field conditions similar to those of synchronous motors following a short circuit across the terminal.

The equivalent circuit consists of an internal voltage source and an impedance. The value of this impedance can be calculated as follows:

$$Z_M = \frac{1}{I_{an}/I_{rM}} \cdot \frac{U_{rM}}{\sqrt{3} \cdot I_{rM}} = \frac{1}{I_{an}/I_{rM}} \cdot \frac{U_{rM}^2}{S_{rM}}, \quad (8.50)$$

$$S_{rM} = \frac{P_{rM}}{\eta_r \cdot \cos \varphi_r} \quad (8.51)$$

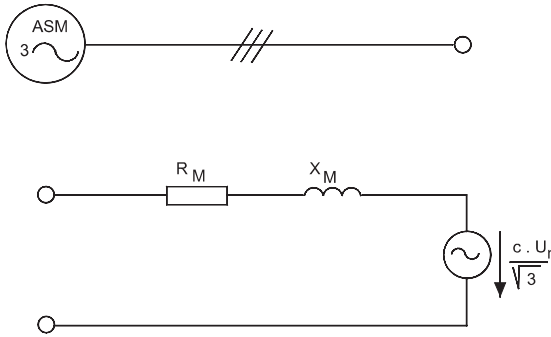


Fig. 8.10: Asynchronous machine and equivalent circuit

The meanings of the symbols are:

- Z_M Impedance of motor
- U_{rM} Rated voltage of motor
- I_{rM} Rated current of motor
- S_{rM} Rated apparent power of motor
- P_{rM} Rated effective power of motor
- I_{an}/I_{rM} Ratio of locked-rotor current to rated current of motor.

8.7

Consideration of capacitors and non-rotating loads

The short circuit currents are determined with the aid of the equivalent voltage source. Not considered here are the load flow before the occurrence of the short circuit, the capacitances of the conductors, the passive loads, the position of the step switch of transformers and the state of the exciter of the generators. Independently of the point in time at which the short circuit occurs, the discharge current of the parallel capacitors can be neglected for the calculation of i_p . The influence of the series capacitors can also be neglected if these are provided with voltage limiting systems connected in parallel, which respond in the event of a short circuit.

8.8**Consideration of static converters**

For the calculation of short circuit currents static converters are treated similarly to asynchronous motors. Reversing mechanisms supplied from a static converter contribute only to the initial symmetrical short circuit current and the peak short circuit current.

9

Impedance Corrections

The magnitude of the short circuit currents in a network depends primarily on the design of the network, the generators or power station blocks and the motors operating and secondarily on the operating state of the network before occurrence of the short circuit. It is therefore difficult to find the loading state which leads to either the greatest or the smallest short circuit current at the different fault locations of the network. IEC 60 909 consequently recommends the method of calculation with the equivalent voltage source $c \cdot U_n / \sqrt{3}$ at the fault location. Investigations have shown that the voltage factor c is no longer sufficient for calculating the maximum short circuit current when the sub-transient behavior of the generators, power station blocks with or without step switches and network transformers is considered. The factor c in Table 1.1 shows that on the average the highest voltage in a normal network does not deviate by more than about +5% for low voltage and +10% for high voltage from the network voltage U_n . In a common network with 50 or 60 Hz the highest and lowest voltage do not differ by more than $\pm 10\%$ from the network voltage. In the North American countries, the highest voltage differs by no more than +5% and the lowest voltage -10% from the network voltage [1].

The conditions of Section 1.4.1 apply only when the voltage differences in a network are less than 10%. Special conditions can occur for generators and power station blocks with high values of x''_d , u_n , causing voltage drops of more than +10%. For this reason the introduction of impedance correction factors is necessary, above all in order to obtain reliable values for the determination of the greatest short circuit current.

For the dimensioning of electrical operational equipment the calculation of the greatest short circuit current and the greatest partial short circuit current is necessary. In this section we will discuss the required correction factors.

For the calculation of the largest short circuit current and the transferred short circuit current it is necessary to make corrections to the generator impedances (K_G) and the power plant block impedances (K_{KW}) in addition to the factor c_{max} , especially when the subtransient reactances x''_d of the generators are large and the transformation ratio of the block transformers differs from the network voltages during operation on both sides of the transformer [1]. The calculation of the smallest short circuit current requires special considerations, such as:

- the smallest power supplied for thermal power stations
- the largest reactive power of machine units for pumping power stations
- special equipment for limiting the load angle
- Loading state of power station units during low-load periods.

9.1

Correction factor K_G for generators

The impedance correction factor K_G is applied to the impedance of generators connected directly to the network (Figure 9.1).

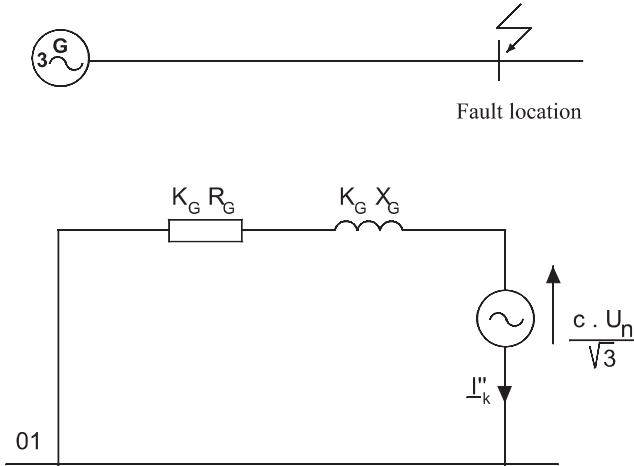


Fig. 9.1: Connection and equivalent circuit of a generator

K_G is derived from the overexcited generator, taking account of the subtransient reactance X_d'' and subtransient internal voltage \underline{E}'' [1]. The impedance of the generator in the positive-phase system is:

$$\underline{Z}_G = R_G + jX_d'', \quad (9.1)$$

$$\underline{Z}_{(GK)} = K_G \cdot \underline{Z}_G = K_G (R_G + jX_d''), \quad (9.2)$$

With the correction factor:

$$K_G = \frac{U_n}{U_{rG}} \cdot \frac{c_{max}}{(1 + x_d'' \cdot \sin \varphi_{rG})}. \quad (9.3)$$

In accordance with IEC 60 909, for three-pole short circuit currents with direct connection to the network:

$$I_k'' = \frac{c \cdot U_n}{\sqrt{3} \cdot |R_G + jk X_d''| \cdot K_G} \quad (9.4)$$

Substituting the correction factor in the above equation then yields:

$$I_k'' = \frac{c}{c_{max}} \cdot \frac{U_{rG}}{\sqrt{3} \cdot |R_G + jk X_d''|} \cdot (1 + x_d'' \cdot \sin \varphi_{rG}) \quad (9.5)$$

For salient-pole machines with different values for X_d'' and X_q'' , we introduce:

$$X_{(2)G} = \frac{1}{2} (X_d'' + X_q''), \quad (9.6)$$

$$Z_{(0)G} = K_G (R_{(0)G} + jk X_{(0)G}). \quad (9.7)$$

The meanings of the symbols are:

| | |
|----------------------|--|
| c_{max} | Voltage factor |
| U_n | Nominal voltage of network |
| U_{rG} | Rated voltage of generator |
| \underline{Z}_{GK} | Corrected impedance of generator |
| \underline{Z}_G | Impedance of generator |
| x_d'' | Subtransient reactance of generator |
| φ_{rG} | Phase angle between $U_{rG}/\sqrt{3}$ and I_{rG} . |

9.2

Correction factor K_{KW} for power plant block

For the determination of the impedance correction factor K_{KW} as in Figure 9.2, the following considerations are necessary [1].

- Whether the block transformer is equipped with a step switch or with a higher transformation ratio
- Whether the rated voltages of the generator and the low voltage side of the block transformer are different
- Whether the rated apparent powers of the generator and transformer are also different.

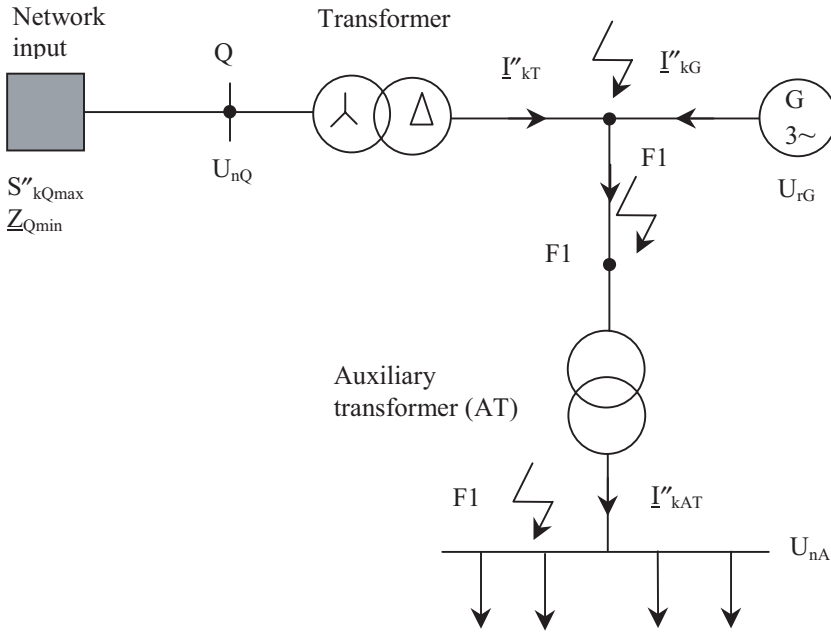


Fig. 9.2: Impedance correction for block transformer

The voltage control is implemented either on the high voltage side of the transformer or via the inherent voltage regulation of the generator. Here, it is necessary to distinguish between a transformer with and without step switching.

Block transformer with step switch:

$$\underline{Z}_{KW} = K_{MS} \cdot (t_r^2 \cdot \underline{Z}_G + \underline{Z}_{THV}), \quad (9.8)$$

$$K_{with} = \frac{U_{nQ}^2}{U_{rG}^2} \cdot \frac{1}{t_r^2} \cdot \frac{c_{max}}{1 + |x_d'' - x_T| \cdot \sin \varphi_{rG}}. \quad (9.9)$$

Block transformer without step switch:

$$\underline{Z}_{KW} = K_{HV} \cdot (t_r^2 \cdot \underline{Z}_G + \underline{Z}_{THV}), \quad (9.10)$$

$$K_{without} = \frac{U_{nQ}}{U_{rG}} \cdot \frac{1}{1 + p_G} \cdot \frac{1}{t_r} \cdot (1 + p_T) \cdot \frac{c_{max}}{1 + x_d'' \cdot \sin \varphi_{rG}}. \quad (9.11)$$

9.3

Correction factor K_T for transformers with two and three windings

The correction factor K_T for transformers with two and three windings in accordance with IEC 73/89/CDV can be calculated as follows.

For transformers with two windings, with or without step switching:

$$\underline{Z}_T = R_T + j X_T \quad (9.12)$$

$$\underline{Z}_{TK} = K_T \cdot \underline{Z}_T \quad (9.13)$$

$$K_T = 0.95 \frac{c_{max}}{1 + 0.6 x_T} \quad (9.14)$$

$$x_T = \frac{X_T}{(U_{rT}^2 / S_{rT})} \quad (9.15)$$

For transformers with three windings, with or without step switching:

$$K_{TAB} = 0.95 \cdot \frac{c_{max}}{1 + 0.6 x_{TAB}} \quad (9.16)$$

$$K_{TAC} = 0.95 \cdot \frac{c_{max}}{1 + 0.6 x_{TAC}} \quad (9.17)$$

$$K_{TBC} = 0.95 \cdot \frac{c_{max}}{1 + 0.6 x_{TBC}} \quad (9.18)$$

The meanings of the symbols are:

| | |
|------------------------|--|
| Z_{KW} | Corrected impedance of power plant block for high voltage side |
| Z_G | Impedance of generator |
| \underline{Z}_{THV} | Impedance of block transformer for high voltage side |
| t_r | Rated value of transformation ratio for transformer with step switch set to principal tapping |
| $\underline{Z}_{T,KW}$ | Corrected impedance of block transformer |
| $\underline{Z}_{G,KW}$ | Corrected impedance of generator |
| $1 + p_T$ | This value is introduced when the block transformer has tappings and is used continuously. Otherwise $1 + p_T = 1$ |
| K_{with} | Correction factor with step switch |
| $K_{without}$ | Correction factor without step switch |
| x_T | Relative reactance of transformer. |

Table 9.1 shows a summary of impedance corrections.

Table 9.1 Impedance corrections

| Appliances | Impedance | Corrections |
|--|--|--|
| Generator | $\underline{Z}_{GK} = \underline{Z}_G \cdot K_G$ | $K_G = \frac{U_n}{U_{rG}} \cdot \frac{c_{\max}}{1 + x_d'' \sin \varphi_{rG}}$ |
| Transformer | $\underline{Z}_{TK} = \underline{Z}_T \cdot K_T$ | $K_T = \frac{U_n}{U_{rT}} \cdot \frac{c_{\max}}{1 + x_T \left(\frac{I_T^b}{I_{rT}} \right) \sin \varphi_T^b}$ $K_T = 0.95 \cdot \frac{c_{\max}}{1 + 0.6x_T}$ |
| Power plant with tapping change (TC) | $\underline{Z}_S = K_{STC} \cdot \left(t_r^2 \underline{Z}_G + \underline{Z}_{THV} \right)$ | $K_{STC} = \frac{U_{nQ}^2}{U_{rG}^2} \cdot \frac{U_{rTLV}^2}{U_{rTHV}^2} \cdot \frac{c_{\max}}{1 + x_d'' - x_T \sin \varphi_{rG}}$ |
| Power plant without tapping change (WTC) | $\underline{Z}_S = K_{SWTC} \left(t_r^2 \underline{Z}_G + \underline{Z}_{THV} \right)$ | $K_{SWTC} = \frac{U_{nQ}}{U_{rG}(1 + p_G)} \cdot \frac{U_{rTLV}}{U_{rTHV}} \cdot \frac{(1 \pm p_T) c_{\max}}{1 + x_d'' \sin \varphi_{rG}}$ |

10 The Method of Symmetrical Components

The method of symmetrical components is used for the calculation of asymmetrical faults. This section discusses the fundamentals of this method. A characteristic rotational operator is a complex number with the magnitude 1. Multiplication with a rotational operator therefore describes the rotation of an arbitrary phasor without changing its magnitude. From the set of complex numbers we know the rotational operator $j = \sqrt{-1}$, which gives rise to a rotation by 90° . Accordingly, $j^2 = -1$ then gives rise to a rotation by 180° and j^4 brings the phasor back to its original position. In three-phase systems the phase angles $\varphi = 120^\circ$ and 240° are of special importance.

Figure 10.1 shows a symmetrical system, which consists of three unit phasors separated by angles of 120° .

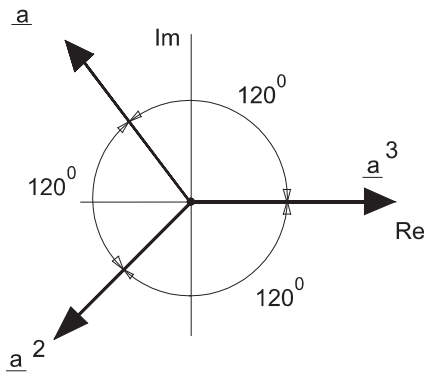


Fig. 10.1: Phasor diagram for the positive-sequence, negative-sequence and zero-sequence systems

The rotational operator for $\varphi = 120^\circ$ is designated \underline{a} and accordingly that for 240° is designated \underline{a}^2 , so that:

$$\underline{a} = e^{j120} = e^{\frac{j2\pi}{3}} = \frac{1}{2}(1 - j\sqrt{3}) \quad (10.1)$$

$$\underline{a}^2 = e^{j240} = e^{\frac{j4\pi}{3}} = \frac{1}{2}(1 + j\sqrt{3}) \quad (10.2)$$

$$\underline{a}^3 = 1 \quad (10.3)$$

As can be seen easily from the above equations, their sum is equal to zero:

$$1 + \underline{a} + \underline{a}^2 = 0 \quad (10.4)$$

With the rotational operators \underline{a} and \underline{a}^2 the symmetrical three-phase system belongs to the set of complex numbers.

$$\underline{U}_R = U_R, \quad (10.5)$$

$$\underline{U}_S = \underline{a}^2 \cdot U_R, \quad (10.6)$$

$$\underline{U}_T = \underline{a} \cdot U_R. \quad (10.7)$$

For the voltages in the external conductors:

$$\underline{U}_{RS} = \underline{U}_R - \underline{U}_S = \sqrt{3} \cdot U_R \cdot e^{j30} \quad (10.8)$$

$$\underline{U}_{ST} = \underline{U}_S - \underline{U}_T = \sqrt{3} \cdot U_R \cdot e^{j270} \quad (10.9)$$

$$\underline{U}_{TR} = \underline{U}_T - \underline{U}_R = \sqrt{3} \cdot U_R \cdot e^{j150} \quad (10.10)$$

10.1

Symmetrical components

Symmetrical faults are calculated from the equivalent circuit in the positive-sequence system. The network is thereby reduced to a single conductor and drawn as a single-phase system. Three-pole short circuits load the network symmetrically. For other types of short circuits, it is no longer possible to use the positive-sequence system because the network is loaded asymmetrically. It is here that the method of symmetrical components is well suited. For each conductor of a three-phase system, the corresponding equations (currents or voltages in the conductors) are written. Asymmetrical operation can be the result of network loading, a short circuit to ground, line interruptions or switching mechanisms.

The voltages and currents at the position of the short circuit are determined by the geometrical addition of the symmetrical component currents and voltages.

With this method, the three-phase network is resolved into three independent single-phase systems, namely the positive-sequence, negative-sequence and zero-sequence systems.

The impedances of these three systems can then be given for individual operational systems at a fault position.

According to the position of the fault, unequal currents can arise in the conductors. The equivalent single-phase circuit can then no longer be used. The transformation of the original R (L1), S (L2), T (L3) to a symmetrical image space with the coordinates 1,2,0 is therefore necessary (method of symmetrical components).

The use of symmetrical components is illustrated in Figure 10.2. The procedure which the method entails will now be discussed in detail [16, 18].

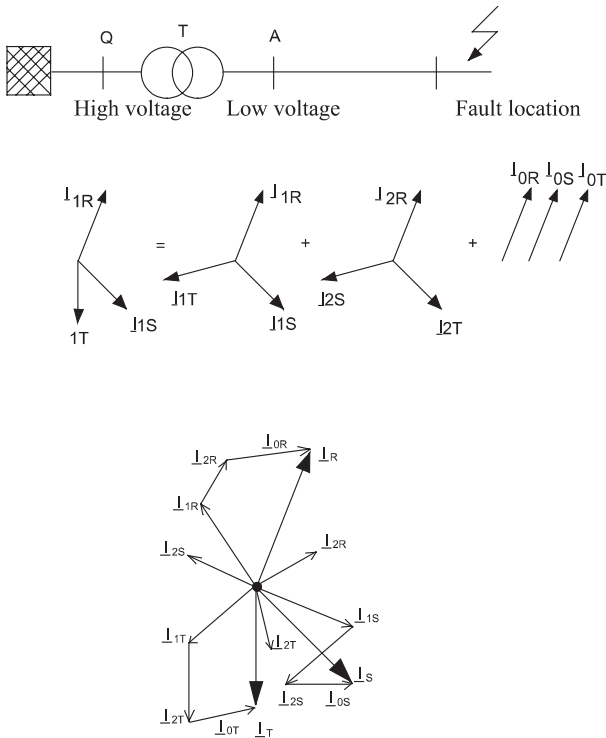


Fig. 10.2 Schematic of a three-phase network and relationship between components of positive-sequence, negative-sequence and zero-sequence systems:

Steps in calculation:

1. Draw the three-phase network with asymmetrical fault in RST space.
2. Summarize the fault conditions.
3. Draw the equivalent single-phase circuit in 120° space.
4. Calculate the currents and voltages in image space.
5. Calculate the asymmetrical fault currents in the original space.

$$\underline{I}_R = \underline{I}_{1R} + \underline{I}_{2R} + \underline{I}_{0R}, \quad (10.11)$$

$$\underline{I}_S = \underline{I}_{1S} + \underline{I}_{2S} + \underline{I}_{0S},$$

$$\underline{I}_T = \underline{I}_{1T} + \underline{I}_{2T} + \underline{I}_{0T},$$

$$\underline{I}_{0R} = \underline{I}_{0S} + \underline{I}_{0T} + \underline{I}_0. \quad (10.12)$$

Calculations in 120° space:

$$\underline{I}_{1S} = \underline{I}_{1R} \cdot \underline{a}^2, \quad (10.13)$$

$$\underline{I}_{1T} = \underline{I}_{1R} \cdot \underline{a},$$

$$\underline{I}_{2S} = \underline{I}_{2R} \cdot \underline{a},$$

$$\underline{I}_{2T} = \underline{I}_{2R} \cdot \underline{a}^2,$$

$$\underline{I}_{0R} = \underline{I}_{0S} \cdot \underline{I}_{0T}.$$

Fault currents in the original space:

$$\underline{I}_R = \underline{I}_{1R} + \underline{I}_{2R} + \underline{I}_{0R}, \quad (10.14)$$

$$\underline{I}_S = \underline{I}_{1R} \cdot \underline{a}^2 + \underline{I}_{2R} \cdot \underline{a} + \underline{I}_{0R},$$

$$\underline{I}_T = \underline{I}_{1R} \cdot \underline{a} + \underline{I}_{2R} \cdot \underline{a}^2 + \underline{I}_{0R}. \quad (10.15)$$

In matrix notation, we then have:

$$\begin{bmatrix} \underline{I}_R \\ \underline{I}_S \\ \underline{I}_T \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 1 & 1 & 1 \\ \underline{a}^2 & \underline{a} & 1 \\ \underline{a} & \underline{a}^2 & 1 \end{bmatrix} \cdot \begin{bmatrix} \underline{I}_{1R} \\ \underline{I}_{2R} \\ \underline{I}_{0R} \end{bmatrix}. \quad (10.16)$$

Inverse transformation from the image space to the original space:

$$\underline{I}_{RST} = T \cdot \underline{I}_{120} \quad (10.17)$$

With this transformation we can transform the unknown current components with the matrix T to the actual currents in the components:

$$\underline{I}_{1R} = \frac{1}{3} \cdot (\underline{I}_R + \underline{I}_S \cdot \underline{a} + \underline{I}_T + \underline{a}^2), \quad (10.18)$$

$$\underline{I}_{2R} = \frac{1}{3} \cdot (\underline{I}_R + \underline{I}_S \cdot \underline{a}^2 + \underline{I}_T + \underline{a}),$$

$$\underline{I}_{0R} = \frac{1}{3} \cdot (\underline{I}_R + \underline{I}_S + \underline{I}_T). \quad (10.19)$$

In matrix notation, this yields:

$$\begin{bmatrix} \underline{I}_{1R} \\ \underline{I}_{2R} \\ \underline{I}_{0R} \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 1 & \underline{a} & \underline{a}^2 \\ 1 & \underline{a}^2 & \underline{a} \\ 1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} \underline{I}_R \\ \underline{I}_S \\ \underline{I}_T \end{bmatrix}. \quad (10.20)$$

$$\underline{I}_{120} = S \cdot \underline{I}_{RST} \quad (10.21)$$

We are now in a position to calculate the asymmetrical currents and voltages, where:

$$S = T^{-1}. \quad (10.22)$$

10.2 Impedances of symmetrical components

Only three-phase short circuits load the network symmetrically. Here it is sufficient to calculate with the “positive-sequence system”. In all other cases it is necessary to use the method of symmetrical components in order to consider the negative-sequence and zero-sequence systems as well.

The method of symmetrical components is based on the principle of superposition. The determination of the voltage and current components requires equivalent single-phase circuits, which during symmetrical operation of the network are fully decoupled from each other.

The three impedances of the component systems are summarized here briefly (Figure 10.3).

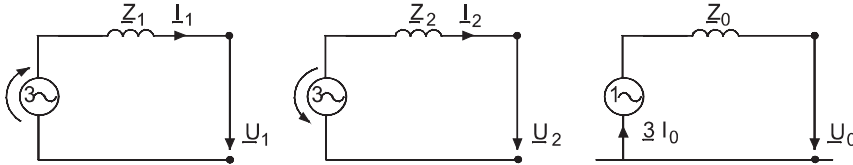


Fig. 10.3: Equivalent circuits for positive-sequence, negative-sequence and zero-sequence systems

1. Positive-phase impedance Z_1 (index m or 1)

A symmetrical positive-sequence system with normal phase angle is present. The equivalent circuit and the data for the operational equipment are identical with the data for the equivalent single-phase circuit for the calculation of the three-pole short circuit.

2. Negative-sequence impedance Z_2 (index i or 2)

A symmetrical negative-sequence system is present.

The negative-sequence impedance is the same as the positive-sequence impedance for operational equipment without load. The impedances are different when the machines are operating.

3. Zero-sequence impedance Z_0 (index 0)

A system consisting of three currents of equal value and having the same phase angle is present if we take the three main conductors connected in parallel for the outgoing line and a fourth conductor as a common return line and apply an AC voltage. Three times the zero-sequence current flows in this return line.

The circuitry of the neutral point is considered in the zero-sequence impedance as follows:

- not grounded
- grounded through a ground fault neutralizer coil
- grounded through resistances or reactance
- direct grounding.

Under the assumption that the symmetrical components for current and voltage are physically real values, then they must be related through general physical laws. It must then be possible to assign an impedance to each of the three component systems according to Ohm's law.

Positive-sequence impedance:

$$\underline{Z}_{(1)} = \frac{\underline{U}_{(1)}}{\underline{I}_{(1)}}, \quad (10.23)$$

Negative-sequence impedance:

$$\underline{Z}_{(2)} = \frac{U_{(2)}}{I_{(2)}}, \quad (10.24)$$

Zero-sequence impedance:

$$\underline{Z}_{(0)} = \frac{U_{(0)}}{I_{(0)}}. \quad (10.25)$$

Furthermore, it is possible to define equivalent circuits for the three component systems. The positive-sequence, negative-sequence and zero-sequence impedances can be determined by measurements by applying the positive-sequence, negative-sequence and zero-sequence voltages to the circuit to be measured, measuring the current and then calculating the impedance from Ohm's law. The positive-sequence impedance is identical with the impedance of a conductor in the three-phase system and is therefore the same as the impedance of an equivalent single-phase circuit in symmetrical operation. It is the sum total of the impedances in the conductor from the overland lines, machines and other components.

The negative-sequence impedance is determined as for the positive-sequence impedance, but with a negative-sequence system voltage. As can be seen from the measurement circuit in Figure 10.4, the negative-sequence impedance must be the same as the positive-sequence impedance for all passive operational equipment such as overhead lines, cables and transformers. For rotating machines, on the other hand, the negative-sequence impedance can be smaller than the positive-sequence impedance.

The zero-sequence impedance is, by definition (no phase shift of the individual components), measured single-phase and the three conductors are connected in parallel.

For imaging a symmetrical three-phase network the positive-sequence, negative-sequence and zero-sequence systems must be linked. The procedure is described in detail in the following sections. Linking requires knowledge of the source voltage. In three-phase networks, the source voltage is generated symmetrically with synchronous generators. For this reason, the source voltage appears only in the positive-sequence system and is set to the value $\frac{c \cdot U_n}{\sqrt{3}}$ for the calculations.

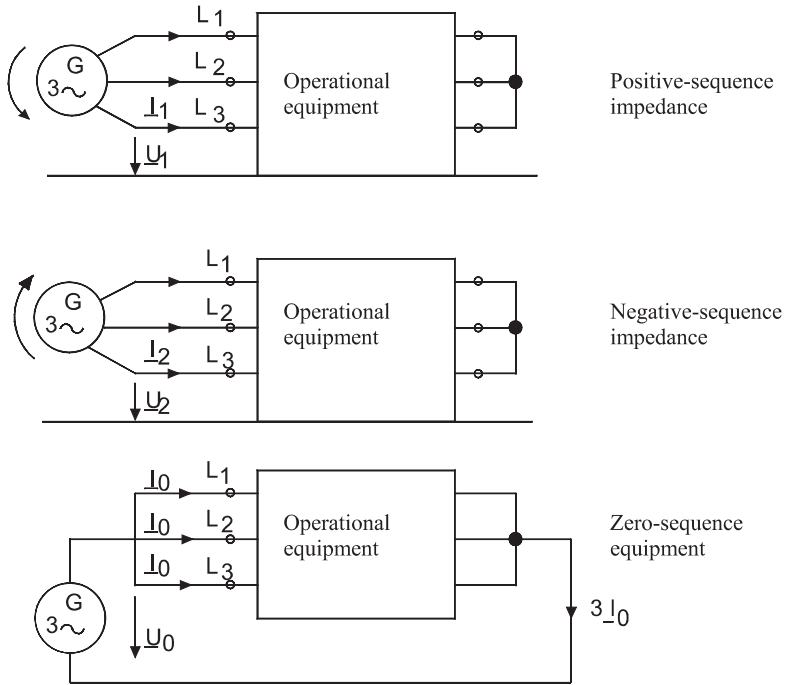


Fig. 10.4: Measuring circuits for determining the positive-sequence, negative-sequence and zero-sequence impedances

All three equivalent circuit components are connected to the fault position and for each type of fault there is a different connection (Figure 10.5).

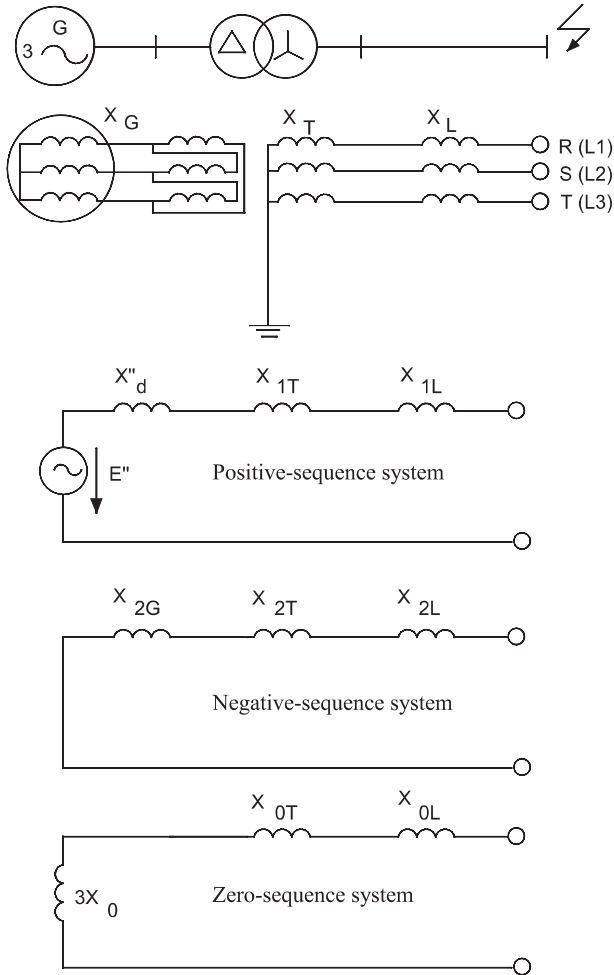


Fig. 10.5: Schematic of the equivalent circuit components

11

Calculation of Short Circuit Currents

In IEC 60 909 the different types of short circuits are clearly defined. This chapter deals with the short circuit currents and sets up the equations required to determine these currents. For the calculation RST components are used instead of L1-L2-L3, for reasons of simplification.

11.1

Three-pole short circuits

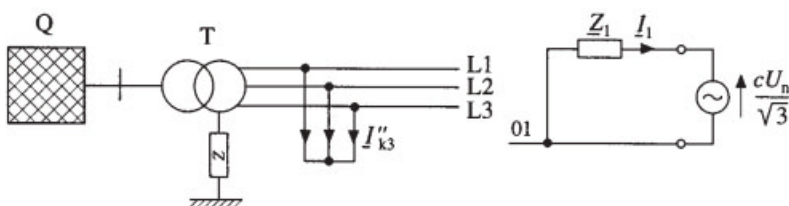


Fig. 11.1: Equivalent circuit for a three-pole short circuit with equivalent voltage source at position of fault

For the dimensioning of electrical systems it is necessary to consider three-pole short circuits in order to guarantee the mechanical and thermal stability of the systems and the rated making and breaking capabilities of the overcurrent protection equipment.

- The requirements for calculating the largest three-pole short circuit current are:
- The temperature of the conductor is 20 °C
- The network circuitry is mostly responsible for this current
- The network feeder deliver the maximum short circuit power
- The voltage factor is chosen in accordance with IEC 60 909.

The three-pole short circuit is a symmetrical fault. The following fault conditions apply for the equivalent circuit shown in Figure 11.1:

$$U_R = U_S = U_T = 0, \quad (11.1)$$

$$I_R + I_S + I_T = 0, \quad (11.2)$$

It then follows that:

$$\begin{bmatrix} \underline{U}_0 \\ \underline{U}_1 \\ \underline{U}_2 \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & \underline{a} & \underline{a}^2 \\ 1 & \underline{a}^2 & \underline{a} \end{bmatrix} \cdot \begin{bmatrix} \underline{U}_R \\ \underline{U}_S \\ \underline{U}_T \end{bmatrix}, \quad (11.3)$$

$$\underline{U}_0 = \underline{U}_1 = \underline{U}_2 = 0, \quad (11.4)$$

$$\begin{bmatrix} \underline{I}_0 \\ \underline{I}_1 \\ \underline{I}_2 \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & \underline{a} & \underline{a}^2 \\ 1 & \underline{a}^2 & \underline{a} \end{bmatrix} \cdot \begin{bmatrix} \underline{I}_R \\ \underline{I}_S \\ \underline{I}_T \end{bmatrix}, \quad (11.5)$$

For three-pole short circuits:

$$\underline{I}''_{k3} = \frac{c \cdot U_n}{\sqrt{3} \cdot \underline{Z}_1} \quad (11.6)$$

whereby for \underline{Z}_1 :

$$\underline{Z}_1 = \sqrt{(R_{1Q} + R_{1T} + R_{1L})^2 + (X_{1Q} + X_{1T} + X_{1L})^2}, \quad (11.7)$$

Or with the impedances of the individual operational equipment:

$$\underline{Z}_1 = \underline{Z}_{1Q} + \underline{Z}_{1T} + \underline{Z}_{1L}. \quad (11.8)$$

11.2

Two-pole short circuits with contact to ground

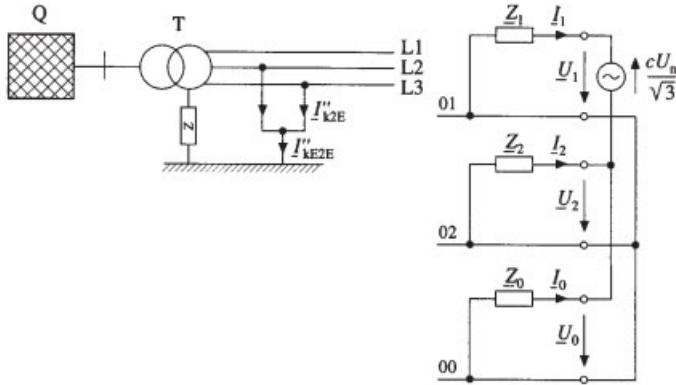


Fig. 11.2: Equivalent circuit of a two-pole short circuit with contact to ground

This represents the general case of a two-pole short circuit. As can be seen from Figure 11.2, for the two-pole short circuit the following boundary conditions apply:

$$\underline{I}_R = 0, \quad \underline{I}_S = \underline{I}_T, \quad \underline{I}_{kE2E} = \underline{I}_S + \underline{I}_T, \quad \underline{U}_S = \underline{U}_T = 0.$$

$$\underline{I}''_{kE2E} = \frac{\sqrt{3} \cdot c \cdot U_n}{|Z_1 + 2Z_0|} \quad (11.9)$$

11.3

Two-pole short circuit without contact to ground

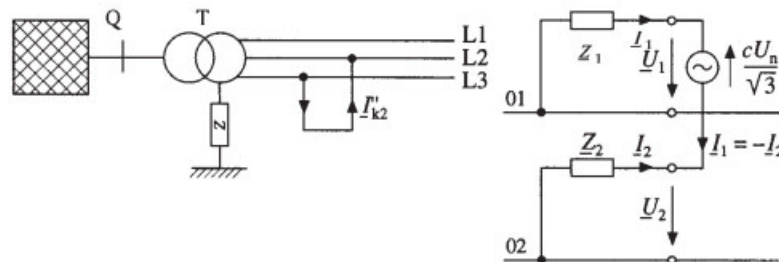


Fig. 11.3: Equivalent circuit of a two-pole short circuit without contact to ground

According to Figure 11.3, a two-pole fault without contact to ground should occur between the two conductors.

For the equations giving the currents:

$$I_S = -I_T, \quad I_R = 0$$

The zero-sequence system current is zero, because no current flows through ground, i.e. $I_0 = 0, U_0 = 0$.

For a two-pole short circuit current, this results in:

$$I''_{k2} = \frac{c \cdot U_n}{|Z_1 + Z_2|} \tag{11.10}$$

$$I''_{k2} = \frac{\sqrt{3}}{2} I''_{k3} \tag{11.11}$$

The voltage system for a two-pole short circuit shifts in such a way that the voltage on the third, fault-free conductor, in this case U_R , remains unchanged.

Two-pole short circuit currents without contact to ground can be larger with powerful asynchronous motors than for three-pole short circuits.

11.4
Single-pole short circuits to ground

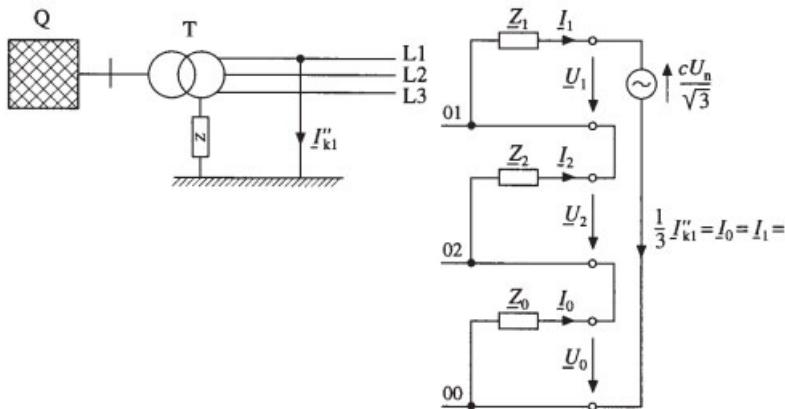


Fig. 11.4: Equivalent circuit of single-pole short circuit to ground

The single-pole short circuit current occurs frequently in electrical networks. Its calculation is necessary in order to ensure

- The maximum conductor lengths (IEC 60 364 Part 52)
 - Protection against indirect contact (IEC 60 364 Part 41)
 - Protection against thermal stress (IEC 60 364 Part 43)
- Calculating the smallest short circuit current requires that:
- The voltage factor used is taken from IEC 60 909
 - Motors can be neglected
 - In low voltage networks the temperature of the conductors is set to 80 °C
 - Setting up the network so that the smallest I''_{k1min} flows.

For the component systems shown in Figure 4, we can then use the values:

$$\underline{I}_S = \underline{I}_T = 0, \quad \underline{I}''_{k1} = \underline{I}_R, \underline{U}_R = 0.$$

Since the currents in the positive-sequence, negative-sequence and zero-sequence systems are identical, this means that the three systems must be connected in series. For the current, then:

$$3 \cdot \underline{I}_0 = \underline{I}_R + \underline{I}_S + \underline{I}_T \quad (11.12)$$

$$\underline{I}_{1R} = \underline{I}_{2R} = \underline{I}_0 \quad (11.13)$$

$$\underline{I}_R = \underline{I}_{1R} + \underline{I}_{2R} + \underline{I}_{0R} = 3 \cdot \underline{I}_{1R} \quad (11.14)$$

$$\underline{I}_{1R} = \frac{\underline{E}''}{\underline{Z}_1 + \underline{Z}_2 + \underline{Z}_0} \quad (11.15)$$

$$\underline{I}_R = \frac{3 \cdot \underline{E}''}{\underline{Z}_1 + \underline{Z}_2 + \underline{Z}_0} \quad (11.16)$$

Using the relationship

$$\underline{E}'' = \frac{3 \cdot U_n}{\sqrt{3}} \quad (11.17)$$

it follows for a single-pole short circuit under the condition $Z_1 = Z_2$ that

$$I''_{k1min} = \frac{\sqrt{3} \cdot c_{min} \cdot U_n}{|2Z_1 + Z_0|} \quad (11.18)$$

For the loop impedance of the short circuit:

$$I''_{k1min} = \frac{c_{min} \cdot U_n}{\sqrt{3} \cdot Z_s} \quad (11.19)$$

Equating the right sides of equations 11.18 and 11.19 yields:

$$Z_s = \frac{2Z_1 + Z_0}{3} \quad (11.20)$$

According to IEC 60 909,

$$I''_{k1min} = \frac{\sqrt{3} \cdot c_{min} \cdot U_n}{\sqrt{(2R_{1Q} + 2R_{1T} + 2R_{1L} + R_{0T} + R_{0L})^2 + (2X_{1Q} + 2X_{1T} + 2X_{1L} + X_{0T} + X_{0L})^2}} \quad (11.20)$$

Equations 11.18, 11.19 and 11.21 are identical and give the same result for the calculation of I''_{k1min} .

For asymmetrical short circuits, the largest short circuit current can be determined with the aid of Figure 11.5 and depends on the network design. The double ground fault I''_{kEE} is not included in this figure, because it leads to smaller short circuits than the two-pole short circuit. The ranges of the different types of short circuits according to the neutral point treatment are indicated in this diagram. The phase angles of the impedances Z_1 , Z_2 and Z_0 in this figure must not differ by more than 15° .

The symbols in Figure 11.5 have the meanings:

$k2$ Two-pole short circuit current

$k3$ Three-pole short circuit current

$k2E$ Two-pole short circuit current without contact to ground

$k1$ Single-pole ground fault current

δ Ground fault factor

$a = \frac{\text{Short circuit current for asymmetrical short circuit}}{\text{Short circuit current for three-pole short circuit}}$

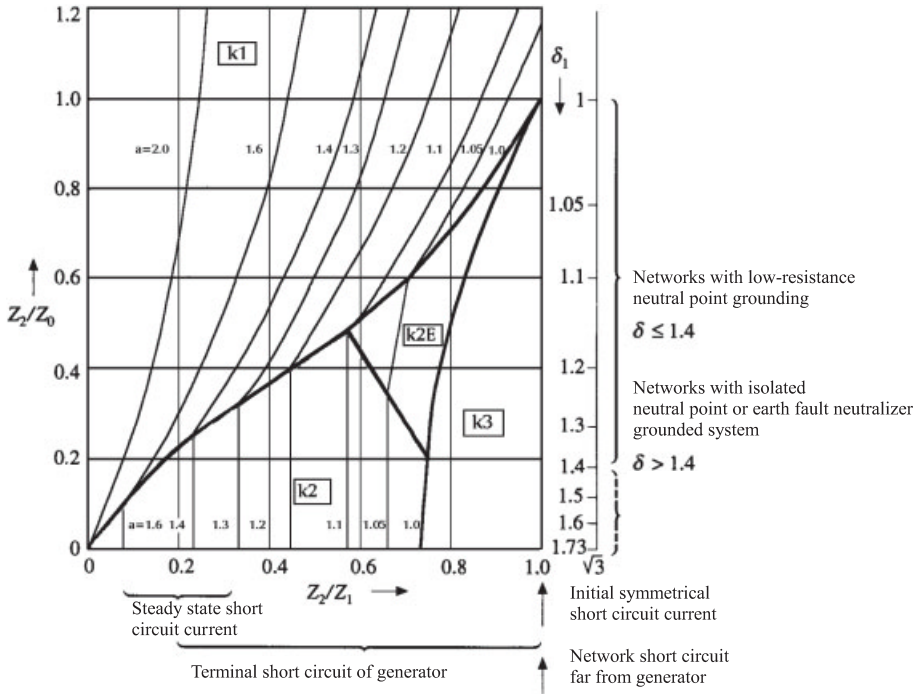


Fig. 11.5: Largest short circuit currents for asymmetrical short circuits [1, 6]

11.5
Peak short circuit current i_p

The initial short circuit current I_k'' and the withstand ratio κ determine the peak short circuit current i_p . The factor κ depends on the ratio R/X of the short circuit path and takes account of the decay of the DC aperiodic component in the short circuit. The peak value i_p occurs during the period immediately following the occurrence of the short circuit (transient period). If the ratio R/X is known, the factor κ can be read from the curves in Figure 11.6.

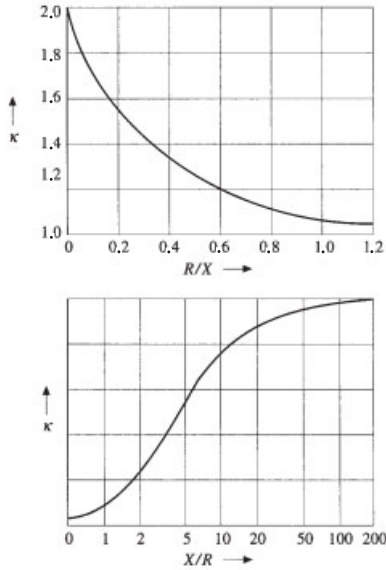


Fig. 11.6: Factor κ for calculating the peak short circuit current i_p [1]

The peak short circuit current calculated determines the dynamic loading of electrical systems.

The peak short circuit current can be calculated in unmeshed networks from the equation:

$$i_p = \kappa \cdot \sqrt{2} I_k'' \tag{11.22}$$

Standard values:

$\kappa < 1.4$: in public networks

$\kappa \leq 1.8 \dots 2.04$: immediately downstream from transformer feeder

κ can also be calculated from the following equation:

$$\kappa = 1.02 + 0.98 \cdot e^{-3 \frac{R}{X}} \tag{11.23}$$

The peak short circuit current i_p can be calculated in all networks using the basic equation $i_p = \kappa \sqrt{2} I_k''$. With the three following procedures it is possible to determine the factor κ in meshed networks [4].

- Procedure A ($\kappa = \kappa_a$):
 κ is determined from the smallest R/X ratio of all branches in the network.
 In low voltage networks, $\kappa \leq 1.8$.

- Procedure B ($\kappa = 1.15\kappa_b$):
 κ is determined from the R/X ratio of the short circuit impedance at the position F of the short circuit and multiplied by a safety factor of 1.15 in order to take account of different R/X ratios in parallel branches.
 1. For low voltage networks: $\kappa \leq 1.8$.
 2. For medium and high voltage networks: $\kappa \leq 2.0$.
- Procedure C ($\kappa = \kappa_c$):
 With procedure C, κ is determined with an equivalent frequency, as below:
 1. Calculation of reactances for all network branches i for the equivalent frequency f_c in the positive-sequence system:

$$X_{ic} = \frac{f_c}{f} X_i.$$

f : nominal frequency – 50 Hz, 60 Hz

f_c : equivalent frequency – 20 Hz, 24 Hz.

2. Calculation of equivalent impedance at the position of the short circuit from the resistances R_i and the reactances X_i of the network branches in the positive-sequence system:

$$\underline{Z}_c = R_c + j X_c.$$

3. Determination of the factor κ_c from the ratio:

$$\frac{R}{X} = \frac{f_c}{f} \frac{R_c}{X_c}.$$

11.6

Symmetrical breaking current I_a

The symmetrical breaking current is the effective value of the short circuit current I_k'' (t), which flows through the switch at the time of the first contact separation and is used for near-to-generator short circuit feeder. For far-from-generator short circuits, the breaking currents are identical with the initial short circuit currents:

$$I_a = \mu \cdot I_k'' \quad (11.24)$$

Synchronous machines

$$I_a = \mu I_{kG}'' \quad (11.25)$$

I_a depends on the duration of the short circuit and the installation position of the switchgear at the position of the short circuit. μ characterizes the decay behavior of the short circuit current and is a function of the variables I_{kG}''/I_{rG}'' and t_{min} (Figure 11.7).

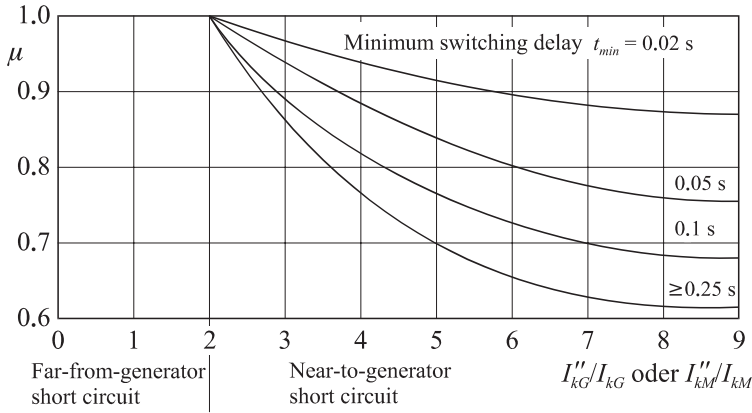


Fig. 11.7: Factor μ for calculating the symmetrical breaking current I_a [1]

The factor μ can be taken from Fig. 11.7 or from the following equations.

$$\mu = 0.84 + 0.26 e^{-0.26} I''_{kG}/I_{rG} \quad \text{for } t_{min} = 0.02 \text{ s}$$

$$\mu = 0.71 + 0.51 e^{-0.30} I''_{kG}/I_{rG} \quad \text{for } t_{min} = 0.05 \text{ s}$$

$$\mu = 0.62 + 0.72 e^{-0.32} I''_{kG}/I_{rG} \quad \text{for } t_{min} = 0.10 \text{ s}$$

$$\mu = 0.56 + 0.94 e^{-0.38} I''_{kG}/I_{rG} \quad \text{for } t_{min} = 0.25 \text{ s}$$

$$\mu_{max} = 1$$

When $I_a = I''_k$, then $\mu = 1$, i.e. a far-from-generator short circuit is present, if for each synchronous machine the following condition is satisfied:

$$\frac{I''_{k3}}{I_{rG}} \leq 2. \tag{11.26}$$

For $I_a < I''_k$, i.e. a near-to-generator short circuit:

$$\frac{I''_{k3}}{I_{rG}} \geq 2. \tag{11.27}$$

In practice:

The minimum switching delay is 0.1 s.

Asynchronous machines

$$I_a = \mu \cdot q \cdot I''_{kM}. \quad (11.28)$$

The factor q depends on the power per pole pair.

Networks

$$I_{aQ} = I''_{kQ}. \quad (11.29)$$

More exact procedure for calculation of symmetrical breaking current in meshed networks [1]

$$I_a = I''_k - \sum_i \frac{\Delta U''_{Gi}}{c \cdot U_n / \sqrt{3}} (1 - \mu_i) \cdot I''_{kGi} - \sum_j \frac{\Delta U''_{Mj}}{c \cdot U_n / \sqrt{3}} (1 - \mu_j \cdot q_j) \cdot I''_{kMj} \quad (11.30)$$

With:

$$\Delta U''_{Gi} = jX''_{di} \cdot I''_{kGi} \quad (11.31)$$

$$\Delta U''_{Mj} = jX''_{Mj} \cdot I''_{kMj} \quad (11.32)$$

Figure 11.8 shows the dependence of the factor q on the effective power per pole pair of the motor and the minimum switching delay t_{min} . For the equations used in calculating q , see IEC 60 909.

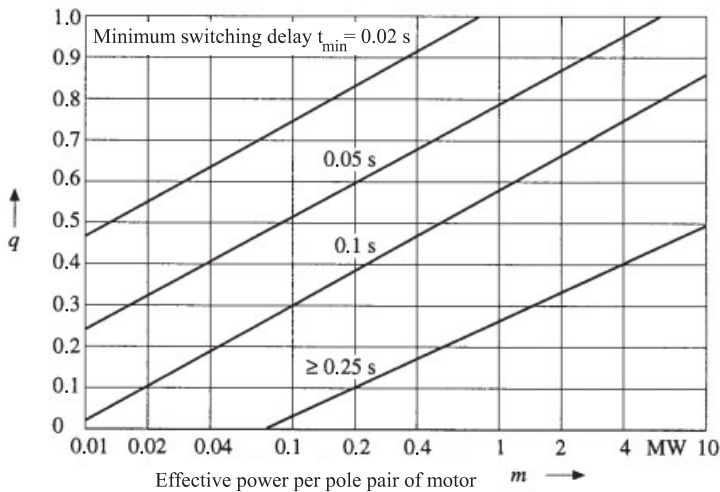


Fig. 11.8: Factor q for calculation of the symmetrical breaking current for asynchronous machines [1]

The factor q applies to induction motors and takes account of the rapid decay of the motor short circuit owing to the absence of an excitation field. It can be taken from Fig. 11.8 or from the following equations.

$$q = 1.03 + 0.12 \ln m \quad \text{for } t_{\min} = 0.02 \text{ s}$$

$$q = 0.79 + 0.12 \ln m \quad \text{for } t_{\min} = 0.05 \text{ s}$$

$$q = 0.57 + 0.12 \ln m \quad \text{for } t_{\min} = 0.10 \text{ s}$$

$$q = 0.26 + 0.12 \ln m \quad \text{for } t_{\min} = 0.25 \text{ s}$$

$$q_{\max} = 1$$

The meanings of the symbols are:

i Generator

j Motor

$\Delta U''_{Gi}$ Initial voltage difference at connection to synchronous machine i

$\Delta U''_{Mj}$ Initial voltage difference at connection to asynchronous machine j

$\frac{c U_{\mu}}{\sqrt{3}}$ Equivalent voltage source at position of short circuit

$I_a I''_k$ Symmetrical breaking current, initial symmetrical short circuit current considering all network inputs, synchronous machines and asynchronous machines

I''_{kGi} Initial symmetrical short circuit current of synchronous machine

I''_{kMj} Initial symmetrical short circuit current of asynchronous machine

μ_j Factor j for asynchronous machines

μ_i Factor i for synchronous machines

q_i Factor j for asynchronous machines

11.7

Steady state short circuit current I_k

The steady state short circuit current is the effective value of the short circuit current I''_k remaining after the decay of all transient processes. It depends strongly on the excitation current, excitation system and saturation of the synchronous machine:

For near-to-generator short circuits: $I_k < I''_k$.

For far-from-generator short circuits: $I_k = I''_k = I_a$.

The following relationships show a dependence on the fault position:

$$I_k = \lambda I_{rG}, \quad (11.33)$$

$$I_k = I''_{k2},$$

$$I_k = \lambda \cdot \sqrt{3} \cdot I_{rG}. \quad (11.34)$$

The factor λ depends on I''_{kG}/I_{rG} , the excitation and the type of synchronous machine.

For the steady state short circuit current, we distinguish between:

- $I_{kmax} = \lambda_{max} \cdot I_{rG}$ (maximum excitation) and
- $I_{kmin} = \lambda_{min} \cdot I_{rG}$ (constant unregulated excitation).

The upper and lower limits of λ can be taken from Figure 11.9. It should also be pointed out that the λ curves depend on the ratio of the maximum excitation voltage to the excitation voltage under normal load conditions (Series 1 and 2).

The following statements can be made for Series 1 and 2 [1]:

Series 1: The largest possible excitation voltage is 1.3 times the rated excitation voltage for the rated apparent power factor for turbo-generators or 1.6 times the rated excitation voltage for salient pole generators.

Series 2: The largest possible excitation voltage is 1.6 times the rated excitation voltage for the rated apparent power factor for turbo-generators or 1.3 times the rated excitation voltage for salient pole generators.

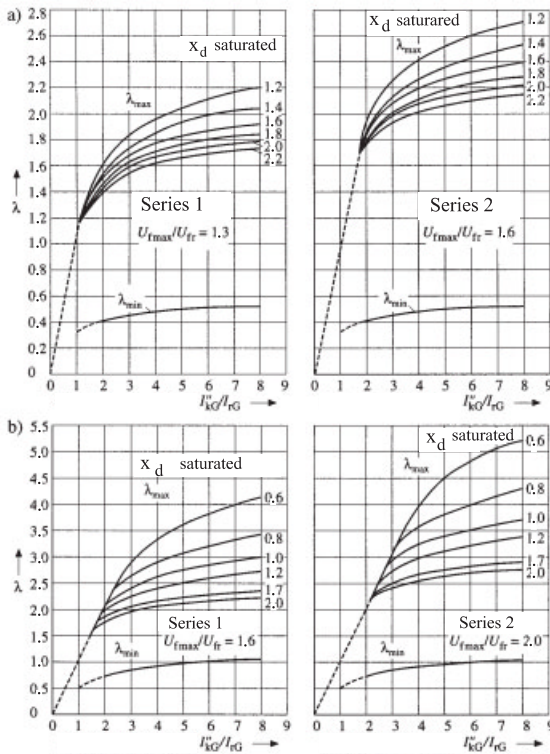


Fig. 11.9: Factors λ_{min} and λ_{max} for calculating the steady state short circuit current I_k [1]

12

Motors in DS Networks

Asynchronous motors are used mostly in industry and for the internal consumption of power stations. For a short circuit, these deliver a part of the initial short circuit current, peak short circuit current, symmetrical breaking current and, for single-pole faults, of the steady state short circuit current as well. The peak short circuit part of the asynchronous motors must be considered. For the calculation of squirrel-cage motors and wound rotor motors there is no difference, since the starting resistors of wound rotor motors are short-circuited during operation. In the following cases, asynchronous motors can be neglected for the calculation of short circuit currents [1]:

- Asynchronous motors in public low voltage networks
- Contributions of asynchronous motors or motor groups which are less than 5% of the initial symmetrical short circuit current without motors
- Asynchronous motors which due to interlocking or type of process control cannot operate at the same time
- Groups of low voltage asynchronous motors which can be combined through their connection cables to an equivalent motor with $\frac{I_{an}}{I_{rM}} = 5$ and $\frac{R_M}{X_M} = 0.42$
- Asynchronous motors can be neglected for single-pole short circuits.

Various connection variants for asynchronous motors in industrial networks will be discussed in the following.

12.1

Short circuits at the terminals of asynchronous motors

The contribution of an asynchronous machine (Figure 12.1) can, in accordance with IEC 60 909, be neglected provided that:

$$I''_{kM} \leq 0.05 \cdot I''_{kQ}, \quad (12.1)$$

$$I''_{kM} = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_M} = \frac{I_{an}}{I_{rM}} \cdot \frac{c \cdot U_n}{U_{rM}^2} \cdot I_{rM}. \quad (12.2)$$

The impedance Z_M of an asynchronous machine in the positive-sequence and negative-sequence systems is calculated from the relationships:

$$Z_M = \frac{1}{\frac{I_{an}}{I_{rM}}} \cdot \frac{U_{rM}}{\sqrt{3} \cdot I_{rM}} = \frac{1}{\frac{I_{an}}{I_{rM}}} \cdot \frac{U_{rM}^2}{S_{rM}}, \quad (12.3)$$

$$Z_M = \frac{\eta_{rM} \cdot \cos \varphi_{rM}}{\frac{I_{an}}{I_{rM}}} \cdot \frac{U_{rM}}{P_{rM}}. \quad (12.4)$$

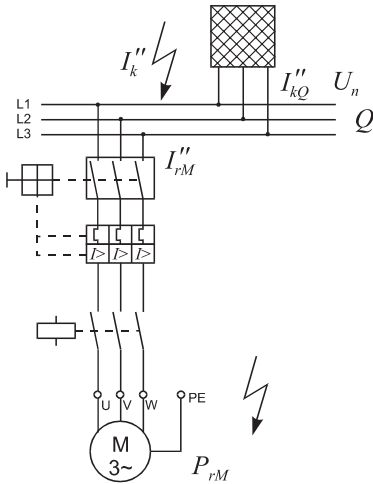


Fig. 12.1: Short circuit at the terminals of an asynchronous motor

Motor groups (Equation 12.1) can be neglected with the assumptions $I_{an}/I_{rM} = 5$ and $c \cdot U_n/U_{rM} \approx 1$:

$$\sum I_{rM} \leq 0.01 I_k''. \quad (12.5)$$

The reactances and resistances can be calculated from the following equations [5]:
For medium voltages with effective power P_{rM} per pole pair ≥ 1 MW:

$$\frac{R_M}{X_m} = 0.10 \text{ mit } X_M = 0.995 \cdot Z_M \quad (12.6)$$

For medium voltage motors with effective power P_{rM} per pole pair < 1 MW:

$$\frac{R_M}{X_m} = 0.15 \text{ mit } X_M = 0.989 \cdot Z_M \quad (12.7)$$

For low voltage motors, including motor connection cable:

$$\frac{R_M}{X_m} = 0.42 \text{ mit } X_M = 0.922 \cdot Z_M \quad (12.8)$$

12.2

Motor groups supplied from transformers with two windings

High voltage and low voltage motors which supply short circuit currents to the short-circuit location Q (Figure 12.2) can be neglected provided that:

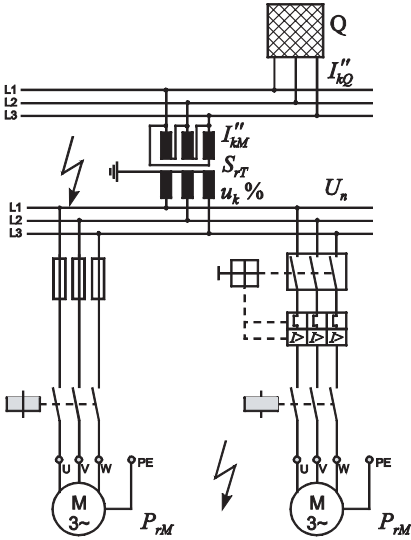


Fig. 12.2: Motor groups supplied from transformers with two windings

$$\frac{\sum P_{rM}}{\sum S_{rT}} \leq \frac{0.8}{\left| \frac{c \cdot 100 \sum S_{rT}}{S''_{kQ}} - 0.3 \right|} \quad (12.9)$$

When this condition is satisfied, asynchronous motors contribute less than 5 % to the short circuit current without motors.

For equation 12.9: $I_{an}/I_{rM} = 5$, $\cos\varphi \cdot \eta_\sigma = 0.8$ and $u_{kr} = 6\%$.

12.3:

Motor groups supplied from transformers with different nominal voltages

High voltage and low voltage motors supplied from transformers with different nominal voltages must be considered (Figure 12.3).

$$\sum I''_{kM} = I''_{kM1} + I''_{kM2} + I''_{kMn}, \quad (12.10)$$

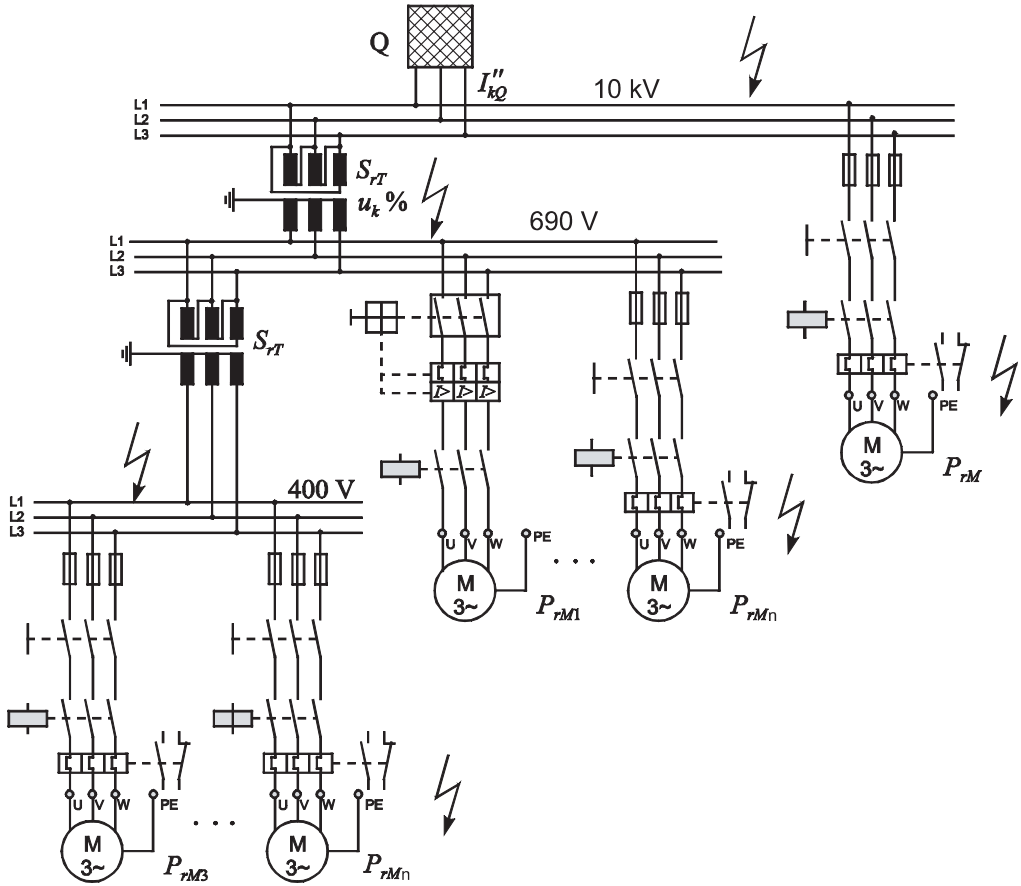


Fig. 12.3: Motor groups supplied from transformers with different nominal voltages

$$\sum S_{rT} = S_{rT1} + S_{rT2} + \dots + S_{rTn}, \quad (12.11)$$

$$\sum P_{rM} = P_{rM1} + P_{rM2} + \dots + P_{rMn}, \quad (12.12)$$

$$\frac{\sum R_{rM}}{\sum S_{rT}} \leq \frac{\cos\varphi_r \cdot \eta_r}{\left| \frac{I_{an}}{I_{rM}} \left(\frac{c \cdot \sum S_{rT}}{0.05 \cdot S''_{kQ}} - \frac{u_{kr}}{100\%} \right) \right|}. \quad (12.13)$$

Equation 12.13 is true only when the conditions of Section 12.2 no longer apply.

The meanings of the symbols are:

| | |
|-----------------|---|
| I_{ah} | Locked-rotor current of motor |
| I''_k | Initial symmetrical short circuit current without influence of motors |
| S''_{kQ} | Initial symmetrical short circuit power without influence of motors |
| $\sum I_{rM}$ | Sum of rated currents of motors |
| U_{rM} | Rated voltage of motor |
| I_{rM} | Rated current of motor |
| I_{ah}/I_{rM} | Ratio of locked-rotor current to rated current for motor |
| $\sum P_{rM}$ | Sum of rated effective powers of motors |
| $\sum S_{rM}$ | Sum of rated apparent powers of transformers is between 4 and 8 |
| R_M/X_M | : 0.42 (when motor power is neglected) |
| Z_M | Short circuit reactance |

Table 12.1 shows a summary of short circuits at the terminals of induction motors.

Table 12.1 Calculation of short circuits at the terminals of motors

| Short circuit type | Three-phase short circuit | Two-phase short circuit |
|--|--|--|
| Initial symmetrical short circuit | $I''_{k3M} = \frac{c U_n}{\sqrt{3} Z_M}$ | $I''_{k2M} = \frac{\sqrt{3}}{2} I''_{k3M}$ |
| Maximum asymmetrical short circuit current | $i_{p3M} = \kappa_M \sqrt{2} I''_{k3M}$ | $i_{p2M} = \frac{\sqrt{3}}{2} i_{p3M}$ |
| Symmetrical breaking current | $I_{b3M} = \mu q I''_{k3M}$ | $I_{b2M} \approx \frac{\sqrt{3}}{2} I''_{k3M}$ |
| Steady-state short circuit current | $I_{k3M} \approx 0$ | $I_{k2M} \approx \frac{1}{2} I''_{k3M}$ |

13

Mechanical and Thermal Short Circuit Strength

The dimensioning of electrical power installations with respect to stability against mechanical and thermal stresses is described exactly in EN 60 865-1 [8]. The present chapter gives a brief account of this information.

Electrical systems are subjected to mechanical and thermal stresses as a result of short circuits.

Bus bars, switchgear and contactors can be destroyed. Due to the evolution of heat the operational equipment and the insulation of conductors and cables are affected. Furthermore, the potential hazards for and injuries to the operating personnel must be considered.

In order to keep short-circuits under control, these systems must be designed and dimensioned so that the operational equipment is able to withstand short circuit conditions.

Here, the construction of the system components and the short circuit current strength are especially important. The short circuit strength is the sum total of all considerations for the prevention of and control over the mechanical consequences of short circuit currents and of the Joule heating which results.

The amount of heat generated over the duration of the short circuit must not exceed the permissible values for cables, conductors and operational equipment.

13.1

Mechanical short circuit current strength

Collecting bars, parallel conductors, switchgear and fuses must be able to withstand the short circuit and the resulting peak short circuit current occurring.

As a result of the magnetic field generated, parallel conductors separated by a distance they attract each other when their currents flow in the same direction and repel each other when their currents flow in opposite directions, whereby these forces are distributed uniformly over the length of the conductors l .

The manufacturers of operational equipment test their products for normal load conditions and for stability under the faulty operating conditions caused by a short circuit. At this point it is useful to briefly discuss the individual circuit breakers and devices used in electrical systems:

- Circuit breakers

The rated short circuit making and breaking capacities are normally given by the manufacturer for the better assessment of short circuit strength. These specified numerical values must be larger than the calculated short circuit value of the short circuit current at the location of the fault.

The contacts and mechanical parts must be able to withstand the short circuit current. The circuit breakers are provided for breaking overload and short circuit currents, for which numerical values can be set accordingly. EN 60 947 (IEC 947) describes the characteristics of low voltage switches and IEC 282-1, IEC 17A the characteristics of high voltage switches.

- Fuses

Fusible links are the oldest forms of protective equipment and are of great importance in certain cases. The principle of these protective devices is based on a rupture joint, e.g. a piece of wire, which melts with the application of a certain amount of heat given by $\int i^2 dt$. The type of time-current characteristic (function class) and the construction determine the locations for use. They are often used as backup protection or as the main protection in a system. The new version of IEC 269-1 describes the regulations for all fuse types.

- Disconnectors, load interrupter switches and load-break switches

In the low voltage range load interrupters are mostly used as disconnect switches for the load circuits which break only operating currents, that is currents under normal load, with an inductive power factor of 0.7. These switches are not able to break short circuit currents and are therefore used together with fuses. By contrast with load interrupter switches load-break switches, which produce a visible isolating distance, are used in the medium voltage range.

13.2

Thermal short circuit current strength

The operational equipment (busbars, insulators, wires or cables) must be protected against the effects of short circuit currents), i.e. the systems must be short circuit proof. The effect of forces acting on conductors with current flowing is of great interest here. Figure 13.1 depicts the effects of forces acting on busbars and parallel conductors.

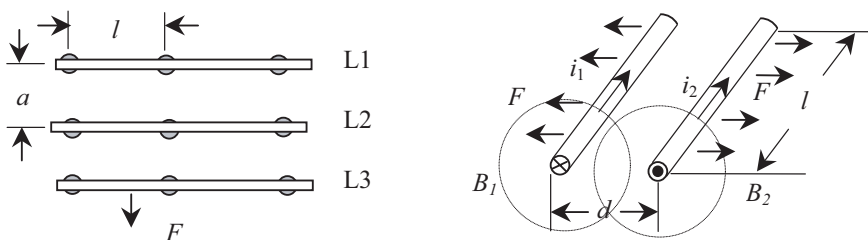


Fig. 13.1: Effects of forces acting on busbars and parallel conductors

In the magnetic field a force acts on the conductors while current is flowing. This force depends on the flux density B , the current intensity I and the length l of the conductor. Two parallel conductors in which current is flowing attract each other when the currents are flowing in the same direction and repel each other when the currents are flowing in opposite directions.

$$F = B \cdot l \cdot I$$

This force is greatest for a double-pole short circuit without contact to ground and for a three-pole short circuit. The maximum force occurring between two conductors is proportional to the square of the current, i.e. $F \sim i^2$. The greatest force acting on the conductors is calculated from the equation. For the current, the effective peak short circuit current i_p is used.

It will be obtained:

$$F_M = \frac{\mu_0}{2\pi} i_p^2 \frac{l}{a_m}$$

or with the constant evaluated

$$F_M = 0.2 i_{p2}^2 \frac{l}{a_m} \text{ or } F_H = 0.17 i_{p3}^2 \frac{l}{a_m}$$

The force between neighboring conductor elements is

$$F_M = \frac{\mu_0}{2\pi} \left(\frac{i_p}{n} \right)^2 \frac{l_s}{a_s}$$

The meanings of the symbols are:

F_M Force for the main conductor in N

B Magnetic induction in T

i Peak short circuit current in kA

l Greatest support spacing in cm

a_m Effective main conductor spacing in cm

μ_0 Permeability constant *abilitätskonstante* ($4\pi \cdot 10^{-7}$ Vs/Am)

n Number of conductors

l_s Greatest center-to-center distance between two neighboring conductor elements in cm

a_s Effective spacing between conductor elements in cm

The forces between the conductor elements in which a short circuit current flows depend on the geometrical arrangement and the profile of the conductors. This is why effective spacings have been introduced in the equation (EN 61660-1).

The effective spacing a_m is determined from:

$$a_m = \frac{a}{k_{12}}$$

The correction factor k_{12} is given in the Figure 13.2.

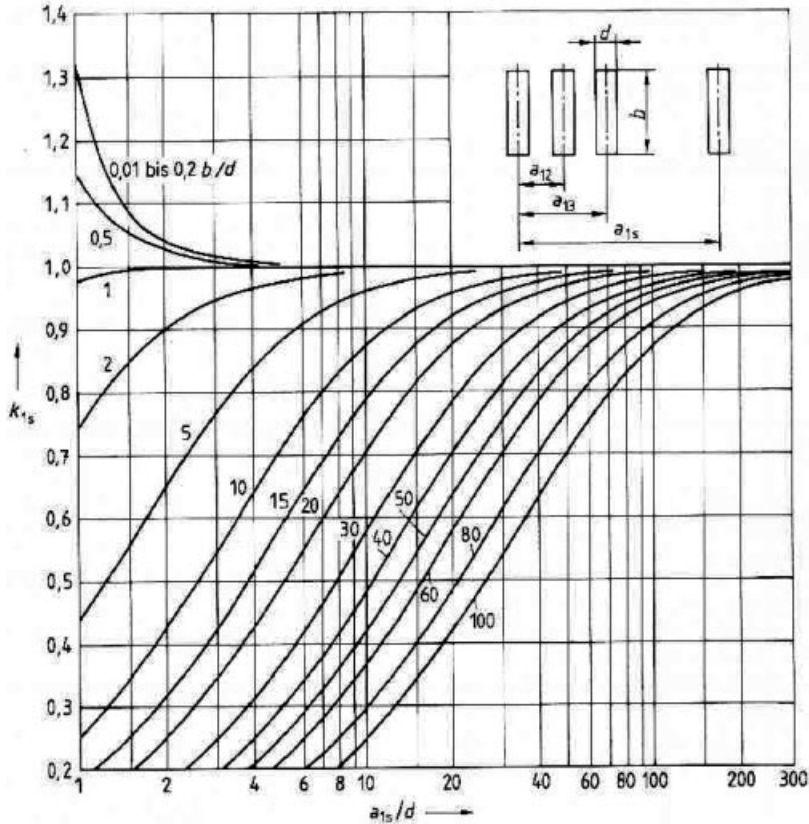


Fig. 13.2: Correction factor k_{12} for the determination of the effective conductor spacing a_m

As the diagram shows, the force is reduced because $k_{12} < 1$ for permanently installed flat ($b/d > 1$). On the other hand, the effect of the force increases slightly because $k_{12} > 1$ for neighboring bars.

The force leads to bending stress in rigid conductors, to tensile stress and deflection in conducting cables and to transverse loading, compressive loading or tensile loading of the support points. The conductors can be clamped, supported or a combination of both and have several support points. The short circuit loading of the busbars with respect to bending is calculated according to the laws of rigidity, so that:

$$M = \frac{F_M \cdot l}{8}$$

The meanings of the symbols are:

- F_M Force due to the short circuit current in N
- M Bending moment in Ncm
- l Support spacing in cm

The bending stress can then be determined using the moment of resistance, i.e.

$$\sigma_H = \frac{\nu_\sigma \cdot \beta \cdot M}{W}$$

The bending stress σ must always be less than the permissible bending stress σ_{per} .

$$\sigma_H \leq \sigma_{per}$$

The bending stress for several conductor elements can be calculated from

$$\sigma_M = \frac{\nu_\sigma \cdot \beta \cdot M}{W_T}$$

The permissible total bending stress of the main (σ_M) conductor and the conductor elements (σ_T) is then

$$\sigma_G = \sigma_M + \sigma_T$$

The dynamic force acting at each support point of the rigid conductors is calculated from

$$F_d = V_F V_r \alpha F$$

For dc systems:

$$V_F V_r = 2$$

Für one-phase ac systems:

$$V_F V_r \leq 2$$

For three-phase systems:

$$V_F V_r \leq 2.7$$

The meanings of the symbols are:

- σ Bending stress in N/cm²
- ν Frequency factor (Table 13.2)
- β Factor for loading of the main conductor (Table 13.2)
- α Depends on type and number of support points (Table 13.2)
- M Bending moment in Ncm
- W Moment of resistance in cm⁴

The moments of resistance and moments of inertia of different tubular profiles can be taken from Table 13.1.

Table 13.1: Moments of resistance and moments of inertia

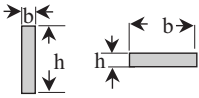
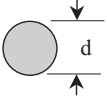
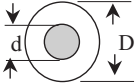

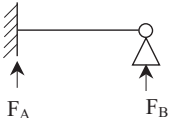
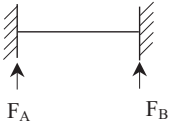
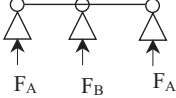
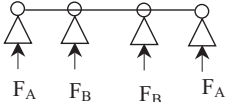
| Representation | Moment of resistance in cm^4 | Moment of inertia in m^3 |
|---|----------------------------------|--|
|  | $I = \frac{b \cdot h^3}{12}$ | $W = \frac{b \cdot h^2}{6}$ |
|  | $I = \frac{\pi \cdot d^4}{64}$ | $W = \frac{\pi \cdot d^3}{32}$ |
|  | $I = \frac{\pi}{64} (D^4 - d^4)$ | $W = \frac{\pi}{32} \frac{(D^4 - d^4)}{D}$ |

Table 13.2: Factors α and β for different support point arrangements

| Type of support | Type of attachment | | Factor α | Factor β | Factor ν |
|--|--------------------------|---|----------------------|----------------|--------------|
| Single-field support | A and B supported |  | A: 0.5 B: 0.5 | 1.0 | 1.57 |
| | A clamped B supported |  | A: 0.625 B: 0.375 | 0.73 | 2.45 |
| | A and B clamped |  | A: 0.5 B: 0.5 | 0.5 | 3.56 |
| Multi-field support with uniform support spacing | 2 fields |  | A: 0.375 B: 1.25 | 0.73 | 2.45 |
| | 3 or more fields |  | A: 0.4 B: 1.1 | 0.73 | 3.56 |

The busbar arrangement must be checked for mechanical resonance. The natural mechanical oscillating frequency must not be close to the simple, double or triple network frequency, since this would lead to damage as a result of resonance. For the natural mechanical oscillating frequency, then:

$$f_0 = 112 \cdot \sqrt{\frac{E \cdot I}{G \cdot l^4}}$$

The meanings of the symbols are:

- f_0 Natural oscillating frequency in s-1
- E Modulus of elasticity of the busbar material
for Cu: $1.1 \cdot 10^6$ kg/cm², for Al: $0.65 \cdot 10^6$ kg/cm²
- I Moment of inertia in cm⁴ [Table 13.1]
- G Weight of bar in kg/cm

Switches, conductors and transformers must as a result of short circuit currents be dimensioned with regard to thermal effects as well. It must be checked whether the thermal equilibrium short-time withstand current I_{th} is correctly determined. The magnitude and the behavior in time of the short circuit current determines the effective short-time withstand current, the effective value of which produces the same quantity of heat as the changing short circuit current during the duration of the short circuit T_K in its DC aperiodic and AC periodic current components. The thermal short circuit current can be calculated from the effective value of the initial symmetrical short circuit current and the m and n factors (Figure 13.3).

Here:

$$I_{th} = I_k'' \cdot \sqrt{m + n}. \quad (13.1)$$

We can also determine the factor m using the relationship:

$$m = \frac{1}{2 f t_k \ln(\kappa - 1)} [e^{4 f T_k \ln(\kappa - 1)} - 1]. \quad (13.2)$$

The factor m takes account of the thermal effect of the DC aperiodic component for three-phase and polyphase currents and the factor n the thermal effect of the AC periodic component for a three-pole short circuit. Electrical operational equipment is dimensioned according to either the permissible short-time withstand current I_{th} or the permissible duration of the short circuit T_K .

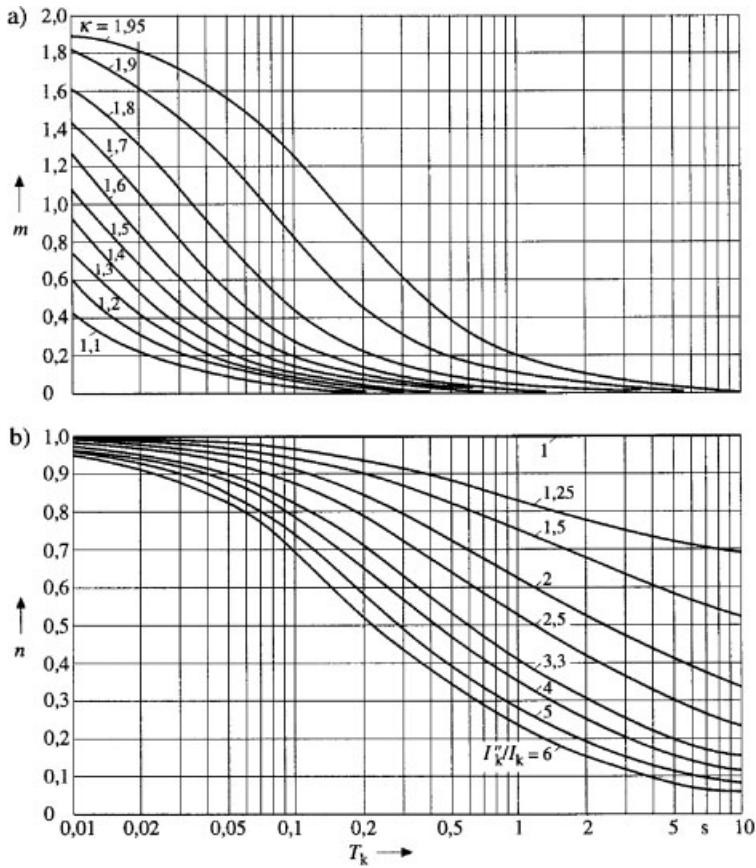


Fig. 13.3: The factors m and n [1]

The duration of the short circuit and the short-time withstand current are given by the manufacturers of protective equipment.

$$I_{th} \leq I_{thz}. \tag{13.3}$$

In accordance with IEC 76-1 I_{th} must not exceed 25 times the nominal current for longer than three seconds with short circuit current limiting reactors. With current transformers, this value is given on the nameplate. Here:

$$I_{th} \leq \sqrt{\frac{I_{kn}}{(T_K + 0.05s)}}. \tag{13.4}$$

For short circuit durations:

$$T_K \geq 0.1s, \tag{13.5}$$

the following relationship holds true:

$$I_a = I_k''. \tag{13.6}$$

If the peak short circuit current i_p is not known and the initial symmetrical short circuit current I_k'' is given, we can then calculate using the withstand ratio $\kappa = 1.8$.

The thermal equivalent short circuit current density S_{th} must be smaller than the rated short time current density S_{thr} . The following equation must be satisfied:

$$S_{th} \leq S_{thr} \cdot \frac{1}{\eta} \cdot \sqrt{\frac{T_{kr}}{T_k}}$$

The factor η takes account of heat transfer for the insulation. The rated short time current density S_{thr} can be taken from Fig 13.4. The initial temperature νb of a conductor is the maximum permissible continuous operating temperature. The ultimate temperature νe is the maximum permissible temperature under short circuit conditions for plastic insulated cables.

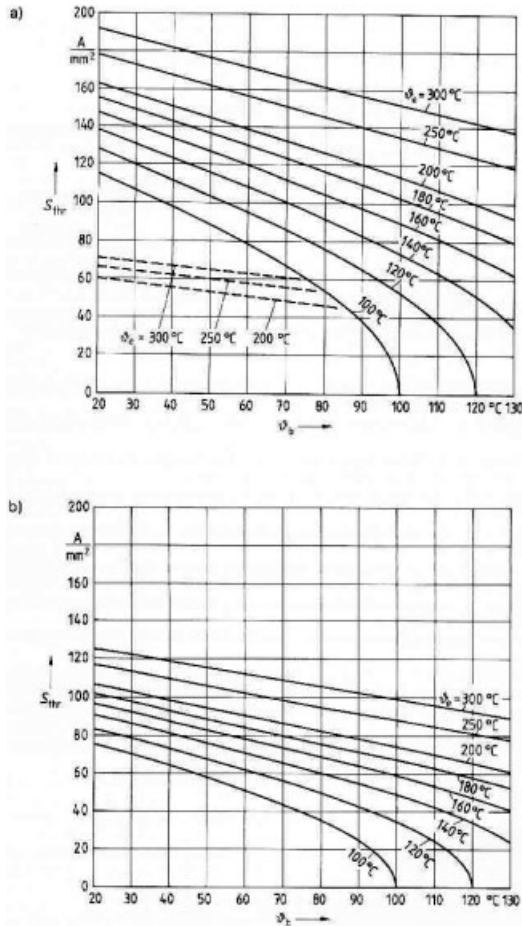


Fig. 13.4: Rated short time current density S_{thr} for $T_{kr} = 1\text{ s}$
 a) for copper and steel (solid-line curves), b) for Aluminium (broken-line curves) Aldrey and Al/St.

13.3

Limitation of short circuit currents

It is necessary to control both the minimum and the maximum short circuit currents in low voltage systems without impairing the selectivity. Investigations have shown that the three-pole short circuit currents are less than 9 kA, with an average value of 2.8 kA [34]. However, this value only applies for low voltage networks. In low voltage networks the single-pole short circuits are generally less than 1 kA. In order to limit the short circuit currents (Figure 13.5) special measures are possible in individual systems according to the various operational equipment.

Fuses are unsuitable for smaller short circuit currents. This is why many power supply companies prescribe line-protection circuit breakers in house installations. The short circuit current limitation in high and medium voltage networks can be achieved through economical (e.g. the choice of nominal network voltage or division of the network into individual groups) and technical (e.g. the use of i_p limiters and fuses).

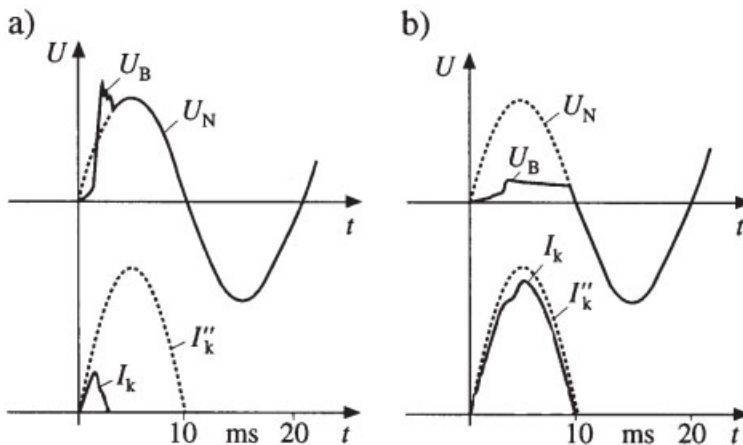


Fig. 13.5: Current limitation through circuit breaker

- a) high power current limitation through circuit breaker,
 b) line-protection circuit breaker with neutral point quencher,
 without definite current limitation

Figures 13.6, 13.7, 13.8, 13.9, 13.10 and 13.11 illustrate the short circuit carrying capacity of different cables as a function of the break time.

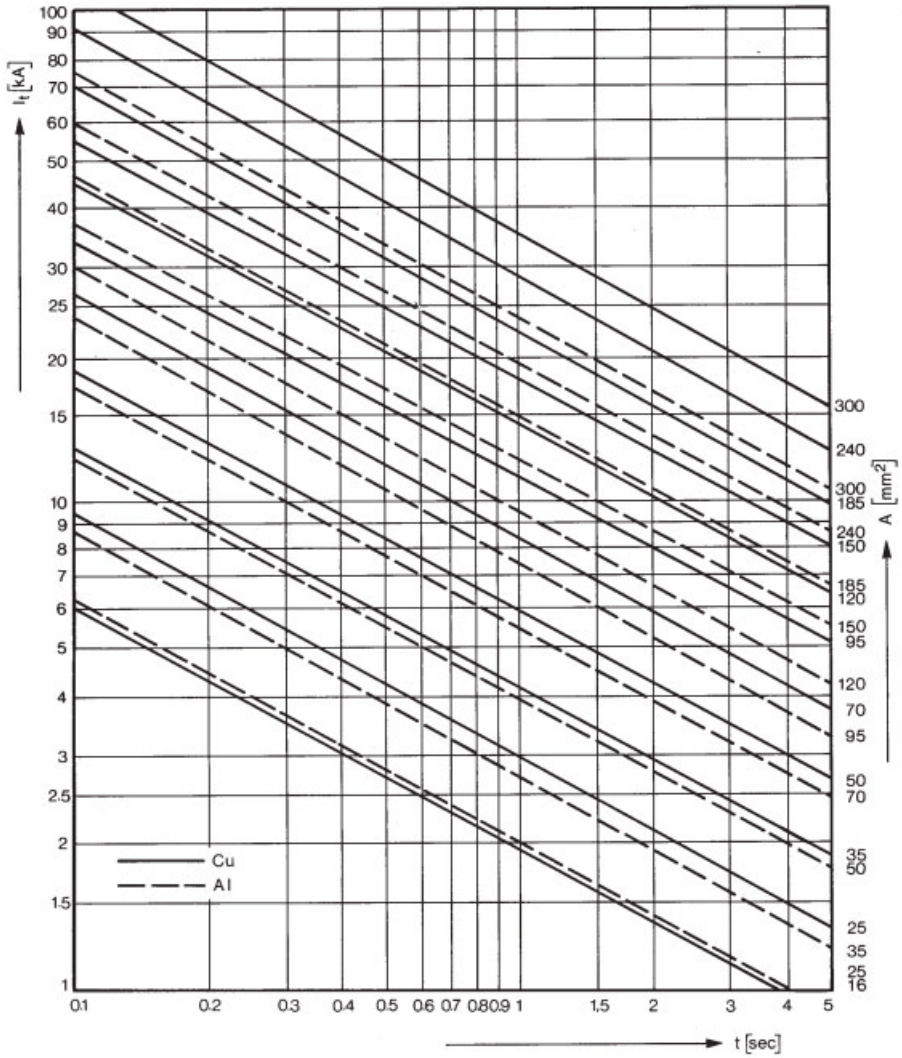


Fig. 13.6: Thermally permissible short circuit current from paper-insulated cables at 1–10 kV [26]

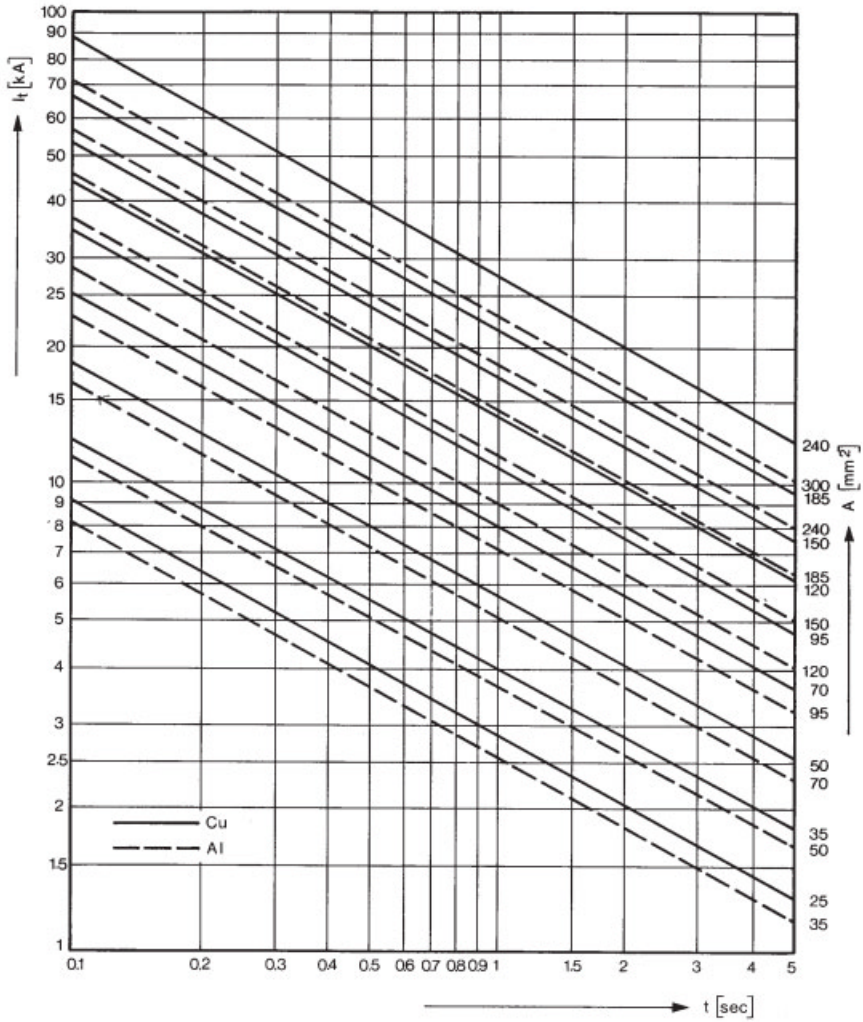


Fig. 13.7: Thermally permissible short circuit current from paper-insulated cables at 12/20 kV [26]

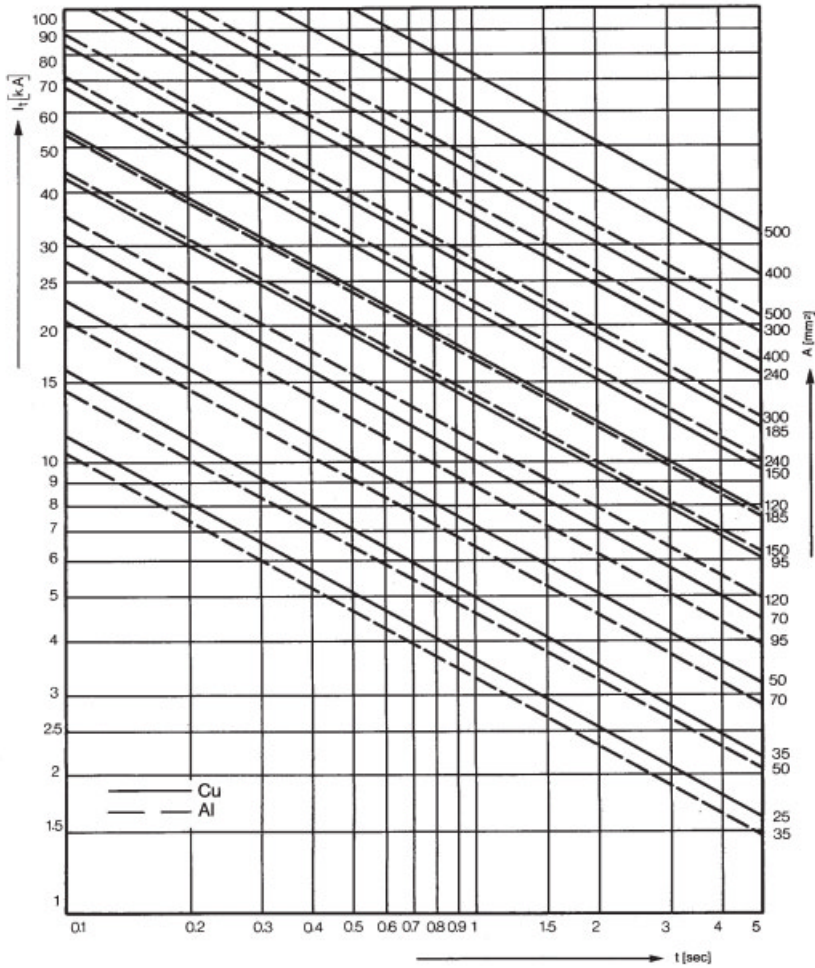


Fig. 13.8: Thermally permissible short circuit current from paper-insulated cables at 18/30 kV [26]

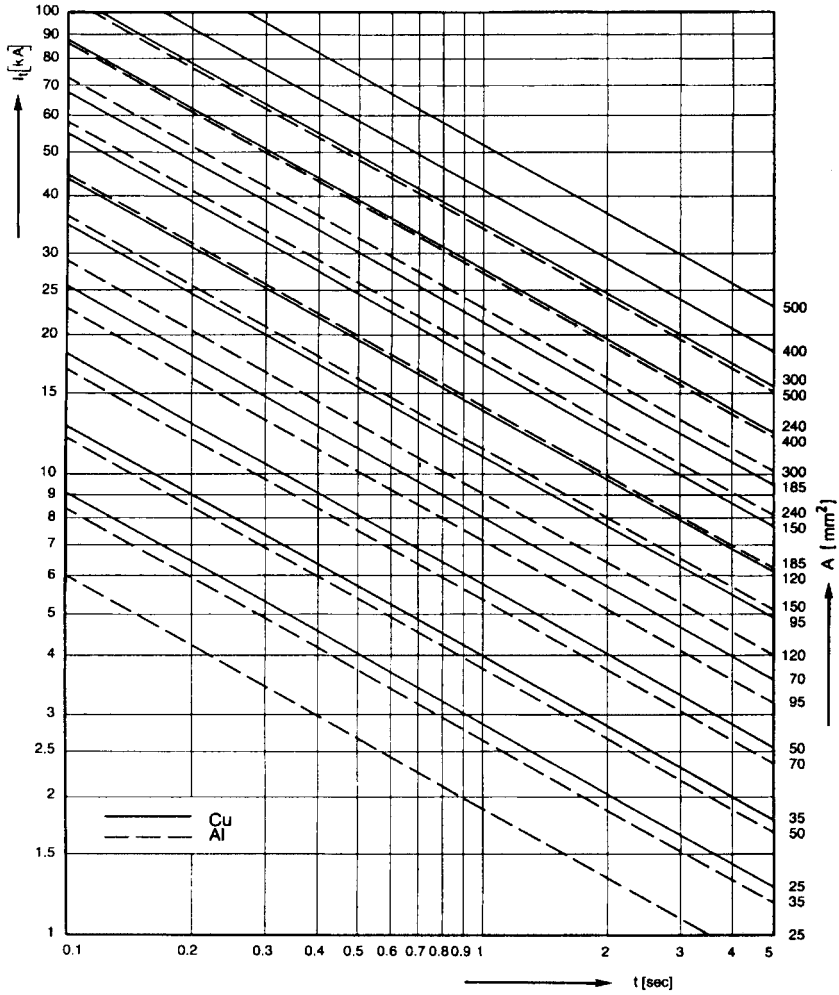


Fig. 13.9: Thermally permissible short circuit current from PVC-insulated cables at 1–10 kV [26]

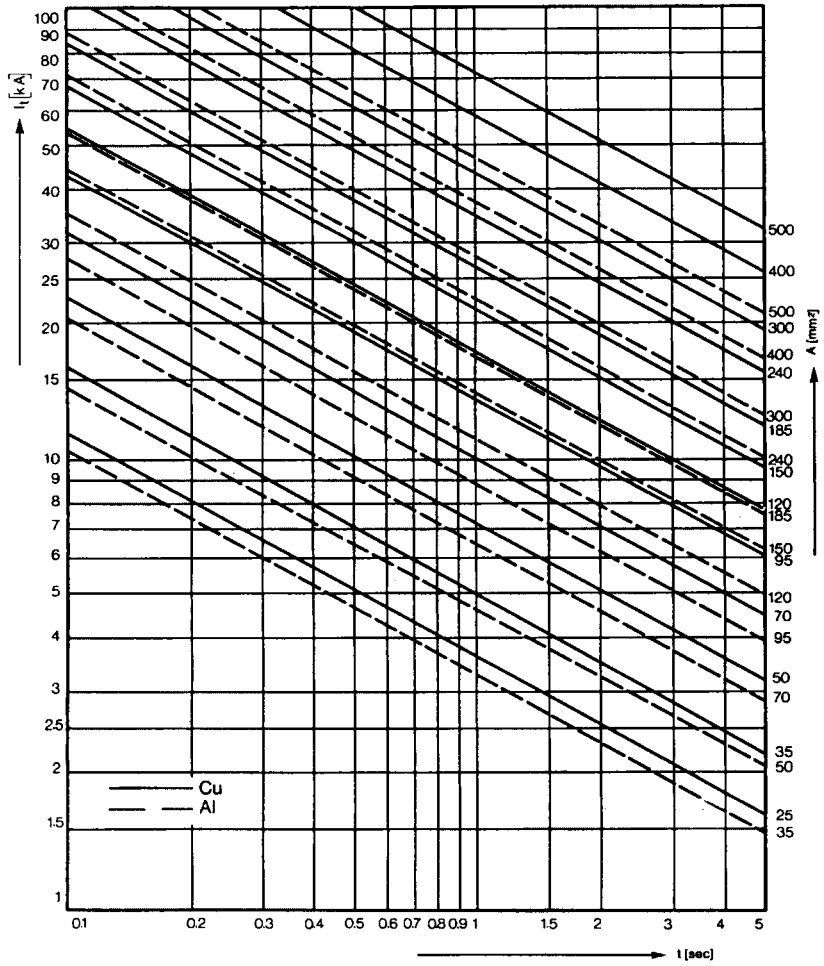


Fig. 13.10: Thermally permissible short circuit current from XLPE-insulated cables [26]

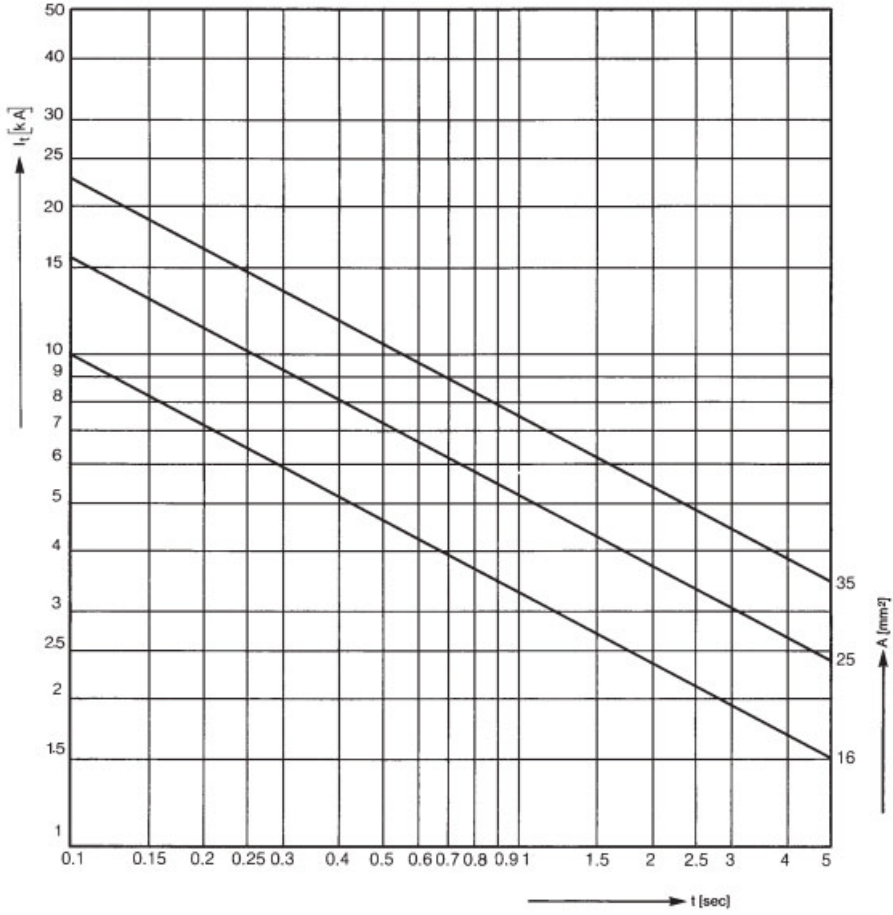


Fig. 13.11: Thermally permissible short circuit current of Cu screening [26]

14

Calculations for Short Circuit Strength

To determine the short circuit strength for switchgear and control gear, the magnitude of the prospective short circuit current is decisive. The choice of switchgear follows from:

- the short circuit strength and
- the rated breaking capacity.

14.1

Short circuit strength for medium voltage switchgear

The following selection criteria are important for the short circuit strength of medium voltage switchgear (HD 637 51):

- The rated short circuit breaking current I_{sc} : this is the effective value of the breaking current at the terminals of the switchgear. The following condition must hold true:

$$I_{sc} \geq I''_k. \quad (14.1)$$

Standardized values for middle voltage systems are:

8 kA, 12.5 kA, 16 kA, 20 kA, 25 kA, 31.5 kA, 40 kA, 50 kA and 63 kA.

- The rated short circuit making current I_{ma} : this is the peak value of the making current for a short circuit at the terminals of the switchgear. The following condition must apply for circuit breakers, load (break) switches and grounding switches of medium voltage switchgear:

$$I_{ma} \geq i_p. \quad (14.2)$$

Standardized values for medium voltage systems are:

20 kA, 25 kA, 31.5 kA, 40 kA, 50 kA, 63 kA, 80 kA, 100 kA, 125 kA and 160 kA.

- The rated short-time current I_{th} : this is the effective value of the short circuit current which the switchgear can carry in the closed state during the rated

short circuit duration t_{th} under the specified conditions for use and operation.

- The thermal short circuit capacity I_{thz} :

$$I_{thz} \geq I_{thm} \quad (14.3)$$

$$I_{thz} = I_{th} \sqrt{\frac{t_{th}}{t_k}} \quad (14.4)$$

The symbols have the meanings:

| | |
|-----------|---|
| I_{sc} | Rated short circuit breaking current |
| I_k'' | Initial symmetrical short circuit current |
| I_{thz} | Thermal short circuit carrying capacity |
| I_{thm} | Thermal equivalent short circuit current |
| I_{ma} | Rated short circuit making current |
| i_p | Peak short circuit current |
| I_{th} | Rated short-time current |
| t_{th} | Rated short circuit duration (1s and 3s) |
| t_k | Maximum short circuit duration |

14.2

Short circuit strength for low voltage switchgear

The following selection criteria must be considered for the short circuit strength of low voltage systems (IEC EN 60 947):

- The rated ultimate short circuit breaking current (breaking capacity) I_{cn} : this is the largest current which switchgear can break without incurring damage. It is given as an effective value. Standardized values for low voltage switchgear are: 18 kA, 25 kA, 40 kA, 70 kA and 100kA.

$$I_{cn} \geq I_k'' \quad (14.5)$$

- The rated short circuit making current (making capacity) I_{cm} : this is the largest current which switchgear can make without incurring damage. It is given as a peak value. The power factor $\cos\phi$ of the short circuit path depends primarily on the reactance of the input transformer. The greater its power, the smaller is the power factor. For this relationship, IEC 947-2 gives a minimum value for circuit breakers:

$$I_{cm} = nI_{cn} = \kappa\sqrt{2}I_{cn} \quad (14.6)$$

According to type, the circuit breakers must be able to interrupt the following short circuit and operating currents:

1. Circuit breakers with $\cos\varphi \geq 0.1$: short circuit currents
 2. Circuit breakers with $\cos\varphi \geq 0.7$: load currents
 3. Circuit breakers with $\cos\varphi < 0.1$: operating currents
- The rated short-time withstand current I_{cu} : this is the permissible effective value of the AC periodic component of the uninfluenced short circuit current which the switchgear can carry for a certain length of time without noticeable effect (e.g. due to excessive evolution of heat), e.g. from 0.05 s to 1 s.

In accordance with IEC 60 947, circuit breakers are tested with two currents for breaking the short circuit current.

The I_{cu} test sequence is 0-t-C0

The I_{cs} test sequence is 0-t-C0-t-C0

The current I_{cs} represents the more severe condition for the circuit breakers, because switching takes place one additional time and is stipulated as 25 %, 50 %, 75 % and 100 % of I_{cu} in order to distinguish the function of the switch following a short circuit break.

The symbols have the meanings:

| | |
|----------|---|
| I_{cu} | Rated short circuit breaking current |
| I''_k | Initial symmetrical short circuit current |
| I_{cm} | Rated short circuit making current |
| i_p | Peak short circuit current |

15

Equipment for Overcurrent Protection

The time-current characteristics of limit switch fuses (Figures 15.1 and 15.2) are plotted in logarithmic scale as a function of current. At higher short circuit currents, they break faster so that the peak short circuit current i_p can no longer occur. The cut-off current is reached during the break process and can be taken from Figure 15.3. The effective current limitation and the very high breaking capacity are the good features of these fuses. The cut-off energy or I^2t values of the fuses are decisive for the selectivity, which is normally guaranteed to be 1.6 times the rated current (better is 2 times). The high voltage – high power fuses (HH fuses) protect equipment and system components from the dynamic and thermal effects of short circuit currents. The HH fuses are used in distribution transformers, high voltage motors, capacitors and middle voltage transformers. The combination of these fuses with load break switches, load switches and vacuum protectors is possible. Figures 15.4 and 15.5 show the time-current characteristics and Figure 15.6 the cut-off characteristics. The miniature circuit breakers according to IEC 898 (Figure 15.7) are used in house installations and systems against overloading and short circuits. Internationally, the characteristics B, C and D are standardized. The function values in the overload region are the same for all miniature circuit breakers, but in the range of short circuits the breaking current is a multiple of the rated current for the breaker. The assessment of capacity is according to the following criteria:

1. Rated breaking capacity 3 kA, 6 kA, 10 kA or 25 kA
2. Short circuit stress and selectivity
3. Limiting class 1, 2 or 3
4. Backup protection.

The characteristics of circuit breakers (Figures 15.8 and 15.9) are derived from IEC 947 and are valid for the cold state with a three-phase load for which in accordance with IEC 60 898 the deviation from the release time from three times the current setting may be a maximum of $\pm 3\%$. In the warm operational state the release times of the thermal tripping devices are reduced by about 25%. The circuit breakers are compact circuit breakers up to 63 A and function according to the principle of current limitation. These devices are used for breaking and protecting motors, cables and conductors, as well as other operational equipment with undelayed overcurrent tripping devices and current-dependent overload tripping devices.

The thermal tripping device a is set to the rated current of the motor to be protected and the magnetic tripping device n to twelve times the current.

For the protection of control transformers, 19 times the current is set. The dependence of the rated short circuit breaking capacity I_{cu} and the rated service short circuit breaking capacity I_{cn} on the rated current I_r and the rated normal current I_r is taken from the respective manufacturer. Whether backup fuses are required must be calculated from the prospective three-pole short circuit current. The circuit breakers which protect the motors, cables and conductors, transformers and other system components satisfy the increased requirements for overloading and short circuit current protection up to 6000 A. They are climatically stable and suitable for operation in closed rooms in which no extreme operating conditions (e.g. dust, caustic vapors or aggressive gases) are present. Otherwise, metal enclosing is required.

Protective functions and setting possibilities:

1. Current-dependent delayed overload tripping
The current setting I_e can be set to between 0.5 and 1 times the rated switch-gear current I_n in four steps.
2. Short-time delay release of short circuit
The pickup value I_d can be set in seven steps between two and eight times the value of I_r . The delay time can be selected between 0 and 500 ms and in some cases higher. This allows a time selectivity.
3. Undelayed release of short circuit
The pickup value I_i for an undelayed short circuit release is set to 15 kA or to 20 kA.
4. Ground fault tripping
The ground fault tripping device senses fault currents which flow to ground and can cause fires in the system. The adjustable delay time allows the use of several switching steps sequentially.

Circuit breakers are used as:

1. Input and branch circuit breakers in three-phase distribution systems
2. Main circuit breakers for machining and processing systems in accordance with IEC 204-1
3. Emergency Off circuit breakers in accordance with IEC 204-1 with undervoltage release and in conjunction with an Emergency Off control station
4. Switching devices and protective equipment for motors, transformers, generators and capacitors
5. Meshed network circuit breakers in meshed low voltage networks with several high voltage inputs
6. Ground fault protection

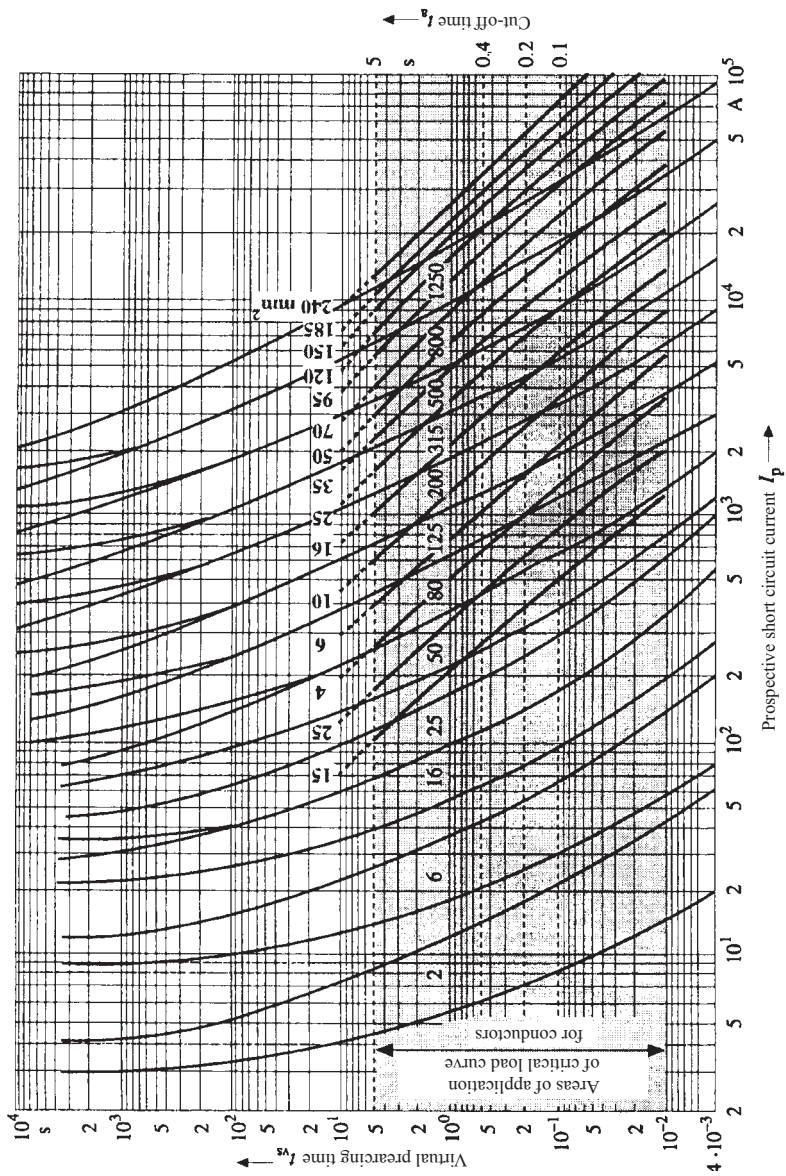


Fig.15.1: Time-current characteristics of limit switch fuses in accordance with IEC 269-1 [31]

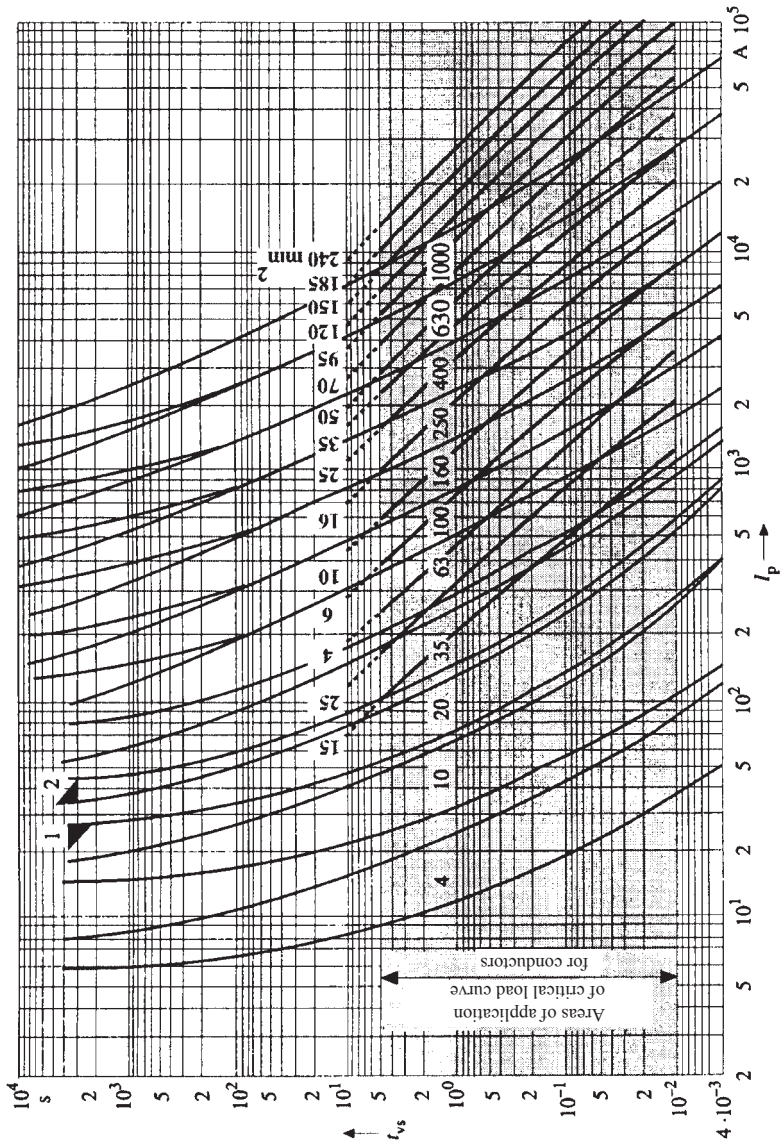


Fig.15.2: Time-current characteristics of limit switch fuses in accordance with IEC 269-1 [31] 1) small test current 2) large test current

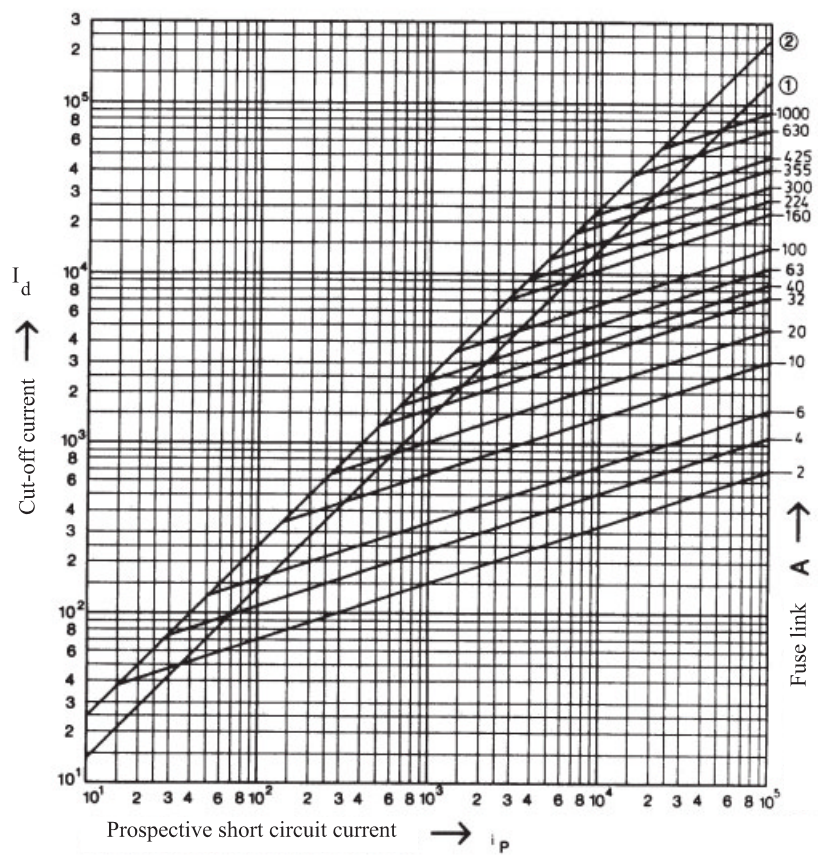


Fig.15.3: Cut-off current of limit switch fuses [32]

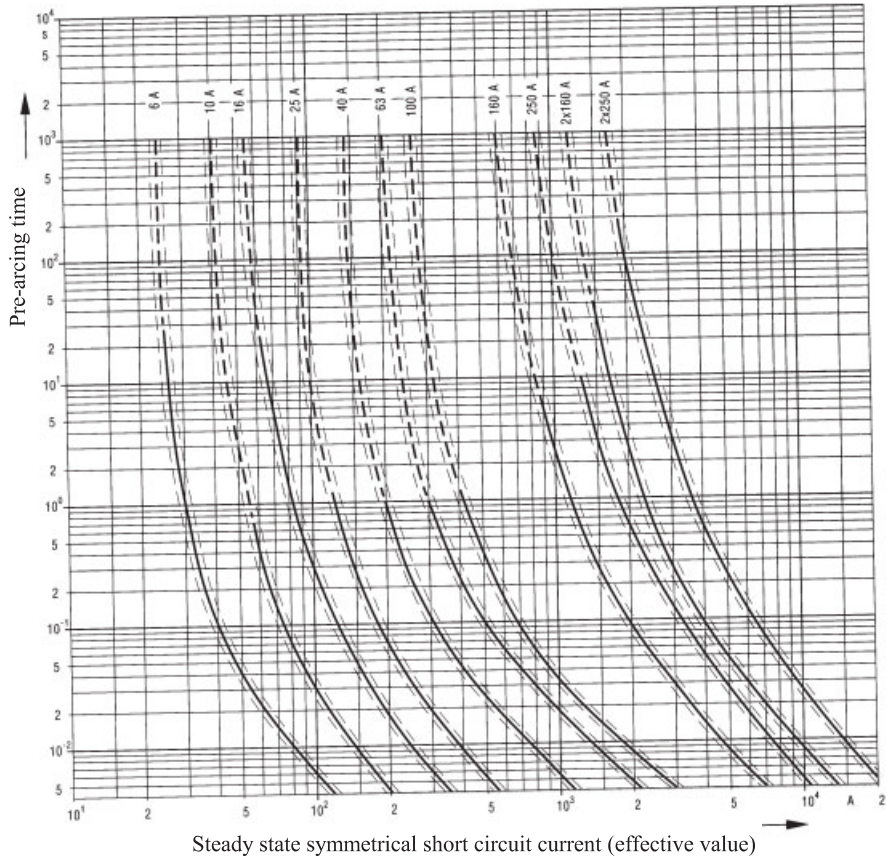


Fig.15.4: Time-current characteristics of HH fuses in accordance with IEC 282, Part 402 [31]

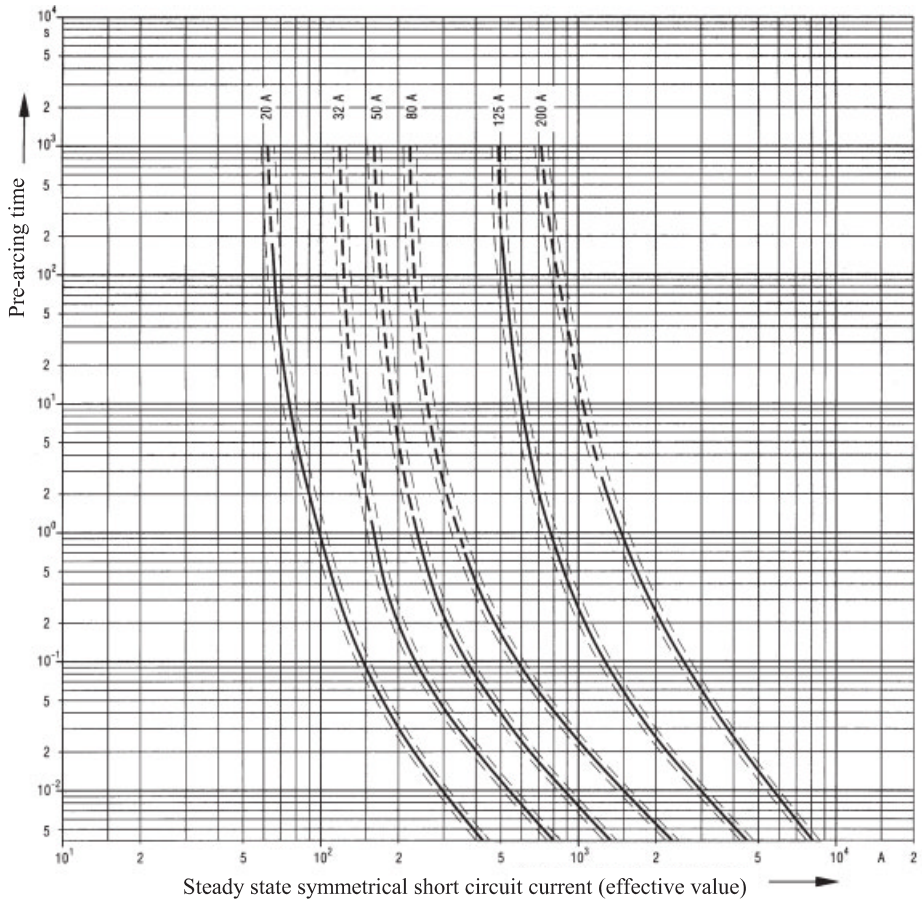


Fig.15.5: Time-current characteristics of HH fuses in accordance with IEC 282, Part 402 [31]

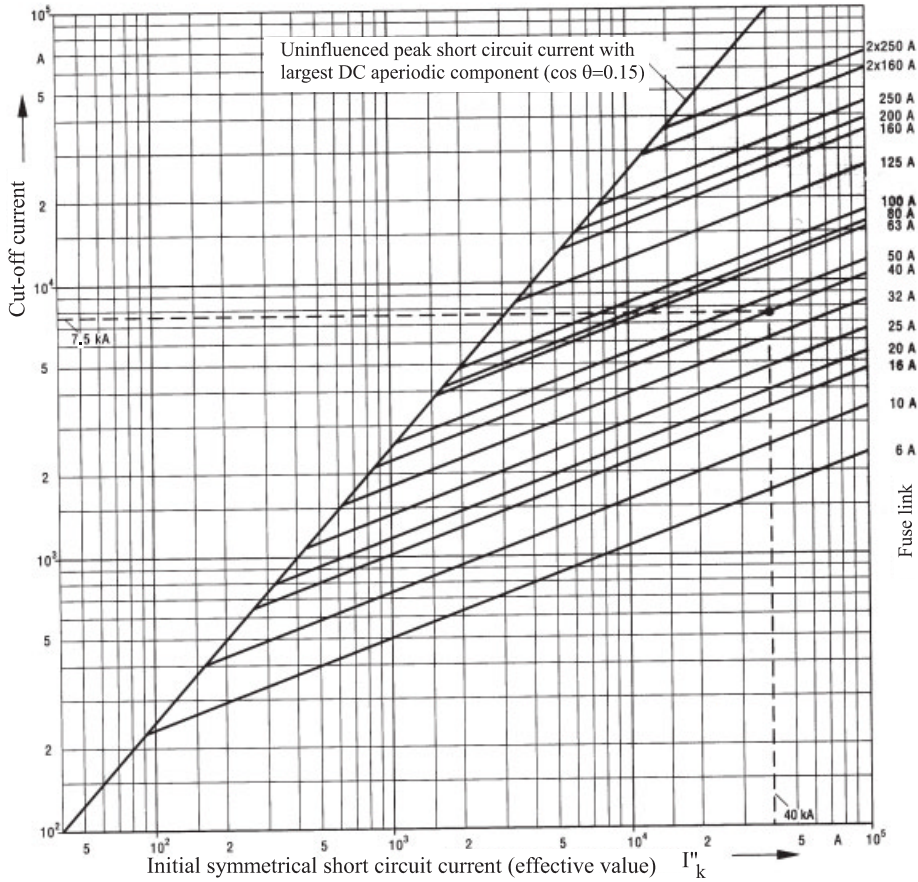


Fig.15.6: Peak let-through current chart for HH fuses in accordance with IEC 282, Part 402 [31]
 (Example: 40 kA initial symmetrical short circuit current is limited to 7.5 kA using a fuse link of 40 A)

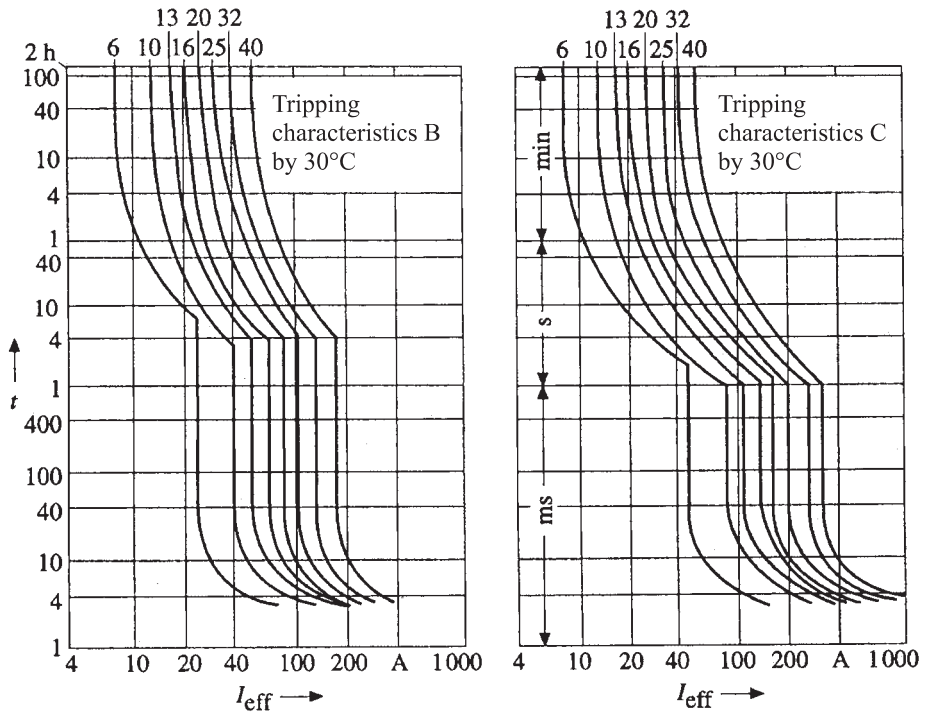


Fig.15.7: Time-current characteristics of miniature circuit breakers [28]

Cut-off currents of miniature circuit breakers:

For the overloading range:

A: $I_a = 1.45 I_n$ B: $I_a = 1.45 I_n$ C: $I_a = 1.45 I_n$ D: $I_a = 1.45 I_n$

For the short-circuit range:

A: $I_a = 3 I_n$ B: $I_a = 5 I_n$ C: $I_a = 10 I_n$ D: $I_a = 20 I_n$

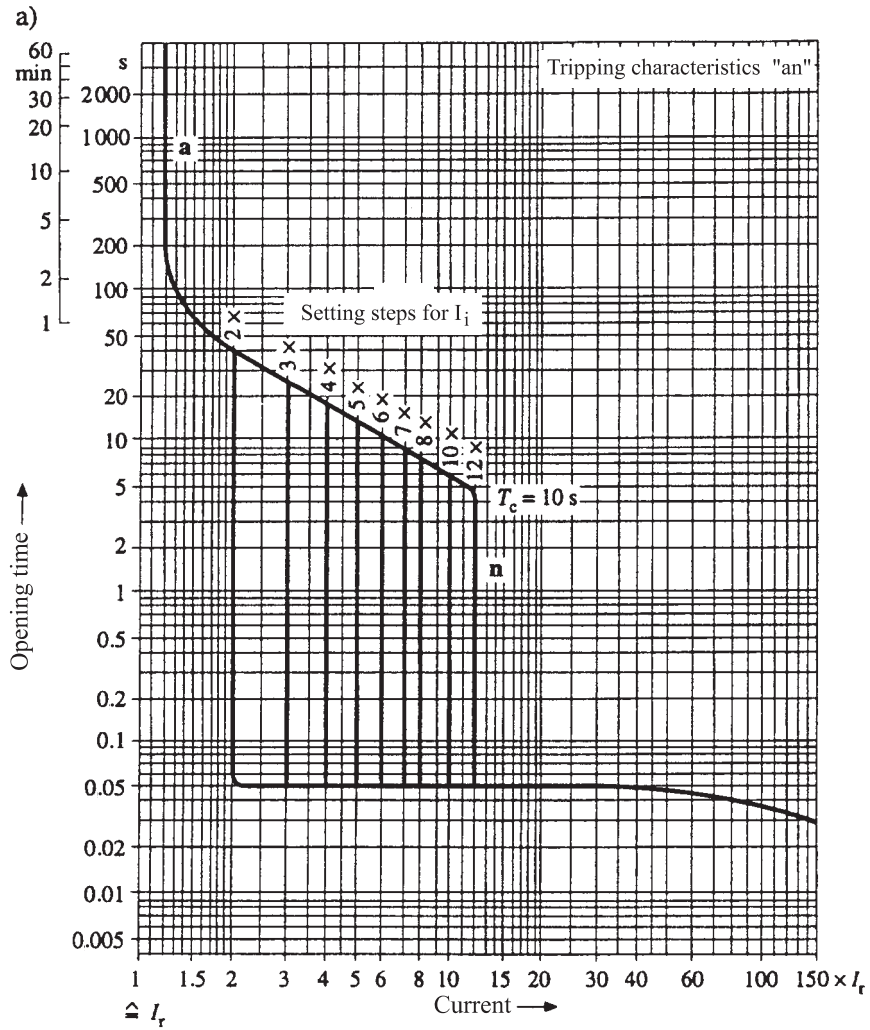


Fig.15.8: Time-current characteristics of circuit breakers for motor protection with electronic tripping [28]

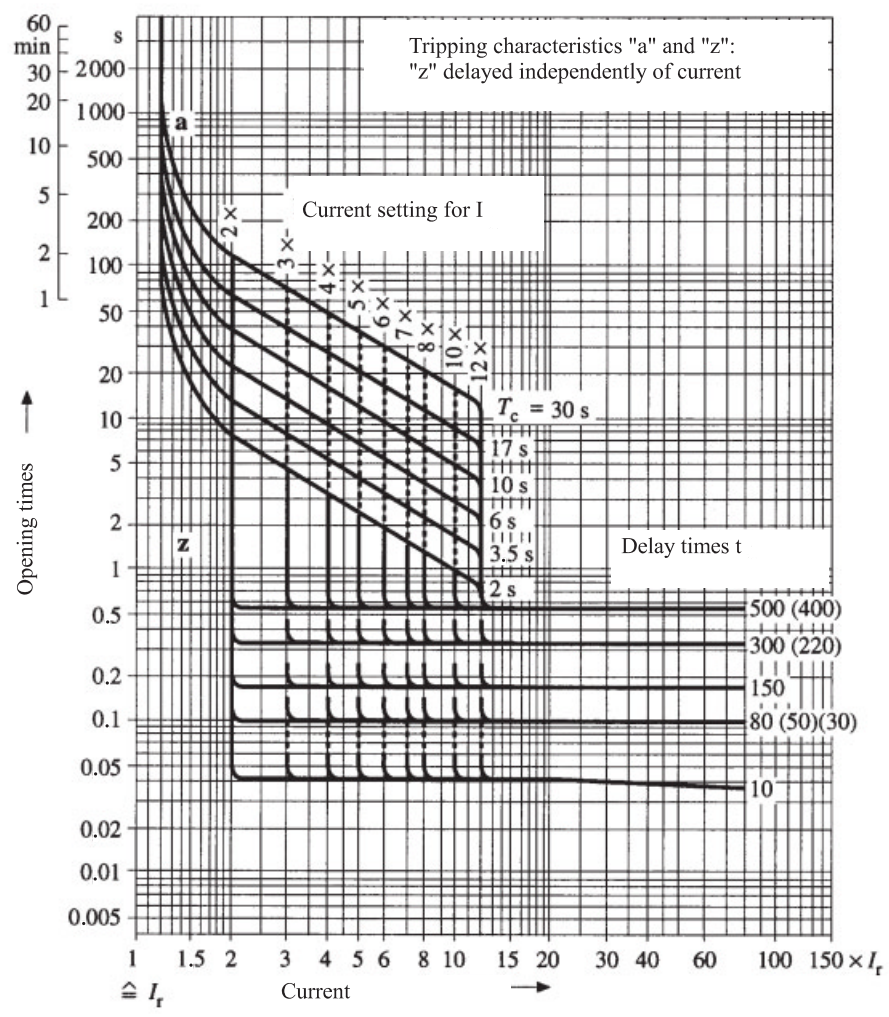


Fig. 15.9: Time-current characteristics of circuit breakers up to 6300 A [28]

The meanings of the symbols are:

| | |
|------------|--|
| I_n | Nominal current |
| I_r | Rated current |
| I_e | Current setting |
| I_d | Threshold current |
| t_d | Delay time |
| z | Short-time delay release |
| n | Undelayed electromagnetic tripping device |
| a | Current-dependent delayed overload tripping device |
| t_{vs} | Virtual prearcing time |
| I_c | Maximum cut-off current |
| I_{ts}^2 | I^2t value of fuse |
| I_{ta}^2 | I^2t break value |
| I_{cn} | Rated short circuit breaking capacity |
| 1 | Peak short circuit current without DC aperiodic component |
| 2 | Peak short circuit current with largest DC aperiodic component |
| I_{eff} | Effective value of uninfluenced short circuit current |

16

Short Circuit Currents in DC Systems

The most important power generator is the three-phase synchronous generator. Consequently, short circuit currents in electrical networks are supplied from the generator feed-ins. In power stations and in industry DC systems such as DC motors, permanently installed lead batteries, smoothing capacitors and converter arms are frequently found. The short circuit current calculation for these systems is described in IEC 61 660–1 and will be discussed briefly here. This standard contains a method for the calculation of short circuit currents in these systems [10]. However, it is also possible to use another method.

The short circuit currents, pure resistances and inductances can be measured or obtained from model experiments. In DC systems it is also necessary to distinguish between short circuit currents of different magnitudes:

1. The smallest short circuit current is used as the basis for the selection of over-current protection equipment. For the calculation of the smallest short circuit currents we must consider under which circuit and operating conditions the smallest short circuit current flows:
 - The resistances of the conductors must be considered in relation to the maximum operating temperature
 - The transition resistances must be considered
 - The short circuit current of the current converter is the rated value of the current limiting
 - The batteries are discharged by up to the discharge voltage of 1.8 V/cell, unless otherwise specified by the respective manufacturer
 - Diodes used to decouple power supply units must be considered
2. The largest short circuit current serves to dimension the electrical operational equipment. For the calculation of the largest short circuit currents we must consider under which circuit and operating conditions the largest short circuit current flows:
 - The resistances of the conductors must be considered in relation to a temperature of 20 °C
 - The transition resistances of the bus bars can be neglected

- The regulation for limiting the current converter current is not functioning
- The batteries are fully charged

Figure 16.1 illustrates typical short circuit currents for different sources. Figure 16.2 shows the standardized approximation functions for all current paths. Figure 16.3 represents a DC system with four sources.

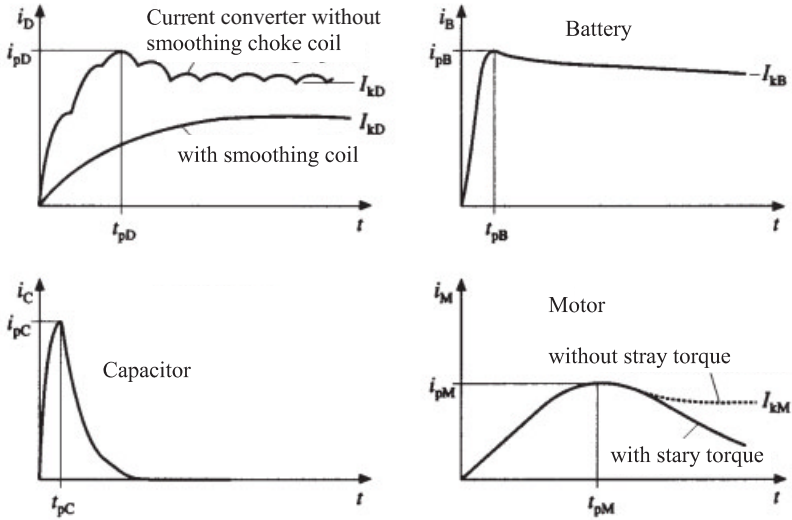


Fig. 16.1: Typical paths for short circuit currents [10]

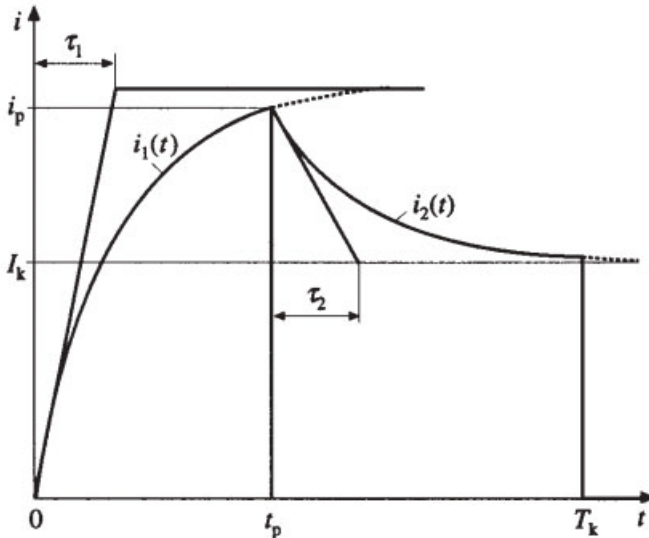


Fig. 16.2: Standardized approximation functions [10]

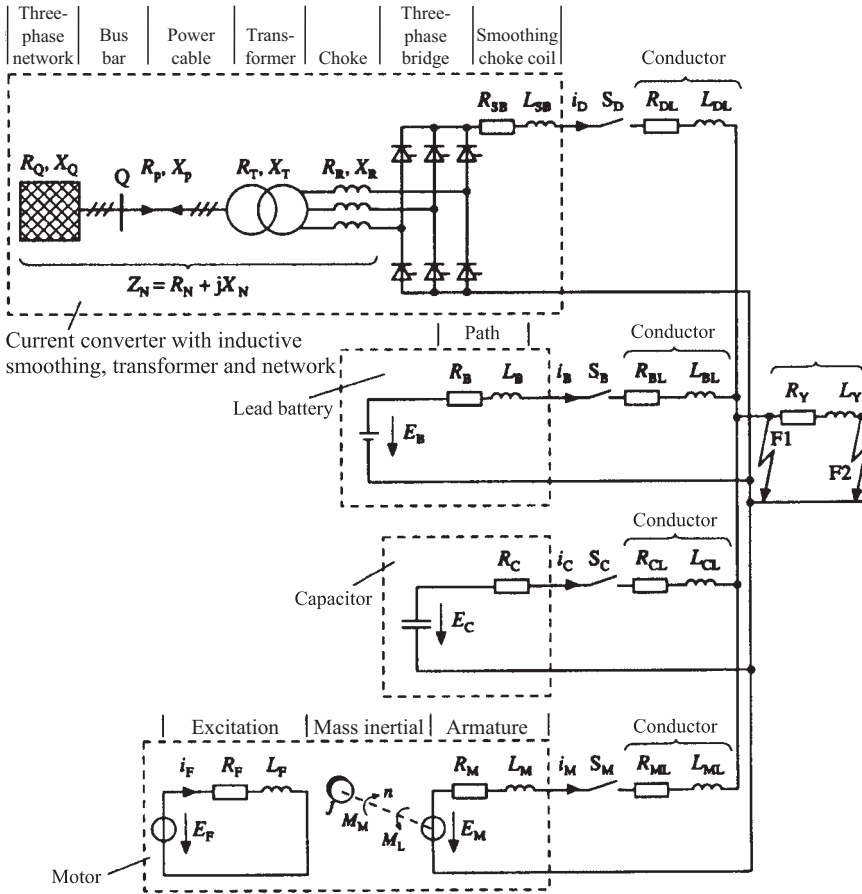


Fig. 16.3: Equivalent circuit for the calculation of short circuit currents [10]

The calculation procedure for this circuit (Figure 16.3) will now be briefly explained in the following section (see IEC 61 660-1 for more detailed information).

16.1 Resistances of line sections

The pure resistance per unit length is:

$$R' = \frac{2 \cdot \rho}{S} \tag{16.1}$$

The touch resistance of screw connections for the smallest short circuit current is:

$$R = \frac{14 \cdot \rho \cdot d}{S} \tag{16.2}$$

where:

- S: Cross-section in mm²
- R': Resistance per unit length in Ω/m
- ρ: Resistivity in Ω · mm²/m
- d: Width of rectangular conductor.

The inductance per unit length of the individual cables is calculated from:

$$L' = \frac{\mu_0}{\pi} \left(\ln \frac{a}{r} + \frac{1}{4} \right) \tag{16.3}$$

The inductance per unit length of bus bars is calculated, for a > b, from:

$$L' = \frac{\mu_0}{\pi} \left(\frac{3}{2} + \ln \frac{a}{b+h} \right) \tag{16.4}$$

where:

- μ₀: 4π · 10⁻⁷ H/m permeability
- a: Average distance between conductors in m
- L': Inductance per unit length in H/m.

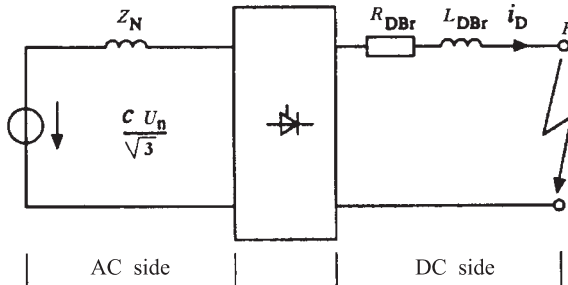


Fig. 16.4: Equivalent circuit of a converter arm [10]

**16.2
Current converters**

The network impedances for the determination of the smallest short circuit current can be taken from Chapter 8. The resistance and the inductance of the current converter are (Figure 16.4):

$$R_{DBr} = R_S + R_{DL} + R_Y, \tag{16.5}$$

$$L_{DBr} = L_S + L_{DL} + L_Y, \quad (16.6)$$

where:

- R_S, L_S : Resistance and inductance of saturated choke coil
 R_Y, L_Y : Resistance and inductance of coupling branch
 R_{DL}, L_{DL} : Resistance and inductance of conductor in current converter

The peak short circuit current is:

$$i_{pD} = \kappa \cdot I_{kD} \quad \text{with} \quad \kappa = f \left[\frac{R_N}{X_N} \left(1 + \frac{2}{3} \cdot \frac{R_{DBr}}{R_N} \right); \frac{L_D Br}{L_N} \right]. \quad (16.7)$$

The steady state short circuit current is:

$$I_{kD} = \lambda_D \cdot \frac{1}{\sqrt{3}} \cdot \frac{\sqrt{2} \cdot c \cdot U_n}{Z_N} \quad \text{with} \quad \lambda_D = f \left[\frac{R_N}{X_N}; \frac{R_{DBr}}{R_N} \right]. \quad (16.8)$$

16.3 Batteries

The simplified equivalent circuit of a permanently installed lead battery for the short circuit current is shown in Figure 16.5.

For the nominal voltage U_{nb} of a battery:

$$U_{nB} = 2.0V/cell. \quad (16.9)$$

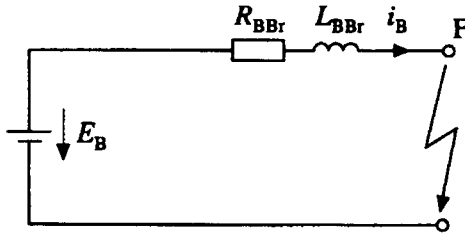


Fig. 16.5: Equivalent circuit of a battery [10]

No-load voltage of the charged battery:

$$E_B = 1.05 \cdot U_{nB}, \quad (16.10)$$

No-load voltage of the uncharged battery:

$$E_B = 0.9 \cdot U_{nB}. \quad (16.11)$$

Resistance of the battery:

$$R_{BBr} = 0.9 \cdot R_B + R_{BL} + R_Y. \quad (16.12)$$

Inductances of the battery

$$L_{BBr} = L_B + L_{BL} + L_Y. \quad (16.13)$$

Peak short circuit current of the battery:

$$I_{pB} = \frac{E_B}{R_{BBr}}. \quad (16.14)$$

Steady state short circuit current of the battery:

$$I_{kB} = 0.95 \cdot \frac{E_B}{R_{BBr} + 0.1 \cdot R_B}. \quad (16.15)$$

where:

- E_B : No-load voltage of the battery
- L_B : Inductance of the battery
- L_{BBr} : Total inductance of the battery
- R_{BL} : Resistance of a battery conductor
- L_{BL} : Inductance of a battery conductor
- R_{BY} : Resistance of battery coupling branch
- L_Y : Inductance of battery coupling branch
- R_B : Resistance of the battery
- R_{BBr} : Total resistance of the battery
- U_{nB} : Nominal voltage of the battery.

16.4 Capacitors

The equivalent circuit and the short circuit parameters of a capacitor are shown in Figure 16.6.

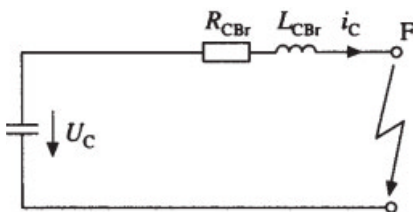


Fig. 16.6: Equivalent circuit of a capacitor [10]

Here:

$$R_{CBr} = R_C + R_{CL} + R_Y, \tag{16.16}$$

$$L_{CBr} = L_C + L_{CL} + L_Y. \tag{16.17}$$

Peak short circuit current of the capacitor:

$$i_{pC} = \kappa_C \cdot \frac{E_C}{R_{CBr}} \text{ with } R_C = f \left[\frac{2 \cdot L_{CB}}{R_{CB}}; \frac{1}{\sqrt{L_{CE} \cdot C}} \right] \tag{16.18} \text{ mit = with}$$

For $L_{CBr} = 0$, $RC = 1$ and $I_{kC} = 0$, where:

- E_C : Voltage of capacitor before occurrence of short circuit
- L_C : Inductance of capacitor
- L_{CBr} : Total inductance of capacitor
- R_{CL} : Resistance of a capacitor conductor
- L_{CL} : Inductance of a capacitor conductor
- R_{CY} : Resistance of coupling branch for capacitor
- L_{CY} : Inductance of coupling branch for capacitor
- R_C : Resistance of capacitor
- R_{CBr} : Total resistance of capacitor.

**16.5
DC motors**

The equivalent circuit of an externally excited DC motor is shown in Figure 16.7.

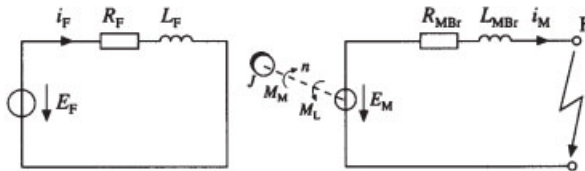


Fig. 16.7: Equivalent circuit of externally excited DC motor [10]

For the resistances and inductances, the following hold true:

$$R_{MBr} = R_M + R_{ML} + R_Y, \tag{16.19}$$

$$L_{MBr} = L_M + L_{ML} + L_Y, \tag{16.20}$$

$$\tau_M = \frac{L_{MBr}}{R_{MBr}}. \quad (16.21)$$

DC motors can be neglected when:

$$\sum I_{rM} < 0.01 \cdot I_{kD}. \quad (16.22)$$

Peak short circuit current of the DC motor:

$$i_{pM} = \kappa_M \cdot \frac{U_{rM} - I_{rM} \cdot R_M}{R_{MBr}}. \quad (16.23)$$

Steady state short circuit current of the DC motor:

$$I_{kM} = \frac{L_F}{T_{OF}} \cdot \frac{U_{rM} - I_{rM} \cdot R_M}{R_{MBr}}, \quad (16.24)$$

where:

- L_M : Inductance of DC motor
- L_{MBr} : Total inductance of DC motor
- R_{ML} : Resistance of DC motor conductor
- L_{ML} : Inductance of DC motor conductor
- R_{MY} : Resistance of coupling branch for DC motor
- L_Y : Inductance of coupling branch for DC motor
- R_M : Resistance of DC motor
- U_{rM} : Rated voltage of DC motor
- R_{MBr} : Total resistance of DC motor.

17

Programs for the Calculation of Short Circuit Currents

The calculation of short circuit currents in electrical systems is hardly possible without the support of computer programs. Furthermore, there are voluminous regulations which must be fulfilled. The following list gives a number of programs used for these calculations. The list makes no claim to being complete.

1. DIGSILENT: Electro-technical calculations, Fichtner GmbH, Telephone: ++49-(0)711-8995-658
2. Integral: Interactive Graphics network planning system. FGH e.V., Mannheim, Telephone: ++49-(0)621-8047-143
3. Sincal: Siemens Network Calculation, Siemens GmbH, Telephone: ++49-(0)9131-734165
4. CAE-N: Short circuit and load flow calculation in low voltage meshed and radial networks, Klöckner Elektrik, Telephone: ++49-(0)228-602-1040
5. Neplan (CALPOS): ABB Mannheim, Telephone: ++49-(0)621-386-2786
6. Hannappel: Electrical calculations, Telephone: ++49-(0)611-950800
7. LUKAS: Load Flow and Short Circuit calculation, Telephone: ++49-(0)681-302-3979
8. PAN: Program system for network planning, AEG, Telephone: ++49-(0)6103-3908-660
9. eNetz and KASILA: Calculations for electrical power, Telephone: ++49-(0)641-81852
10. ElektraSoft, CAE/CAD Tools for calculations of power systems, Telephone: ++49-(0)69-66 563-600, www.elaplan.com
11. SIMARIS deDESIGN, Siemens Network Calculation, Siemens GmbH, Telephone: ++49-(0)7000-746 2747, www.siemens.de/simaris

18

Examples: Calculation of Short Circuit Currents

This Chapter presents a large number of examples taken from practice, worked by hand through the corresponding equations and also an example calculated with KUBS plus. For a low voltage network, a TN-C or a TN-S system is assumed.

18.1

Example 1: Radial network

Given a 400 V network, as shown in Figure 19.1.

1. Calculate the resistances and reactances.
2. Calculate the single-pole and three-pole short circuit currents for the circuit with r.c.d.-operated circuit breaker.

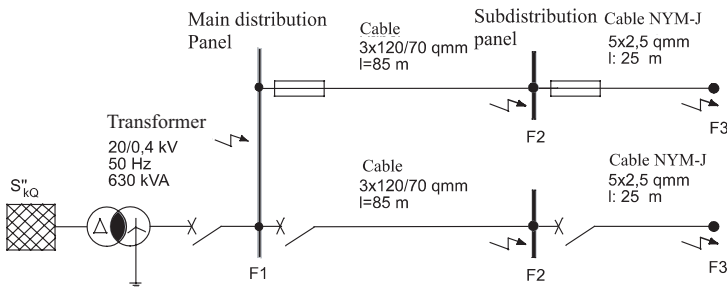


Fig. 18.1: Example 1: Network representation

Smallest short circuit current:

Resistances and reactances of transformer (Fig. 8.6):

$$R_T = 3.5 m\Omega \quad X_T = 13 m\Omega$$

Resistances and reactances of cable:

$$R_{K_{L1}} = 1.24 \cdot \frac{l}{\kappa \cdot S}$$

$$R_{K_{L1}} = 1.24 \cdot \frac{85\text{m}}{56 \frac{\text{m}}{\Omega\text{mm}^2} \cdot 120\text{mm}^2} = 15.68\text{m}\Omega$$

$$R_{K_{PEN}} = 1.24 \cdot \frac{85\text{m}}{56 \frac{\text{m}}{\Omega\text{mm}^2} \cdot 70\text{mm}^2} = 26.68\text{m}\Omega$$

$$X_{k_{L1}} = x'_{k_{L1}} \cdot l = 0.08 \frac{\text{m}\Omega}{\text{m}} \cdot 85\text{m} = 6.8\text{m}\Omega$$

$$X_{k_{PEN}} = x'_{k_{PE}} \cdot l = 0.08 \frac{\text{m}\Omega}{\text{m}} \cdot 85\text{m} = 6.8\text{m}\Omega$$

Resistances and reactances of conductor:

$$R_{K_{L1}} = 1.24 \cdot \frac{l}{\kappa \cdot S_{L1}} = 1.24 \cdot \frac{25\text{m}}{56 \frac{\text{m}}{\Omega\text{mm}^2} \cdot 2.5\text{mm}^2} = 221.4\text{m}\Omega$$

$$R_{K_{PE}} = 1.24 \cdot \frac{l}{\kappa \cdot S_{PE}} = 1.24 \cdot \frac{25\text{m}}{56 \frac{\text{m}}{\Omega\text{mm}^2} \cdot 2.5\text{mm}^2} = 221.4\text{m}\Omega$$

$$X_{k_{L1}} = x'_{k_{L1}} \cdot l = 0.08 \frac{\text{m}\Omega}{\text{m}} \cdot 25\text{m} = 2\text{m}\Omega$$

$$X_{k_{PE}} = x'_{k_{PE}} \cdot l = 0.08 \frac{\text{m}\Omega}{\text{m}} \cdot 25\text{m} = 2\text{m}\Omega$$

Sum of resistances and reactances:

$$\sum R = 488.86\text{m}\Omega \quad \sum X = 30.6\text{m}\Omega$$

Calculation of short circuit impedance:

$$z_k = \sqrt{r^2 + X^2} = 489.8\text{m}\Omega$$

$$I''_{k1} = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_k} = \frac{0.95 \cdot 400\text{V}}{\sqrt{3} \cdot 489.8\text{m}\Omega} = 448\text{A}$$

Three-pole short circuit current:

Resistances and reactances of transformer:

$$R_T = 3.5 \text{ m}\Omega \quad X_T = 13 \text{ m}\Omega$$

Resistances and reactances of cable:

$$R_k = \frac{l}{\kappa \cdot S} \text{m}\Omega = \frac{85\text{m}}{56 \frac{\text{m}}{\Omega\text{mm}^2} \cdot 120\text{mm}^2} = 12.65\text{m}\Omega$$

$$X_k = x'_i l = 0.08 \frac{\text{m}\Omega}{\text{m}} \cdot 85\text{m} = 6.8\text{m}\Omega$$

Resistances and reactances of conductor:

$$R_L = 178.6m\Omega$$

$$X_L = 2m\Omega$$

$$\Sigma R = 204.25m\Omega$$

$$\Sigma X = 21.8m\Omega$$

$$Z_k = \sqrt{(R_k^2 + X_k^2)} = \sqrt{(204.25^2 + 21.8^2)}m\Omega = 205.4m\Omega$$

$$I''_{k3} = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_k} = \frac{1 \cdot 400V}{\sqrt{3} \cdot 205.4m\Omega} = 1.068kA$$

18.2

Example 2: Proof of protective measures

Given a 230/400 V network, as shown in Figure 19.2, with a source impedance of 0.3Ω the protective measures must be proven.

1. Calculate the resistances and reactances of the network at the fault locations.
2. Calculate the single-pole short circuit current.
3. Are the cut-off conditions fulfilled?

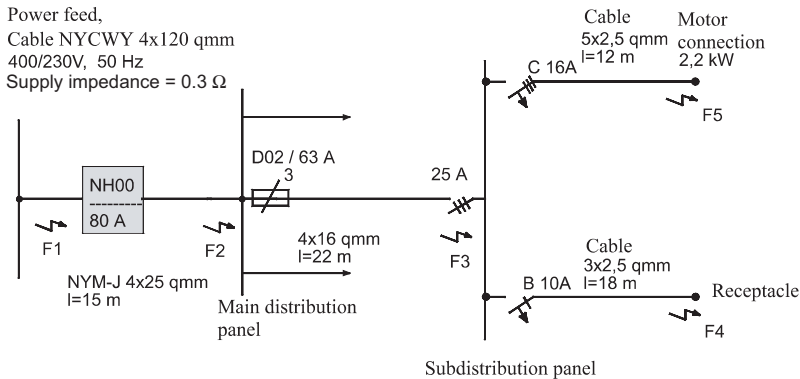


Fig. 18.2: Example 2: Calculation with source impedance

Calculation of impedances for supply conductors

Conductor NYM-J $4 \times 25 \text{ mm}^2$, $l = 15 \text{ m}$

$$R = 1.24 \cdot \frac{2 \cdot l}{\kappa \cdot S}$$

$$R = 1.24 \frac{2 \cdot 15m}{56 \frac{m}{\Omega \text{mm}^2} \cdot 25\text{mm}^2} = 0.0265\Omega$$

$$X = x' \cdot 2 \cdot l \approx 0.08 \frac{m\Omega}{m} \cdot 2 \cdot 15m = 0.0024\Omega$$

$$Z_1 = \sqrt{R^2 + X^2} = \sqrt{0.0265^2 + 0.00024^2} \Omega = 0.0266\Omega$$

Conductor NYM-J $4 \times 16 \text{ mm}^2$, $l = 22 \text{ m}$

$$R = 1.24 \cdot \frac{2 \cdot l}{\kappa \cdot S}$$

$$R = 1.24 \cdot \frac{2 \cdot 22m}{56 \frac{\Omega mm^2}{m} \cdot 16mm^2} = 0.0608\Omega$$

$$X = x' \cdot 2 \cdot l \approx 0.08 \frac{m\Omega}{m} \cdot 2 \cdot 22m = 0.00352\Omega$$

$$Z_2 = \sqrt{R^2 + X^2} = \sqrt{0.0608^2 + 0.00352^2} \Omega = 0.0609\Omega$$

Conductors for outlet NYM-J $3 \times 2.5 \text{ mm}^2$, $l = 18 \text{ m}$

$$R = 1.24 \cdot \frac{2 \cdot l}{\kappa \cdot S} = 1.24 \cdot \frac{2 \cdot 18m}{56 \frac{\Omega mm^2}{m} \cdot 2.5mm^2} = 0.318\Omega$$

$$X = x' \cdot 2 \cdot l \approx 0.08 \frac{m\Omega}{m} \cdot 2 \cdot 18m = 0.00288\Omega$$

$$Z_3 = \sqrt{R^2 + X^2} = \sqrt{0.318^2 + 0.00288^2} = 0.319\Omega$$

Conductors for motor, $l = 12 \text{ m}$

$$R = 1.24 \cdot \frac{2 \cdot l}{\kappa \cdot S} = 1.24 \cdot \frac{2 \cdot 12m}{56 \frac{\Omega mm^2}{m} \cdot 2.5mm^2} = 0.212\Omega$$

$$X = x' \cdot 2 \cdot l \approx 0.08 \frac{m\Omega}{m} \cdot 2 \cdot 12m = 0.00192\Omega$$

$$Z_4 = \sqrt{R^2 + X^2} = \sqrt{0.212^2 + 0.00192^2} \Omega = 0.212\Omega$$

Impedance at fault location F1

with $Z_V = 0.3 \Omega$

Single-pole short circuit current:

$$I''_{k1} = \frac{c \cdot U_1}{\sqrt{3} \cdot Z_V} = \frac{0.95 \cdot 400V}{\sqrt{3} \cdot 0.3\Omega} = 731.3A$$

Impedance at fault location F2:

$$Z_A = Z_V + Z_1 = 0.3\Omega + 0.0266\Omega = 0.3266\Omega$$

$$I''_{k1} = \frac{0.95 \cdot 400V}{\sqrt{3} \cdot 0.3266\Omega} = 671.7A$$

Impedance at fault location F3:

$$Z_B = Z_A + Z_2 = 0.3266\Omega + 0.0609\Omega = 0.3875\Omega$$

$$I''_{k1} = \frac{0.95 \cdot 400V}{\sqrt{3} \cdot 0.3875\Omega} = 566.17A$$

Impedance at outlet F4:

$$Z_C = Z_B + Z_3 = 0.3875\Omega + 0.318\Omega = 0.7055\Omega$$

$$I''_{k1} = \frac{0.95 \cdot 400V}{\sqrt{3} \cdot 0.7055\Omega} = 310.97A$$

Impedance at motor F5:

$$Z = Z_B + Z_4 = 0.3875\Omega + 0.212\Omega = 0.5995\Omega$$

$$I''_{k1} = \frac{0.95 \cdot 400V}{\sqrt{3} \cdot 0.5995\Omega} = 365.96A$$

Protection by cut-off is the most important condition for satisfying the protective measures up to 1000 V. In accordance with IEC 60 364, Part 41 the faults must be protected by cut-off within 0.4 seconds for portable equipment of Protection Class I and in 5 seconds for permanently installed operational equipment. The cut-off currents of fuses and power breakers can be found in tables or diagrams (see IEC 60 364, Part 43 and Part 61).

In this example the cut-off currents I_a have the values:

$$B16A \quad I_a = 5 \cdot I_n = 5 \cdot 16A = 80A$$

$$C16A \quad I_a = 10 \cdot I_n = 10 \cdot 16A = 160A$$

$$\frac{D02}{63A} \quad \begin{aligned} I_{a(0.4s)} &= 600A \\ I_{a(5s)} &= 310A \end{aligned}$$

$$\frac{NH00}{80A} \quad \begin{aligned} I_{a(0.4s)} &= 800A \\ I_{a(5s)} &= 450A \end{aligned}$$

The condition $I''_{k1min} > I_a$ must always hold true.

Table 19.1: Summary of results

| Fault location | I''_{k1min} | I_a |
|-----------------------|---------------|-------|
| F1 | 731.3A | 450A |
| F2 | 671.7A | 450A |
| F3 | 566.17A | 310A |
| F4 outlet | 310.97A | 80A |
| F5 motor | 365.96 | 160A |

Table 19.1 shows that the cut-off condition is satisfied.

18.3

Example 3: Connection box to service panel

A power plant network as in Figure 19.3 supplies an on-site connection box. The single-pole short circuit current is 575 A.

1. Calculate the resistances and reactances.
2. Calculate the single-pole short circuit current at the outlet and at the light.
3. Is protection by cut-off guaranteed?

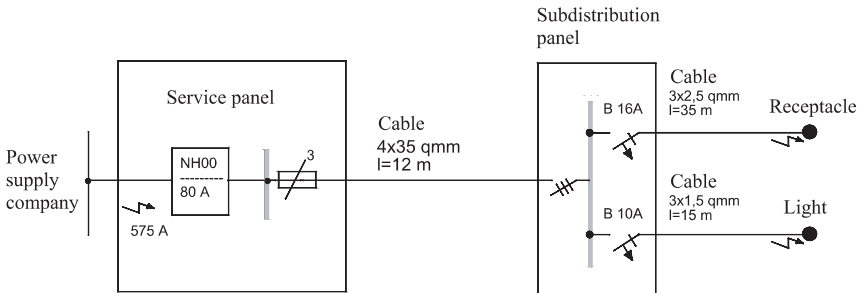


Fig. 18.3: Example 3: Power plant network with service panel.

The impedance of the connection box is:

$$Z = \frac{c \cdot U_n}{\sqrt{3} \cdot I''_{k1}} = \frac{0.95 \cdot 400V}{\sqrt{3} \cdot 575A} = 381.6m\Omega$$

$$Z_{l1} = 2 \cdot z \cdot l_1 = 2 \cdot 0.654\Omega/km \cdot 0.012km = 15.7m\Omega$$

The total impedance of the sub-distributor is:

$$Z_k = Z + Z_{l1} = 397.3m\Omega$$

The single-pole short circuit current is:

$$I''_{k1} = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_k} = \frac{0.95 \cdot 400V}{\sqrt{3} \cdot 397.3\Omega} = 542A$$

For the short circuit at the outlet:

$$z' = 2 \cdot z \cdot l_2 = 2 \cdot 9.02\Omega/km \cdot 0.035km + 0.3973\Omega = 1.0287\Omega$$

$$I''_{k1} = 213.27A$$

The cut-off current of a 16 A circuit breaker is 80 A. Since the single-pole short circuit current is greater than the cut-off current, the cut-off condition is satisfied.

Short circuit on light:

$$z' = 2 \cdot z \cdot l_3 = 2 \cdot 15\Omega/\text{km} \cdot 0.015\text{km} + 0.3973\Omega = 0.8473\Omega$$

$$I''_{k1} = 258.9\text{A}$$

The cut-off current of a 10 A circuit breaker is 50 A. The cut-off condition is therefore again satisfied.

18.4

Example 4: Transformers in parallel

Two transformers are connected in parallel, as shown in Figure 19.4.

1. Draw the equivalent circuit.
2. Calculate the resistances and reactances.
3. Calculate the three-pole short circuit current.

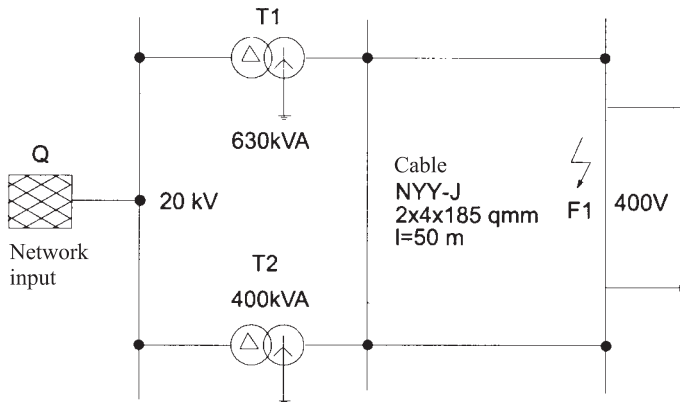


Fig. 18.4: Example 4: Transformers in parallel

Total transformer power:

$$\Sigma S_{rT} = 630\text{kVA} + 400\text{kVA} = 1030\text{kVA}$$

$$u_{Rm} = \frac{u_{R1} + u_{R2}}{2} = 1.125\%$$

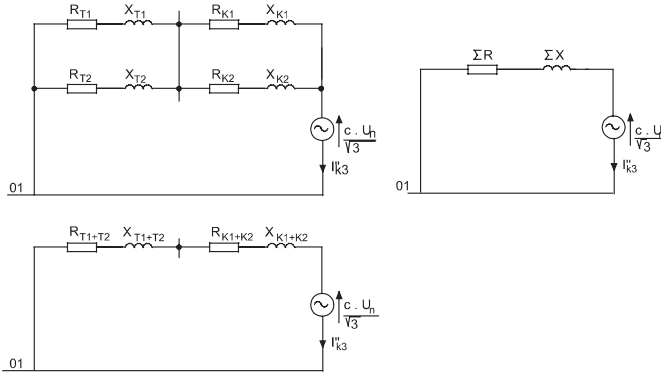


Fig. 18.5: Equivalent circuit

$$Z_T = \frac{u_{Rm}}{100\%} \frac{U_{nT}^2}{S_{rT}} = \frac{5\%}{100\%} \frac{(400\text{V})^2}{1030\text{kVA}} = 7.77\text{m}\Omega$$

$$R_T = \frac{u_{Rm}}{100\%} \frac{U_{nT}^2}{S_{rT}} = \frac{1.125}{100\%} \frac{(400\text{V})^2}{1030\text{kVA}} = 1.75\text{m}\Omega$$

$$X_T = \sqrt{Z_T^2 - R_T^2} = 7.57\text{m}\Omega$$

Cables:

$$R_L = \frac{l}{\kappa \cdot S \cdot n} = \frac{50\text{m}}{56 \frac{\text{m}}{\Omega \cdot \text{mm}^2} \cdot 185\text{mm}^2 \cdot 2} = 2.4\text{m}\Omega$$

$$X_L = x'_L \cdot \frac{l}{n} = 0.08\text{m}\Omega \cdot \frac{50\text{m}}{2} = 2\text{m}\Omega$$

$$Z_k = \sqrt{R_k^2 + X_k^2} = \sqrt{4.15^2 + 9.57^2}\text{m}\Omega = 10.43\text{m}\Omega$$

$$I''_{k3} = \frac{c \cdot U_{nT}}{\sqrt{3} \cdot Z_k} = \frac{1.0 \cdot 400\text{V}}{\sqrt{3} \cdot 10.43\text{m}\Omega} = 22.14\text{kA}$$

18.5

Example 5: Connection of a motor

A transformer as shown in Figure 19.6 supplies a motor through an overhead line, cables and conductors.

1. Calculate the resistances and reactances.
2. Calculate the single-pole short circuit current.

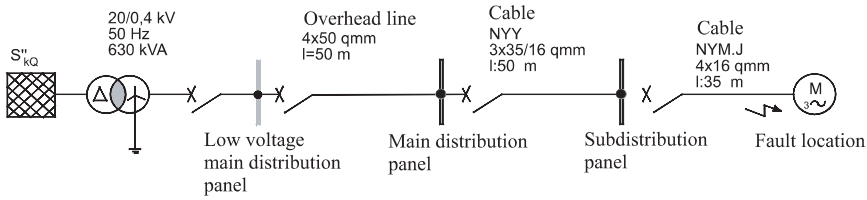


Fig. 18.6: Example 5: Connection of a motor

Transformer:

$$Z_T = 15.238 m\Omega$$

$$R_T = 2.8 m\Omega$$

$$X_T = 15 m\Omega$$

Overhead line:

$$R_{L1} = 1.24 \cdot \frac{l}{\kappa \cdot S}$$

$$R_{L1} = 1.24 \cdot \frac{50m}{56 \frac{m}{\Omega \cdot mm^2} \cdot 50mm^2} = 22.1 m\Omega$$

$$R_{PEN} = 0.2 m\Omega$$

$$X_{L1} = x' \cdot l = 0.33 \frac{\Omega}{km} \cdot 50m = 16.5 m\Omega$$

$$X_{PEN} = 16.5 m\Omega$$

Cables:

$$R_{L2} = 1.24 \cdot \frac{50m}{56 \frac{m}{\Omega \cdot mm^2} \cdot 35mm^2} = 31.6 m\Omega$$

$$R_{PEN} = 1.24 \cdot \frac{50m}{56 \frac{m}{\Omega \cdot mm^2} \cdot 16mm^2} = 69.2 m\Omega$$

$$X_{L2} = x' \cdot l = 0.08 \frac{\Omega}{km} \cdot 50m = 4 m\Omega$$

$$X_{PEN} = 4 m\Omega$$

Conductors:

$$R_{L3} = 1.24 \cdot \frac{35m}{56 \frac{m}{\Omega \cdot mm^2} \cdot 16mm^2} = 48.4 m\Omega$$

$$R_{PEN} = 1.24 \cdot \frac{35m}{56 \frac{m}{\Omega \cdot mm^2} \cdot 16mm^2} = 48.4 m\Omega$$

$$X_{L3} = x' \cdot l = 0.08 \frac{\Omega}{\text{km}} \cdot 35 \text{ m} = 2.8 \text{ m}\Omega$$

$$X_{PEN} = 2.8 \text{ m}\Omega$$

$$\Sigma R = 222.7 \text{ m}\Omega$$

$$\Sigma X = 61.6 \text{ m}\Omega$$

$$Z_k = \sqrt{R_k^2 + X_k^2} = \sqrt{222.7^2 + 61.6^2} \text{ m}\Omega = 231.06 \text{ m}\Omega$$

$$I''_{k1} = \frac{c \cdot U_{nT}}{\sqrt{3} \cdot Z_k} = \frac{0.95 \cdot 400 \text{ V}}{\sqrt{3} \cdot 231.06 \text{ m}\Omega} = 949.5 \text{ kA}$$

18.6

Example 6: Calculation for a load circuit

A grounding cable is connected to a transformer (Figure 19.7). The data for the cable are: $r' = 0.482 \Omega/\text{km}$, $x' = 0.083 \Omega/\text{km}$ $\frac{R_{0L}}{R_L} = 4$ and $\frac{X_{0L}}{X_L} = 3.76$.

1. Calculate the resistances and reactances.
2. Calculate the three-pole and single-pole short circuit currents.

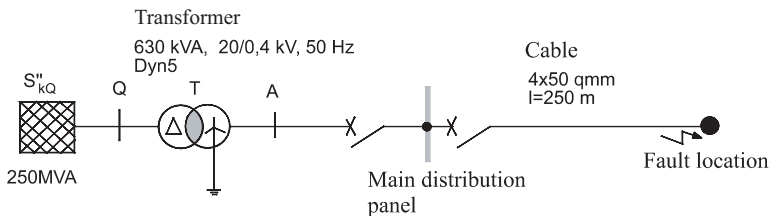


Fig. 18.7: Example 6: Calculation for a load

Calculation of I''_{k3} :

$$Z_{QT} = \frac{c \cdot U_n^2}{S''_{kQ}} = \frac{1.1 \cdot (0.4 \text{ kV})^2}{250 \text{ MVA}} = 0.704 \text{ m}\Omega$$

$$X_{QT} = 0.995 \cdot Z_{Qt} = 0.7 \text{ m}\Omega$$

$$R_{QT} = 0.1 \cdot X_{Qt} = 0.07 \text{ m}\Omega$$

$$R_T = \frac{u_R}{100\%} \frac{U_n^2}{S_{rT}} = \frac{1.1 \cdot 0\%}{100\%} \cdot \frac{(400 \text{ V})^2}{630 \text{ kVA}} = 2.8 \text{ m}\Omega$$

$$Z_T = \frac{u_k \cdot U_n^2}{100\% \cdot S_{rT}} = \frac{6 \cdot 0\%}{100\%} \cdot \frac{(400 \text{ V})^2}{630 \text{ kVA}} = 15.2 \text{ m}\Omega$$

$$X_T = \sqrt{Z^2 - R_T^2} = \sqrt{15.2^2 - 2.8^2} \text{ m}\Omega = 14.9 \text{ m}\Omega$$

$$R_{0T} = R_T = 2.8 \text{ m}\Omega$$

$$X_{0T} = 0.995 \cdot X_T = 0.995 \cdot 14.9 \text{ m}\Omega = 14.83 \text{ m}\Omega$$

$$R_l = R' \cdot l = 0.482 \Omega/\text{km} \cdot 0.25 \text{ km} = 120.5 \text{ m}\Omega$$

$$X_l = X' \cdot l = 0.083 \Omega/\text{km} \cdot 0.25 \text{ km} = 20.75 \text{ m}\Omega$$

$$R_{0l} = 4 \cdot R_l = 482 \text{ m}\Omega$$

$$X_{0l} = 3.76 \cdot X_l = 78.02 \text{ m}\Omega$$

$$R_k = (R_{0T} + R_T + R_l) = 123.4 \text{ m}\Omega$$

$$X_k = (X_{0T} + X_T + X_l) = 36.35 \text{ m}\Omega$$

$$Z_k = \sqrt{R_k^2 + X_k^2} = \sqrt{123.4^2 + 36.35^2} \text{ m}\Omega = 128.6 \text{ m}\Omega$$

$$I''_{k3} = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_k} = 1.80 \text{ kA}$$

Calculation of I''_{k1} (Figure 19.8):

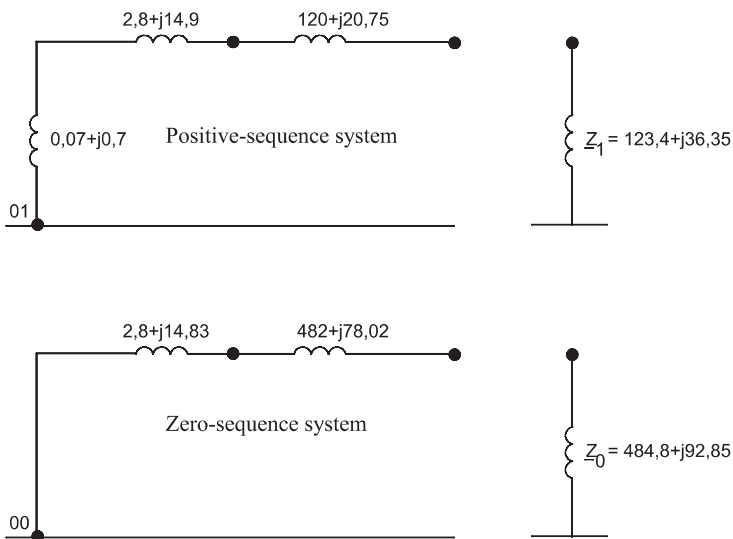


Fig. 19.8: Equivalent circuit for I''_{k1}

$$2Z_1 + Z_0 = 2 \cdot (123.4 + j36.35)m\Omega + (484.8 + j92.85)m\Omega$$

$$2Z_1 + Z_0 = (731.6 + j165.6)m\Omega = 750.1m\Omega$$

$$I''_{k1} = \frac{\sqrt{3} \cdot c \cdot U_n}{|2 \cdot Z_1 + Z_0|} = \frac{\sqrt{3} \cdot 0.95 \cdot 400V}{750.1m\Omega} = 877A$$

Simplified method for calculating the single-pole short circuit current (Table 8.7):

Transformer impedance:

$$Z_T = \frac{u_k}{100\%} \frac{U_n^2}{S_{rT}} = \frac{6 \cdot \% \cdot (400V)^2}{100\% \cdot 630kVA} = 0.015\Omega$$

Line impedance (outgoing and return lines):

$$Z_L = 2 \cdot z' \cdot l = 2 \cdot 0.486\Omega/km \cdot 0.250km = 0.243\Omega$$

Total impedance:

$$Z_{tof} = Z_T + Z_L = 0.258\Omega$$

Single-pole short circuit current:

$$I''_{k1} = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_{tof}} = \frac{0.95 \cdot 400V}{\sqrt{3} \cdot 0.258\Omega} = 850.36A$$

The result is nearly the same by both methods.

18.7

Example 7: Calculation for an industrial system

A transformer as shown In Figure 19.9 supplies the main distributor of an industrial system.

1. Calculate the resistances and reactances.
2. Calculate the three-pole short current at the main distributor.
3. Calculate the single-pole short circuit current at the outlet and at the light switch.

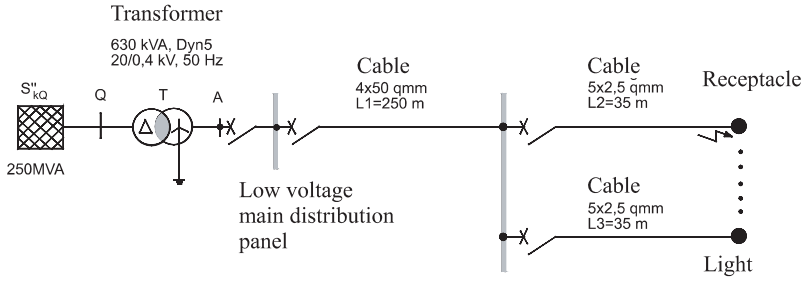


Fig. 18.9: Example 7: Network diagram

Determination of individual impedances:

$$Z_{Qf} = \frac{c \cdot U_n^2}{S''_{kQ}} = \frac{1.1 \cdot (400V)^2}{250MVA} = 0.704m\Omega$$

$$X_{Qf} = 0.995 \cdot Z_{Qf} = 0.7m\Omega$$

$$R_{Qf} = 0.1 \cdot X_{Qf} = 0.07m\Omega$$

$$Z_T = \frac{u_k \cdot U_n^2}{100\% \cdot S_{rT}} = \frac{6\% \cdot (400V)^2}{630kVA} = 15.24m\Omega$$

$$Z_{L1} = 2 \cdot z \cdot l_1 = 2 \cdot 0.486\Omega/km \cdot 0.25km = 243m\Omega$$

$$Z_{L2} = 2 \cdot z \cdot l_2 = 2 \cdot 9.02\Omega/km \cdot 0.035km = 631.4m\Omega$$

$$Z_{L3} = 2 \cdot z \cdot l_2 = 2 \cdot 15\Omega/km \cdot 0.015km = 450m\Omega$$

I''_{k1} at main distributor:

$$Z_{L1} = 2 \cdot z \cdot l_1 = 2 \cdot 0.396\Omega/km \cdot 0.25km = 99m\Omega$$

$$Z_{HV} = Z_{Qf} + Z_T + Z_{L1} = 115m\Omega$$

$$I''_{k1} = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_{HV}} = \frac{0.95 \cdot 400V}{\sqrt{3} \cdot 115m\Omega} = 1.9kA$$

I''_{k1} at outlet:

$$Z_{out} = Z_{Qf} + Z_T + Z_{L1} + Z_{L2} = 890.344m\Omega$$

$$I''_{k1} = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_{out}} = \frac{0.95 \cdot 400V}{\sqrt{3} \cdot 890.344m\Omega} = 246.4A$$

I''_{k1} at light switch:

$$Z_{Li} = Z_{Qt} + Z_T + Z_{l1} + Z_{l2} = 708.944m\Omega$$

$$I''_{k1} = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_{Li}} = \frac{0.95 \cdot 400V}{\sqrt{3} \cdot 708.944m\Omega} = 309.46A$$

18.8

Example 8: Calculation of three-pole short circuit current and peak short circuit current

Given the network of Figure 19.10

1. Calculate the resistances and reactances.
2. Calculate the three-pole short circuit currents and the peak short circuit currents at the fault locations.

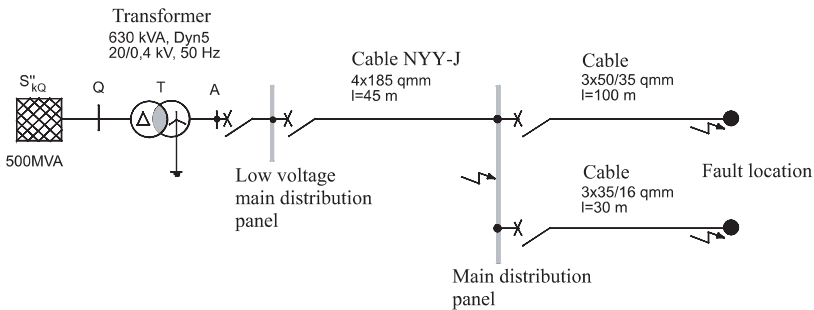


Fig. 18.10: Example 8: Network diagram

Medium voltage:

$$Z_{Qt} = \frac{1.1 \cdot U_{nT}^2}{S_Q} = \frac{1.1 \cdot (400V)^2}{500MVA} = 0.352m\Omega$$

$$R_Q = 0.1 \cdot X_Q = 0.1 \cdot 0.35 = 0.0352m\Omega$$

Transformer:

$$u_x = \sqrt{u_k^2 - u_R^2} = 5.9\%$$

$$R_T = \frac{u_{Rr} \cdot U_{nT}^2}{100\% \cdot S_{rT}} = 2.8m\Omega$$

$$X_T = \frac{u_{xr} \cdot U_{nT}^2}{100\% \cdot S_{rT}} = 15m\Omega$$

Supply cables:

$$R'_1 = 0.101\Omega/km$$

$$X'_1 = 0.08\Omega/km$$

$$R_{l1} = r' \cdot l = 4.545m\Omega$$

$$X_{l1} = x' \cdot l = 3.6m\Omega$$

Main low voltage distributor (three-pole short circuit):

$$\underline{Z}_k = R_{Qt} + R_T + R_{l1} + j(X_{Qt} + X_T + X_{l1})$$

$$\underline{Z}_k = (0.0352 + 2.8 + 4.545)m\Omega + j(0.352 + 15 + 3.6)m\Omega$$

$$\underline{Z}_k = (7.38 + j18.952)m\Omega$$

$$Z_k = \sqrt{7.38^2 + 18.952^2}m\Omega = 20.34m\Omega$$

$$I''_{k3} = \frac{c \cdot U_{nT}}{\sqrt{3} \cdot Z_k} = \frac{400V}{\sqrt{3} \cdot 20.34m\Omega} = 11.35kA$$

$$\frac{R_k}{X_k} = \frac{7.38m\Omega}{18.952m\Omega} = 0.389 \text{ from Fig. 11.6 we get } \kappa = 1.32$$

$$i_p = \kappa \cdot \sqrt{2} \cdot I''_{k3} = 1.32 \cdot \sqrt{2} \cdot 11.35kA = 21.26kA$$

Supply lines (cables and lines):

$$R_{l2} = r \cdot l = 35.71m\Omega$$

$$X_{l2} = x \cdot l = 0.08\Omega/km \cdot 0.100km = 8m\Omega$$

$$Z_k = \sqrt{35.71^2 + 8^2}m\Omega = 36.6m\Omega$$

Sub-distribution I (three-pole short circuit):

$$Z_k = (20.34 + 36.6)m\Omega = 57m\Omega$$

$$I''_{k3} = \frac{c \cdot U_{nT}}{\sqrt{3} \cdot Z_k}$$

$$I''_{k3} = \frac{400V}{\sqrt{3} \cdot 57m\Omega} = 4.05kA$$

$$i_p = \kappa \cdot \sqrt{2} \cdot I''_{k3} = 5.88kA$$

Sub-distribution II (three-pole short circuit):

$$R_{l3} = \frac{l}{\kappa \cdot S}$$

$$R_{l3} = \frac{30m}{56 \frac{m}{\Omega mm^2} \cdot 35mm^2} = 15.3m\Omega$$

$$X_{l3} = x \cdot l = 0.08\Omega/km \cdot 30m = 2.4m\Omega$$

$$Z_k = R_{Qt} + R_T + R_{l1} + R_{l3} + j(X_{Qt} + X_T + X_{l1} + X_{l3})$$

$$= (22.68 + j21.352)m\Omega$$

$$Z_k = \sqrt{R^2 + X^2} = 31.15m\Omega$$

$$I''_{k3} = \frac{c \cdot U_{nT}}{\sqrt{3} \cdot Z_k}$$

$$I''_{k3} = \frac{1.0 \cdot 400V}{\sqrt{3} \cdot 31.15m\Omega} = 7.4kA$$

$$i_p = \kappa \cdot \sqrt{2} \cdot I''_{k3} = 11.1kA$$

18.9

Example 9: Meshed network

Given a meshed network as shown in Figure 19.11

1. Calculate the impedances.
2. Carry out the network transformations.
3. Calculate the three-pole short circuit currents and the peak short circuit currents at the fault location F.

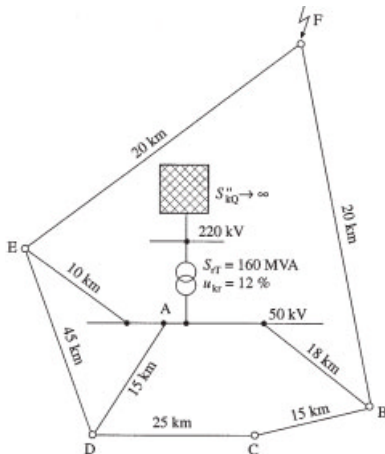


Fig. 18.11: Example 9: Meshed network

The following data are given:

with $S_{rT} = 160 \text{ MVA}$, $u_k = 12\%$, $U_n = 50 \text{ kV}$ and $Z = 0.5\Omega/\text{km}$ for all lines

The impedance of the transformer is:

$$Z_T = \frac{u_k \cdot U_n^2}{100 \cdot S_{rT}} = \frac{12\% \cdot (50 \text{ kV})^2}{100\% \cdot 160 \text{ MVA}} = 1.875\Omega$$

The impedances of the individual conductors:

$$Z_{AE} = 10 \text{ km} \cdot 0.5 \frac{\Omega}{\text{km}} = 5\Omega$$

$$Z_{AD} = 15 \text{ km} \cdot 0.5 \frac{\Omega}{\text{km}} = 7.5\Omega$$

$$Z_{AB} = 18 \text{ km} \cdot 0.5 \frac{\Omega}{\text{km}} = 9\Omega$$

$$Z_{ED} = 45 \text{ km} \cdot 0.5 \frac{\Omega}{\text{km}} = 22.5\Omega$$

$$Z_{EF} = 20 \text{ km} \cdot 0.5 \frac{\Omega}{\text{km}} = 10\Omega$$

$$Z_{BD} = 40 \text{ km} \cdot 0.5 \frac{\Omega}{\text{km}} = 20\Omega$$

$$Z_{BF} = 20 \text{ km} \cdot 0.5 \frac{\Omega}{\text{km}} = 10\Omega$$

Transformation of the delta star impedances (Figure 17.17b):

$$Z_{AG} = \frac{Z_{AE} \cdot Z_{AD}}{Z_{AD} + Z_{AE} + Z_{ED}} = \frac{5 \cdot 7.5}{7.5 + 5 + 22.5} = 1.07\Omega$$

$$Z_{EG} = \frac{Z_{AE} \cdot Z_{ED}}{Z_{AD} + Z_{AE} + Z_{ED}} = \frac{5 \cdot 22.5}{7.5 + 5 + 22.5} = 3.21\Omega$$

$$Z_{DG} = \frac{Z_{AD} \cdot Z_{ED}}{Z_{AD} + Z_{AE} + Z_{ED}} = \frac{7.5 \cdot 22.5}{7.5 + 5 + 22.5} = 4.82\Omega$$

Addition of series impedances (Figure 17.17c):

$$Z_{EG} + Z_{EF} = Z_{GEF} = 13.21\Omega$$

$$Z_{DG} + Z_{BD} = Z_{GDB} = 24.82\Omega$$

Transformation of the delta star impedances (Figure 17.17d):

$$Z_{AH} = \frac{Z_{AB} \cdot Z_{AG}}{Z_{AB} + Z_{AG} + Z_{GDB}} = \frac{9 \cdot 1.07}{9 + 1.07 + 24.82} = 0.276\Omega$$

$$Z_{BH} = \frac{Z_{AB} \cdot Z_{GDB}}{Z_{AB} + Z_{AG} + Z_{GDB}} = \frac{9 \cdot 24.82}{9 + 1.07 + 24.82} = 6.397\Omega$$

$$Z_{GH} = \frac{Z_{AG} \cdot Z_{GDB}}{Z_{AB} + Z_{AG} + Z_{GDB}} = \frac{1.07 \cdot 24.82}{9 + 1.07 + 24.82} = 0.76\Omega$$

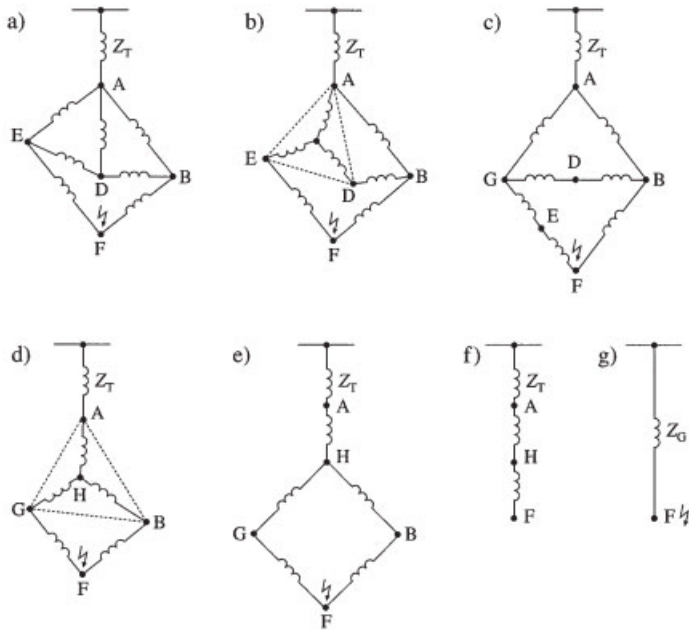


Fig. 18.12: Delta star transformations

Addition of series impedances (Figure 17.17e):

$$Z_{GH} + Z_{GEF} = Z_{HGF} = 0.76\Omega + 13.21\Omega = 13.97\Omega$$

$$Z_{BH} + Z_{BF} = Z_{HBF} = 6.7\Omega + 10\Omega = 16.4\Omega$$

Calculation of parallel impedances (Figure 17.17f):

$$Z_{HF} = \frac{Z_{HGF} \cdot Z_{HBF}}{Z_{HGF} + Z_{HBF}} = 7.54\Omega$$

Sum of all impedances (Figure 17.17g):

$$Z_k = Z_T + Z_{AH} + Z_{HF} = 9.69\Omega$$

$$I''_{k3} = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_k} = \frac{1.1 \cdot 50kV}{\sqrt{3} \cdot 9.69\Omega} = 3.26kA$$

$$S''_{k3} = \frac{c \cdot U_n^2}{Z_k} = \frac{1.1 \cdot (50kV)^2}{9.69\Omega} = 282.5MVA$$

$$i_p = 1.8 \cdot \sqrt{2} \cdot I''_{k3} = 1.8 \cdot \sqrt{2} \cdot 3.26kA = 8.29kA$$

18.10

Example 10: Supply to a factory

A factory is supplied from an overhead line and cables with two transformers, as shown in Figure 19.13.

1. Calculate the impedances at the fault locations.
2. Calculate I''_{k3} at the fault locations.

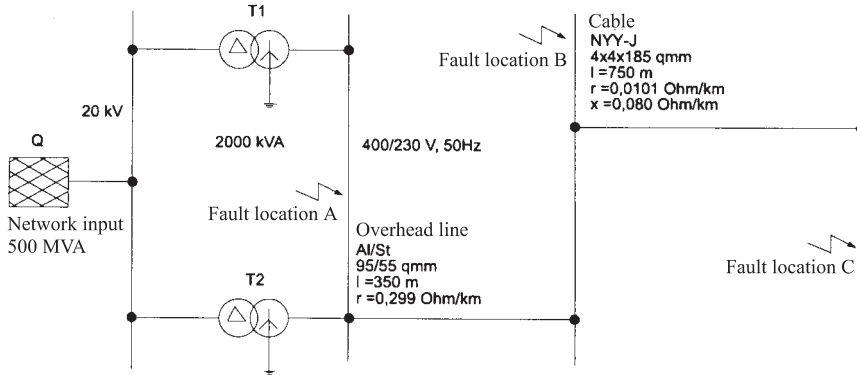


Fig. 18.13: Supply to a factory

Impedances at the fault locations:

$$Z_{Qt} = \frac{c \cdot U_{nQ}^2}{S''_{kQ}} = \frac{1.1 \cdot (0.4 \text{ kV})^2}{500 \text{ MVA}} = 0.352 \text{ m}\Omega$$

$$X_{Qt} = 0.995 \cdot Z_{Qt} = 0.995 \cdot 0.352 \text{ m}\Omega = 0.35 \text{ m}\Omega$$

$$R_{Qt} = 0.1 \cdot X_{Qt} = 0.1 \cdot 0.35 \text{ m}\Omega = 0.035 \text{ m}\Omega$$

$$Z_T = \frac{u_{kr}}{100\%} \cdot \frac{U_{rT}^2}{\sum S_{rT}} = \frac{6\%}{100\%} \cdot \frac{(400 \text{ V})^2}{4 \text{ MVA}} = 2.4 \text{ m}\Omega$$

$$R_T = \frac{u_{Rr}}{100\%} \cdot \frac{U_{rT}^2}{S_{rT}} = \frac{1.05\%}{100\%} \cdot \frac{(400 \text{ V})^2}{4 \text{ MVA}} = 0.42 \text{ m}\Omega$$

$$X_T = \sqrt{Z_T^2 - R_T^2}$$

$$X_T = \sqrt{2.4^2 - 0.42^2} \text{ m}\Omega = 2.363 \text{ m}\Omega$$

Overhead line:

$$R_F = r' \cdot l = 0.299 \Omega/\text{km} \cdot 0.350 \text{ km} = 104.7 \text{ m}\Omega$$

$$X_F = x' \cdot l = 0.075 \Omega/\text{km} \cdot 0.350 \text{ km} = 26.3 \text{ m}\Omega$$

$$Z_F = \sqrt{R^2 + X^2} = \sqrt{104.7^2 + 26.3^2} \text{ m}\Omega = 107.95 \text{ m}\Omega$$

Cables:

$$R_k = r' \cdot \frac{l}{n} = 0.101\Omega/\text{km} \cdot \frac{0.750\text{km}}{4} = 18.94\text{m}\Omega$$

$$X_k = x' \cdot \frac{l}{n} = 0.080\Omega/\text{km} \cdot \frac{0.750\text{km}}{4} = 15\text{m}\Omega$$

$$Z_k = \sqrt{R^2 + X^2} = \sqrt{18.94^2 + 15^2}\text{m}\Omega$$

$$Z_k = 24.16\text{m}\Omega$$

$$Z_{kA} = Z_{QT} + Z_T = 2.75\text{m}\Omega$$

Short circuit at position A:

$$I''_{k3} = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_{kA}} = \frac{1.0 \cdot 400\text{V}}{\sqrt{3} \cdot 2.75\text{m}\Omega} = 83.98\text{kA}$$

Three-pole short circuit at position B:

$$Z_{kB} = Z_{kA} + Z_F = 2.75\text{m}\Omega + 107.95\text{m}\Omega = 110.7\text{m}\Omega$$

$$I''_{k3} = \frac{1.0 \cdot 400\text{V}}{\sqrt{3} \cdot 110.7\text{m}\Omega} = 2.09\text{kA}$$

Short circuit at position C:

$$Z_{kC} = Z_{kB} + Z_K = 110.7\text{m}\Omega + 24.16\text{m}\Omega = 134.86\text{m}\Omega$$

$$I''_{k3} = \frac{1.0 \cdot 400\text{V}}{\sqrt{3} \cdot 134.86\text{m}\Omega} = 1.71\text{kA}$$

18.11

Example 11: Calculation with impedance corrections

Given the network diagram shown in Figure 19.14

1. Calculate the impedances at the fault locations.
2. Calculate the impedance corrections.
3. Calculate the transferred short circuit currents.
4. Calculate I''_{k3} , i_{p3} and I_a .

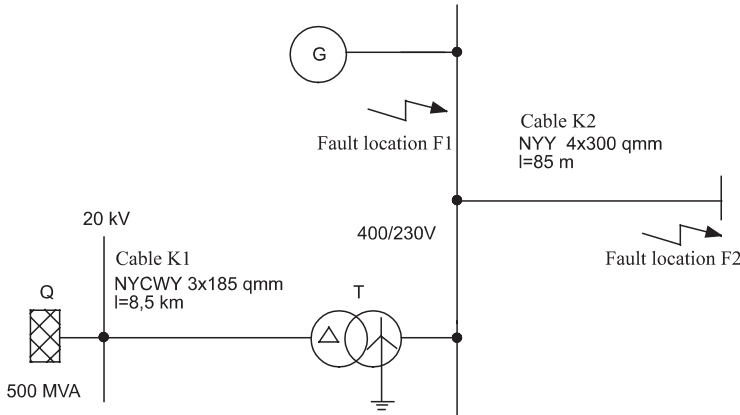


Fig. 18.14: Calculation with impedance corrections

The following data are known:

Transformer:

$$S_{rT} = 1000 \text{ kVA}, \text{ connection symbol: Dyn5}, u_{krT} = 6\%, u_{RrT} = 1.05\%$$

Generator:

$$S_{rG} = 600 \text{ kVA}, U_{rG} = 0.4 \text{ kV}, \cos \varphi_{rG} = 0.8, x''_d = 12\%, x''_{(0)G} = 8\%$$

Cable K1:

$$r' = 0.105 \Omega/\text{km}, x' = 0.072 \Omega/\text{km}$$

Cable K2:

$$r' = 0.066 \Omega/\text{km}, x' = 0.079 \Omega/\text{km}, \frac{R_{0L}}{R_L} = 4, \frac{X_{0L}}{X_L} = 3.66.$$

Impedances of the network feed-in:

$$\underline{Z}_Q = \frac{1.1 \cdot U_n^2}{S''_{kQ}} = \frac{1.1 \cdot (20 \text{ kV})^2}{500 \text{ MVA}} = 0.88 \Omega$$

$$\underline{Z}_Q = \sqrt{R_Q^2 + X_Q^2}$$

$$X_Q = \frac{\underline{Z}_Q}{1.005} = \frac{0.88 \Omega}{1.005} = 0.8756 \Omega$$

$$R_Q = 0.1 \cdot 0.8756 \Omega = 0.08756 \Omega$$

$$\underline{Z}_Q = (0.08756 + j0.8756) \Omega$$

Impedances of the supply cable:

$$\underline{Z}_{K1} = l \cdot (r' + jx') = 8.5 \text{ km} (0.105 + j0.072) \Omega/\text{km} = (0.8925 + j0.612) \Omega$$

$$\underline{Z}_{G1} = \underline{Z}_Q + \underline{Z}_K = (0.98 + j1.4876) \Omega$$

$$\underline{Z} = \underline{Z}_{G1} \left(\frac{U_{rTLV}}{U_{rTHV}} \right)^2 = (0.98 + j1.4876) \left(\frac{0.4\text{kV}}{20\text{kV}} \right)^2$$

$$= (0.000392 + j0.000595)\Omega$$

$$u_{xrT} = \sqrt{u_{krT}^2 - u_{rRT}^2} = \sqrt{(6^2 - 1.05^2)\%} = 5.9\%$$

$$R_T = \frac{u_{rRT}}{100\%} \frac{U_{rTLV}^2}{S_{rT}} = \frac{1.05\%}{100\%} \frac{(0.4\text{kV})^2}{1000\text{kVA}} = 0.00168\Omega$$

$$X_T = \frac{u_{xrT}}{100\%} \frac{U_{rTLV}^2}{S_{rT}} = \frac{5.9\%}{100\%} \frac{(0.4\text{kV})^2}{1000\text{kVA}} = 0.00944\Omega$$

$$\underline{Z}_T = (0.00168 + j0.00944)\Omega$$

$$\underline{Z}_G = \underline{Z} + \underline{Z}_T = (0.002072 + j0.01)\Omega$$

$$Z_G = 0.01\Omega$$

$$X_{Gen} = X_d'' = \frac{x_d'' \cdot U_{rG}^2}{100\% \cdot S_{rG}} = \frac{12\%}{100\%} \frac{(0.4\text{kV})^2}{600\text{kVA}} = 0.032\Omega$$

$$R_{Gen} = 0.15 \cdot X_d'' = 0.15 \cdot 0.032\Omega = 0.0048\Omega$$

Correction for generator impedance:

$$K_G = \frac{U_n}{U_{rG}} \cdot \frac{c_{max}}{1 + X_d'' \cdot \sin\varphi_{rG}} = \frac{0.4\text{kV}}{0.4\text{kV}} \frac{1}{1 + 0.12 \cdot 0.6} = 0.93$$

$$\underline{Z}_{GK} = K_G \cdot \underline{Z}_G = 0.93 \cdot (0.048 + j0.0298)\Omega$$

$$Z_{GK} = \sqrt{0.0445^2 + 0.0298^2}\Omega = 0.0536\Omega$$

Calculation of initial symmetrical short circuit current:

Contribution of network feed-in:

$$I_{k3}'' = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_G} = \frac{1.0 \cdot 0.4\text{kV}}{\sqrt{3} \cdot 0.01\Omega} = 23.09\text{kA}$$

Contribution of generator:

$$I_3'' = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_{Gen}} = \frac{1.0 \cdot 0.4\text{kV}}{\sqrt{3} \cdot 0.0536\Omega} = 4.31\text{kA}$$

Sum of transferred short circuit currents:

$$\sum I_{k3}'' = I_{k3Net}'' + I_{k3Gen}'' = 27.4\text{kA}$$

Calculation of peak short circuit currents:

Contribution of network feed-in:

$$i_{p3Net} = \kappa \cdot \sqrt{2} \cdot I''_{k3}$$

$$\frac{R}{X} = \frac{0.002072}{0.01} = 0.2 \quad \kappa = 1.58$$

$$i_{p3Net} = 1.58 \cdot \sqrt{2} \cdot 23.09kA = 51.59kA$$

Contribution of generator:

$$i_{p3Gen} = \kappa \cdot \sqrt{2} \cdot I''_{k3Gen}$$

$$\frac{R}{X} = 0.15 \longrightarrow \kappa = 1.03$$

$$i_{p3Net} = 1.03 \cdot \sqrt{2} \cdot 4.31kA = 10.36kA$$

Sum of transferred short circuit currents:

$$\sum i_{p3} = i_{p3Net} + i_{p3Gen} = 61.95kA$$

Calculation of symmetrical cut-off current:

Contribution of network feed-in:

$$I_{aNet} = I''_{k3Net} = 23.09kA \quad (\text{far from generator})$$

Contribution of generator:

$$I_{aGen} = \mu \cdot I''_{k3Gen} = 0.755 \cdot 4.31kA = 3.25kA$$

$$I_{rG} = \frac{S_{rG}}{\sqrt{3} \cdot U_{rG}} = \frac{600kVA}{\sqrt{3} \cdot 0.4kV} = 866A$$

$$\frac{I''_{k3Gen}}{I_{rG}} = \frac{4.31kA}{0.866kA} = 4.98$$

Sum:

$$\sum I_a = I_{a3Net} + I_{a3Gen} = 26.34kA$$

Total impedance at fault location F1:

$$\begin{aligned} Z_p &= \frac{Z_G \cdot Z_{GK}}{Z_G + Z_{GK}} = \frac{(0.00207 + j0.01) \cdot (0.0445 + j0.0298)}{(0.00207 + j0.01) + (0.0445 + j0.0298)} \Omega \\ &= \frac{-0.000206 + j0.000507}{0.0466 + j0.0398} \Omega \\ &= 0.00282 + j0.00847 \Omega \end{aligned}$$

$$Z_G = \sqrt{0.00282^2 + 0.00847^2} \Omega = 0.00893 \Omega$$

Impedances of cable K2:

$$\begin{aligned}\underline{Z}_{k2} &= l(r' + jx') = 0.085 \text{ km} \cdot (0.066 + j0.079) \Omega/\text{km} \\ &= (0.00561 + j0.006715) \Omega\end{aligned}$$

$$\begin{aligned}\underline{Z}_k &= \underline{Z}_p + \underline{Z}_{k2} \\ &= (0.00282 + j0.00847) \Omega + (0.00561 + j0.006715) \Omega \\ &= (0.00843 + j0.0152) \Omega\end{aligned}$$

$$\underline{Z}_k = \sqrt{(0.00843 + 0.0152)^2} \Omega = 0.0174 \Omega$$

The initial symmetrical short circuit current is then:

$$I''_{k3} = \frac{c \cdot U_n}{\sqrt{3} \cdot \underline{Z}_k} = \frac{0.4 \text{ kV}}{\sqrt{3} \cdot 0.0174 \Omega} = 13.3 \text{ kA}$$

18.12**Example 12: Connection of a transformer through an external network and a generator**

A transformer is connected through an external network and a generator as shown in Figure 19.15.

1. Calculate the impedances at the fault location
2. Calculate I''_{k3} , I''_{k2E} , I''_{k2} and I''_{k1} at the fault location.
3. Which is the largest current?

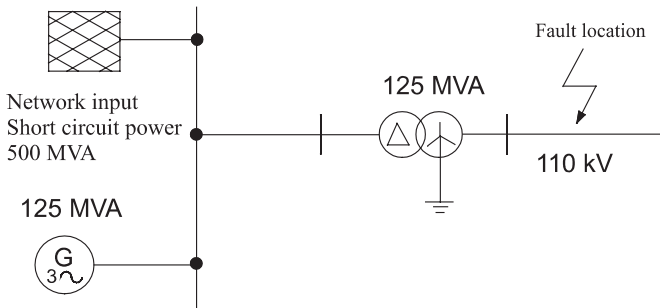


Fig. 18.15: Example 12: Connection of a transformer through an external network and a generator

Generator:

$$X''_d = x''_d \cdot \frac{(1.05 \cdot U_n)^2}{S_{rG}} = 0.12 \cdot \frac{(1.05 \cdot 110 \text{ kV})^2}{500 \text{ MVA}} = 12.8 \Omega$$

Network:

$$Z_{Qt} = \frac{1.1 \cdot U_n^2}{S''_{kQ}} = \frac{1.1 \cdot (110kV)^2}{125MVA} = 26.62\Omega$$

Transformer:

$$Z_T = \frac{u_R}{100\%} \cdot \frac{U_n^2}{S_{rT}} = 0.15 \cdot \frac{(110kV)^2}{125MVA} = 14.52\Omega$$

Parallel impedance:

$$Z_p = \frac{Z_{Gt} \cdot Z_{Qt}}{Z_{Gt} + Z_{Qt}} = \frac{(12.8 \cdot 26.62)\Omega}{(12.8 + 26.62)\Omega} = 8.64\Omega$$

Three-pole current:

$$I''_{k3} = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_G} = \frac{1.1 \cdot 110kV}{\sqrt{3} \cdot 23.16\Omega} = 3kA$$

Single-pole short circuit current:

$$I''_{k1} = \frac{\sqrt{3} \cdot c \cdot U_n}{Z_1 + Z_2 + Z_0}$$

Positive-sequence system: $Z_1 = 23.16\Omega$

Negative-sequence system: $Z_2 = Z_1$

Zero-sequence system: $R_0 = 0, X_0 = 0.75 \cdot X_1 = 0.75 \cdot 14.52\Omega = 10.89\Omega$

$$I''_{k1} = \frac{\sqrt{3} \cdot 1.1 \cdot 110kV}{|2 \cdot 23.16\Omega + 10.89\Omega|} = 3.66kA$$

Two-pole short circuit current with contact to ground:

$$I''_{k2E} = \frac{\sqrt{3} \cdot c \cdot U_n}{\left| Z_0 + Z_1 + Z_0 \cdot \frac{Z_1}{Z_2} \right|} = \frac{\sqrt{3} \cdot 1.1 \cdot 110kV}{\left| 10.89 + 23.16 + 10.89 \cdot \frac{23.16}{23.16} \right| \Omega} = 4.66kA$$

Two-pole short circuit current without contact to ground:

$$I''_{k2} = \frac{c \cdot U_n}{Z_1 + Z_2} = \frac{c \cdot U_n}{2 \cdot Z_1} = \frac{\sqrt{3}}{\sqrt{2}} \cdot I''_{k3} = 3.67kA$$

The two-pole short circuit current with contact to ground is the largest.

18.13

Example 13: Motors in parallel and their contributions to the short circuit current

In a 20/6 kV network as in Figure 19.16 there are four motors connected, with the following data:

Transformer:

$S_{rT} = 25 \text{ MVA}, u_{krT} = 13\%, 20/6.3 \text{ kV}.$

Motors 1 and 2:

$$2xP_{rm} = 2.3 \text{ MW}, U_{rG} = 6 \text{ kV}, \cos\varphi_{rG} = 0.86,$$

$$p = 2, I_a/I_{rm} = 5, \eta = 0.97.$$

Motors 3 and 4:

$$2xP_{rm} = 0.36 \text{ MW}, U_{rG} = 6 \text{ kV}, \cos\varphi_{rG} = 0.87,$$

$$p = 1, I_a/I_{rm} = 5.5, \eta = 0.98.$$

1. Calculate the reactances.
2. Calculate the currents at the motors.
3. Calculate the cut-off currents at the motors.

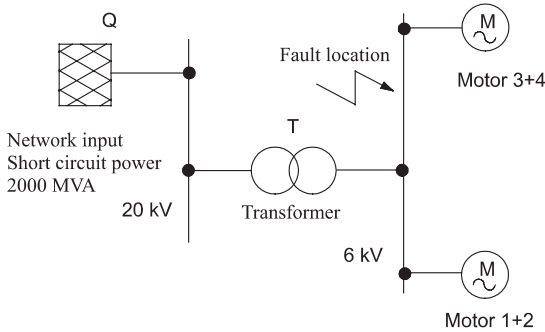


Fig. 18.16: Example 13: Influence of motors on the current

Network input:

$$Z_{Qt} = \frac{c \cdot U_{nQ}^2}{S''_{kQ}} \cdot \frac{1}{f^2} = \frac{1.1 \cdot (20 \text{ kV})^2}{1000 \text{ MVA}} \cdot \frac{(6.3 \text{ kV})^2}{(20 \text{ kV})^2} = 0.044 \Omega$$

Transformer:

$$Z_T = \frac{u_{krT}}{100\%} \cdot \frac{U_{rTUS}^2}{S_{rT}} = \frac{13\%}{100\%} \cdot \frac{(6.3 \text{ kV})^2}{25 \text{ MVA}} = 0.206 \Omega$$

Impedance:

$$Z_k = Z_{Qt} + Z_T = 0.25 \Omega$$

Initial current without motors:

$$I''_{k3} = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_k} = \frac{1.1 \cdot 6 \text{ kV}}{\sqrt{3} \cdot 0.25 \Omega}$$

Impedances for the asynchronous machines:

$$Z_{m1} = \frac{1}{2} \cdot \frac{\eta \cdot \cos\varphi}{I_{an}/I_{rm}} \cdot \frac{U_{rm}^2}{P_{rm}} = \frac{1}{2} \cdot \frac{0.86 \cdot 0.97}{5} \cdot \frac{(6 \text{ kV})^2}{2.3 \text{ MVA}} = 1.305 \Omega$$

$$Z_{m2} = \frac{1}{2} \cdot \frac{\eta \cdot \cos\varphi}{I_{an}/I_{rm}} \cdot \frac{U_{rm}^2}{P_{rm}} = \frac{1}{2} \cdot \frac{0.87 \cdot 0.98}{5.5} \cdot \frac{(6 \text{ kV})^2}{0.36 \text{ MVA}} = 7.75 \Omega$$

Transferred currents:

$$I''_{km1} = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_{m1}} = \frac{1.1 \cdot 6kV}{\sqrt{3} \cdot 1.305\Omega} = 2.92kA$$

$$I''_{km2} = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_{m2}} = \frac{1.1 \cdot 6kV}{\sqrt{3} \cdot 7.75\Omega} = 0.492kA$$

Initial symmetrical short circuit current with influence of motors at the position:

$$\begin{aligned} \sum I''_k &= I''_k \text{ (without motors)} + I''_{km1} + I''_{km2} \\ &= 15.24kA + 2.92kA + 0.492kA = 18.65kA \end{aligned}$$

Short circuit power:

$$S''_k = \sqrt{3} \cdot U_n \cdot I''_k = \sqrt{3} \cdot 6kV \cdot 18.65kA = 193.8MVA$$

Calculation of μ factors, with $t = 0.1$ s:

$$I_{rm1} = \frac{S_{rm1}}{\sqrt{3} \cdot U_{rm1}} = 0.221kA$$

$$I_{rm2} = \frac{S_{rm2}}{\sqrt{3} \cdot U_{rm2}} = 0.035kA$$

$$\frac{I''_{km1}}{I_{rm1}} = \frac{2.92kA}{0.221kA} = 11.2 \rightarrow \mu = 0.64$$

$$\frac{I''_{km2}}{I_{rm2}} = \frac{0.492kA}{0.035kA} = 12.1 \rightarrow \mu = 0.634$$

Calculation of q factors:

$$\frac{\text{Motor power}}{\text{pole pair number}} = \frac{2.3MVA}{2} = 1.15 \rightarrow q = 0.587$$

$$\frac{\text{Motor power}}{\text{pole pair number}} = \frac{0.36MVA}{1} = 0.36 \rightarrow q = 0.447$$

Cut-off current of motors:

$$I_{am1} = \mu \cdot q \cdot I''_{km1} = 0.64 \cdot 0.587 \cdot 2.92kA = 1.0997kA$$

$$I_{am2} = \mu \cdot q \cdot I''_{km2} = 0.634 \cdot 0.447 \cdot 0.492kA = 0.139kA$$

$$\sum I_a = 16.4kA$$

18.14

Example 14: Proof of the stability of low voltage systems

For the selection and project management of electrical systems it is necessary to check the short current strength of the operational equipment against the mechanical and thermal stresses resulting from short circuits. This assumes the knowledge required for calculating short circuit currents. In this section the short circuit currents are calculated and the operational equipment is dimensioned. After calculating the required short circuit currents, it must be assessed whether protection during indirect contact and stability against short circuits is ensured.

Tables 19.2 to 19.5 summarize the calculated short circuit currents for Example 1 of this chapter.

Table 19.2: Summary of results for I''_{k1min} at sub-distributor

| <i>Operational equipment</i> | <i>R in mΩ (120 mm²)</i> | <i>R_{PE} in mΩ (70 mm²)</i> | <i>X in mΩ</i> | <i>X_{PE} in mΩ</i> |
|---|---|---|---------------------------|-----------------------------|
| Primary network | – | – | – | – |
| Transformer | 3.5 | | 13 | |
| Cable | 15.68 | 26.88 | 6.8 | 6.8 |
| | Total resistance = 46.06mΩ | | Total reactance = 26.6 mΩ | |
| Short circuit impedance is 53.18 mΩ | | | | |
| Short circuit current $I''_{k1min} = 4.12\text{kA}$ | | | | |

Table 19.3: Summary of results for I''_{k1min} at load

| <i>Operational equipment</i> | <i>R in mΩ (120 mm²)</i> | <i>R_{PE} in mΩ (70 mm²)</i> | <i>X in mΩ</i> | <i>X_{PE} in mΩ</i> |
|---|---|---|---------------------------|-----------------------------|
| Primary network | – | – | – | – |
| Transformer | 3.5 | | 13 | |
| Cable | 15.68 | 26.88 | 6.8 | 6.8 |
| Conductor | 221.4 | 221.4 | 2 | 2 |
| Sum of resistances | 239.78 | 248.28 | 23.8 | 8.8 |
| | Total resistance = 488.86mΩ | | Total reactance = 30.6 mΩ | |
| Short circuit impedance is 489.8 mΩ | | | | |
| Short circuit current $I''_{k1min} = 448\text{A}$ | | | | |

Table 19.4: Summary of results for I''_{k3min} at distributor

| Operational equipment | R in mΩ | X in mΩ |
|---|----------------|----------------|
| Primary network | – | |
| Transformer | 3.5 | 13 |
| Cable | 12.65 | 6.8 |
| Total | 16.15mΩ | 19.8mΩ |
| Short circuit impedance is 25.55mΩ | | |
| Short circuit current $I''_{k3} = 9.14kA$ | | |

Table 19.5 Summary of results for I''_{k3min} at load

| Operational equipment | R in mΩ | X in mΩ |
|--|----------------|----------------|
| Primary network | – | |
| Transformer | 3.5 | 13 |
| Cable | 12.65 | 6.8 |
| Total | 178.6mΩ | 2 |
| Short circuit impedance is 204.25mΩ | | |
| Short circuit current $I''_{k3} = 1.068kA$ | | |

Determination of the peak short circuit current:

$$\kappa = 1.02 + 0.98 \cdot e^{-\frac{3R}{X}}$$

$$\kappa = 1.02 + 0.98 \cdot e^{-\frac{3 \cdot 15.35}{21.8} = -1.138}$$

$$i_p = \kappa \cdot \sqrt{2} \cdot I''_{k3} = 1.138 \cdot \sqrt{2} \cdot 9.14kA = 14.7kA$$

Determination of the thermal equivalent short circuit current:

$$I_{thm} = I''_k \cdot \sqrt{m+n}$$

For far-from-generator short circuits we set $n=1$.

$$m = \frac{1}{2 \cdot f \cdot t_k \cdot \ln(\kappa-1)} [e^{4 \cdot f \cdot t_k \cdot \ln(\kappa-1)} - 1]$$

$$m = \frac{1}{2 \cdot 50Hz \cdot 0.9s \cdot \ln(1.138-1)} [e^{4 \cdot 50Hz \cdot 1s \cdot \ln(1.138-1)} - 1] = 0.005$$

so that the thermal equivalent short circuit current is then:

$$I_{thm} = 9.14kA \cdot \sqrt{0.005 + 1} = 9.16kA$$

Thermal short circuit strength of sub-distributor:

$$I_{thz} = 12.5kA \cdot \sqrt{\frac{S}{0.9S}} = 17.17kA$$

Thermal short circuit strength of main distributor:

$$I_{thz} = 20kA \cdot \sqrt{\frac{S}{0.9S}} = 21.8kA$$

for $t_{th} = 1s$ and $t_k = 0.9s$.

The stability of the main and sub distributors against short circuits is ensured by means of the following stress parameters (Table 19.6):

Table 19.6: Checking the short circuit strength

| 400 V side | Short circuit current calculation | | | Required short circuit current strength | | | |
|-------------------|-----------------------------------|---------|-----------|---|----------|----------|-----------|
| | I''_{k3} | i_p | I_{thm} | I_{sc} | I_{ma} | I_{th} | I_{thz} |
| Main distribution | 17.15kA | 33.95kA | | 20kA | 40kA | | 21.08kA |
| Sub-distribution | 8.58kA | 13.8kA | | 12.5kA | 20kA | 8.6kA | 17.17kA |
| Load | 1kA | | | 6kA | 6kA | | |

18.15

Example 15: Proof of the stability of medium and high voltage systems

The basic network design is shown in single-phase representation with fault locations and with a 110 kV network input, supply lines, transformers and bus bars (Figure 19.17). Figure 19.18 gives the single-phase equivalent circuit, consisting of resistances and reactances, required for the calculation.

The short circuit impedance of the network relative to the 110 kV side is:

$$Z_Q = \frac{c(U_{rQ})^2}{S''_{kQ}} = \frac{1.1(110kV)^2}{5000MVA} = 2.662\Omega$$

$$X_Q = Z_Q = 2.662\Omega$$

The impedance is converted using the square of the transformation ratio t_{max}^2 to give the value relative to the 20 kV side:

$$Z_{Qt} = 2.662\Omega \cdot \frac{1}{t_{max}^2} = 72.1m\Omega$$

$$X_{Qt} = 72.1m\Omega$$

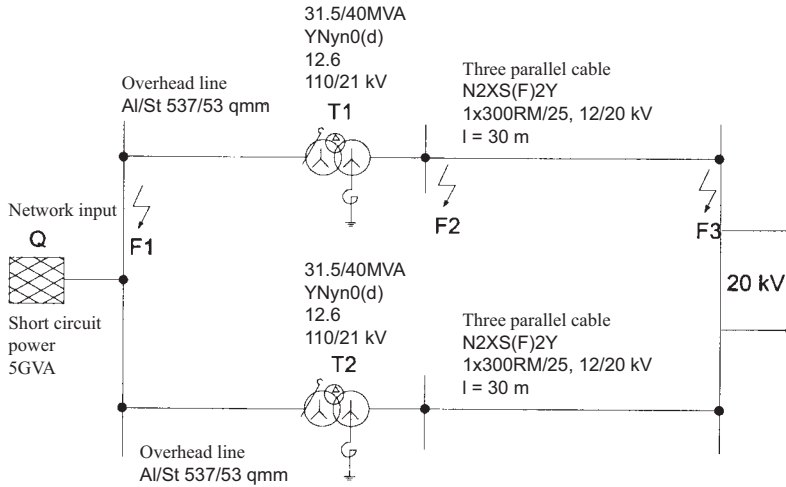


Fig. 18.17: Network design – single-phase representation with network input and transformers

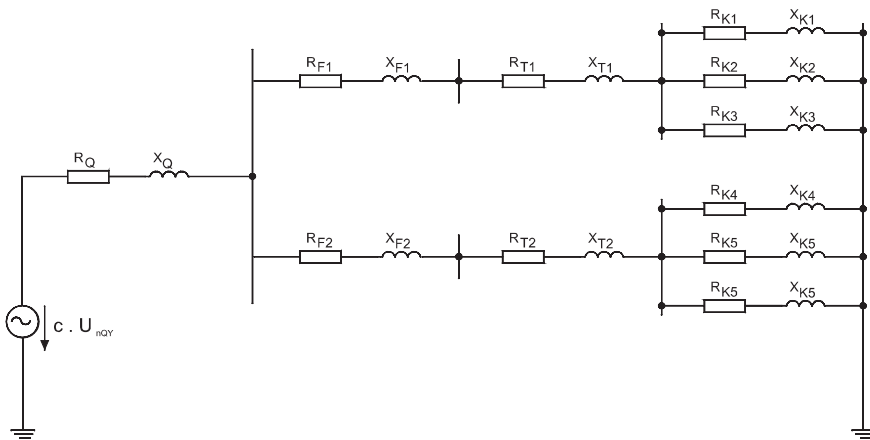


Fig. 18.18: Imaging of operational equipment with equivalent circuit

Checking for far from generator short circuits:
In accordance with IEC 60 909:

$$X_{TSV} \geq 2X_{Qt} = 1.265\Omega \geq 2 \cdot 71.74m\Omega$$

The requirement is therefore satisfied.

Calculation of positive-sequence short circuit impedances for the transformer:

The following data can be taken from the nameplate of the transformer:

11,000 V \pm 16 % in 13 steps (27 settings), 21 kV, 31.5/110 kV.

Maximum setting (step 1):

$$Z_k = 68.8\Omega, I_{TpV} = 124.5/181A, U_{TpV} = 127.6kV$$

Middle setting (step 14m):

$$Z_k = 46.7\Omega, I_{TpV} = 165.3/209.9A, U_{TpV} = 110kV$$

Minimum setting (step 27):

$$Z_k = 30.7\Omega, I_{TpV} = 196.8/249.9A, U_{TpV} = 92.4kV$$

Here, it is necessary to clarify whether, in accordance with DIN VDE 0102, the calculation can be performed only with the middle position. The following relationship holds true:

$$U_{TpV} = U_{nTpV}(1 \pm p_T)$$

p_T is obtained from the relationship:

$$p_T = 0.16 > 0.05$$

The step incrementation must be chosen so that the largest short circuit current occurs. The transformation ratio is:

$$t_{max} = \frac{U_{TpV}}{U_{TSV}} = \frac{127.6kV}{21kV} = 6.08$$

The transformer resistance is found from:

$$R_T = \frac{P_{krT}}{3I_{rTpV}^2} = \frac{136kW}{3 \cdot (209.9A)^2} = 1.03\Omega$$

The impedances are converted to the values relative to the 20 kV side:

$$Z_T = X_T = 46.7\Omega \cdot \frac{1}{t_{max}^2} = 1.265\Omega$$

$$R_T = 1.03\Omega \cdot \frac{1}{t_{max}^2} = 27.84m\Omega$$

Calculation of cable impedances:

The following cable data [29] is given: N2XS(F)2Y 1x300 Rm/25, 12/20 kV:

from the resistance per unit length of the cable, we can calculate the resistance of the cable:

$R' = 0.0601\Omega/km \cdot 30m \cdot \frac{km}{1000m} = 1.8m\Omega$ and with the inductance per unit length of cable $L' = 0.347mH/km$ we can calculate the inductance of the cable:

$$X' = 2\pi \cdot 50Hz \cdot 0.347mH/km = 109m\Omega/km \cdot 30m = 3.27m\Omega.$$

Overland lines:

The overland lines are of type Al/St 537/53 mm². Due to the large cross-section, the resistances expected can be neglected.

Calculation of short circuit currents for different fault locations:

For the dimensioning of operational equipment the short circuit currents are calculated according to Figure 19.19. First, a three-pole short circuit with simple input through parallel current paths is calculated.

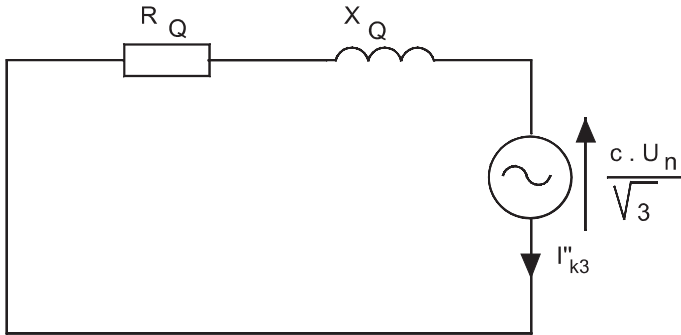


Fig. 18.19: Equivalent circuit in the positive-sequence system at fault location F1

The data for the resistance values in the short circuit current path are:

$$\begin{aligned} Z_Q & 2.662\Omega \\ X_Q & 2.662\Omega \\ R_Q & 0 \end{aligned}$$

The calculation of the initial symmetrical short circuit current results from:

$$I''_k = \frac{c(U_{rQ})}{\sqrt{3}Z_k} = \frac{1.1 \cdot 110kV}{\sqrt{3} \cdot 2.662\Omega} = 26.24kA$$

$$I''_k = I_k = I_a = 26.24kA$$

$$\frac{R_k}{X_k} = \frac{R_Q}{X_Q} = \frac{0}{2.662} = 0$$

κ is obtained from the relationship:

$$\kappa = 1.02 + 0.98e^0 = 2$$

We can then determine the peak short circuit current with.

$$i_p = 2 \cdot \sqrt{2} \cdot 26.24kA = 74.23kA$$

Three-pole short circuit on transformer bus bar

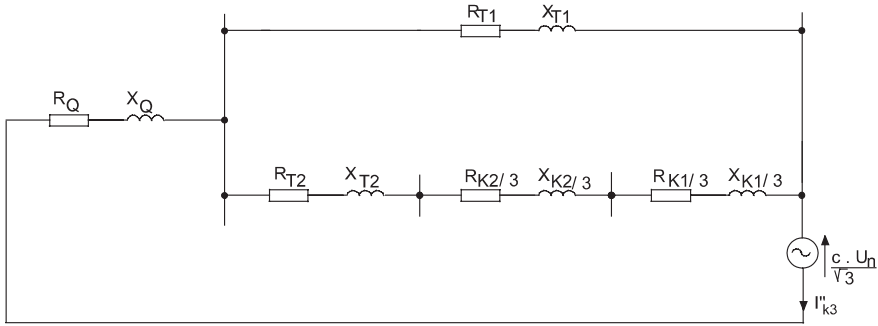


Fig. 18.20: Equivalent circuit in the positive-sequence system at fault location F2

The three-pole short circuit on the transformer bus bar (Figure 19.20) is made up of the transferred short circuit currents, which can be calculated as in the following.

The data for the operational equipment in the short circuit current path are (the same values are used for transformers and cables):

| Network feed-in | Transformer | Cable |
|-----------------|---------------|-----------------|
| Z_Q 2.662Ω | Z_T 1265mΩ | $X_K/3$ 1.09mΩ |
| X_Q 2.662Ω | X_T 1265mΩ | $R_K/3$ 0.601mΩ |
| R_Q 0 | R_T 27.87mΩ | $X_K/3$ |

Branch 1:

$$\frac{R_k}{X_k} = \frac{27.87m\Omega}{1265m\Omega} = 0.02203$$

$$R_k = 0.02203 \cdot X_k < 0.3X_{k1}$$

Here we can neglect R_k .

Branch 2:

$$\frac{R_k}{X_k} = \frac{27.87m\Omega + 0.601m\Omega + 0.601m\Omega}{1265m\Omega + 1.09m\Omega + 1.09m\Omega} = 0.02294$$

$$R_k = 0.02294 \cdot X_k < 0.3X_k$$

Here again we can neglect R_k . For the calculation of the initial symmetrical short circuit current we use the reactances.

Short circuit reactance:

$$X_k = X_{Qt} + \frac{X_{T1} (X_{T2} + \frac{X_{k1}}{2} + \frac{X_{k2}}{3})}{X_{T1} + (X_{T2} + \frac{X_{k1}}{3} + \frac{X_{k2}}{3})}$$

$$\begin{aligned} X_k &= 72.1\text{m}\Omega + \frac{1265\text{m}\Omega \cdot (1265\text{m}\Omega + 1.09\text{m}\Omega + 1.09\text{m}\Omega)}{1265\text{m}\Omega + (1265\text{m}\Omega + 1.09\text{m}\Omega + 1.09\text{m}\Omega)} \\ &= 705.1\text{m}\Omega \end{aligned}$$

The initial symmetrical short circuit current is then:

$$\begin{aligned} I''_k &= \frac{cU_{nTSV}}{\sqrt{3}Z_k} = \frac{1.1 \cdot 20\text{kV}}{\sqrt{3} \cdot 705.1\text{m}\Omega} = 18.014\text{kA} \\ I''_k &= I_k = I_a = 18.014\text{kA} \end{aligned}$$

The fictitious magnitude of the initial symmetrical short circuit current is:

$$S''_k = \sqrt{3} \cdot 20\text{kA} \cdot 18.014\text{kA} = 624\text{MVA}$$

Calculation of the transferred short circuit currents:

$$\begin{aligned} \frac{I''_{k-\text{branch2}}}{I''_{k-\text{branch1}}} &= \frac{X_T}{X_T + X_k/3 + X_k/3} = \frac{X_T}{X_T + 2/3 \cdot X_k} = \frac{1}{1 + 2/3 \cdot \frac{X_k}{X_T}} \\ I''_{k-\text{branch2}} &= I''_{k-\text{branch1}} \cdot \frac{1}{1 + 2/3 \cdot \frac{X_k}{X_T}} \end{aligned}$$

The initial symmetrical short circuit current results from the parallel current branches as follows:

$$I''_k = I''_{k-\text{branch1}} + I''_{k-\text{branch2}} + \dots + I''_{k-\text{branchn}}$$

The same conditions therefore apply as for the peak short circuit, cut-off and steady state short circuit currents. We can then determine the transferred short circuit current for the first branch by rewriting the equations:

$$\begin{aligned} I''_{k-\text{branch1}} &= I''_k \cdot \left[\frac{1}{1 + \frac{1}{1 + \frac{2}{3} \cdot \frac{X_k}{X_T}}} \right] \\ I''_{k-\text{branch1}} &= 18.014\text{kA} \cdot \left[\frac{1}{1 + \frac{1}{1 + \frac{2}{3} \cdot \frac{1.09\text{m}\Omega}{1265\text{m}\Omega}}} \right] = 9.0095\text{kA} \end{aligned}$$

For branch 2:

$$I''_{k-\text{branch2}} = I''_k - I''_{k-\text{branch1}} = 18.014\text{kA} - 9.015\text{kA} = 8.999\text{kA}$$

Determination of the peak short circuit current for branch 1:

$$\kappa_1 = 1.02 + 0.98 \cdot e^{-3\frac{R}{X}} = 1.02 + 0.98 \cdot e^{-3 \cdot 0.02203} = 1.937$$

$$i_{p-\text{branch1}} = 1.937 \cdot \sqrt{2} \cdot I''_{k-\text{branch1}} = 1.937 \cdot \sqrt{2} \cdot 9.015\text{kA} = 24.7\text{kA}$$

Determination of the peak short circuit current for branch 2:

$$\kappa_2 = 1.02 + 0.98 \cdot e^{-\frac{3R}{X}} = 1.02 + 0.98 \cdot e^{-3 \cdot 0.02294} = 1.935$$

$$i_{p\text{-branch1}} = 1.935 \cdot \sqrt{2} \cdot I''_{k\text{-branch1}} = 1.937 \cdot \sqrt{2} \cdot 8.999 \text{ kA} = 24.6 \text{ kA}$$

The total peak short circuit current is the sum of the currents in branches 1 and 2:

$$i_p = i_{p\text{-branch1}} + i_{p\text{-branch2}} = 49.32 \text{ kA}$$

Here it must be noted that the transferred short circuit current per cable branch is only one third of the calculated current.

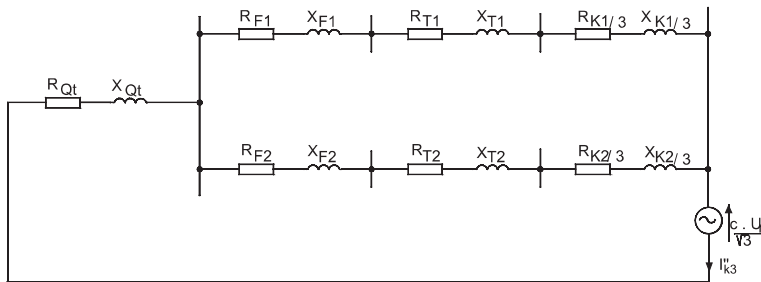
Three-pole short circuit on the 20 kV bus bar:


Fig. 18.21: Equivalent circuit in the positive-sequence system at fault location F3

Only the reactances are used here.

$$X_k = X_{Qt} + \frac{(X_{T1} + \frac{X_{k1}}{3})(X_{T2} + \frac{X_{k2}}{3})}{X_{T1} + \frac{X_{k1}}{3} + X_{T2} + \frac{X_{k2}}{3}}$$

$$\begin{aligned} X_k &= 72.1 \text{ m}\Omega + \frac{(1265 \text{ m}\Omega + 1.09 \text{ m}\Omega) \cdot (1265 \text{ m}\Omega + 1.09 \text{ m}\Omega)}{(1265 \text{ m}\Omega + 1.09 \text{ m}\Omega) + (1265 \text{ m}\Omega + 1.09 \text{ m}\Omega)} \\ &= 705.1 \text{ m}\Omega \end{aligned}$$

$$I''_k = \frac{cU_{nTLV}}{\sqrt{3}Z_k} = \frac{1.1 \cdot 20 \text{ kV}}{\sqrt{3} \cdot 705.1 \text{ m}\Omega} = 18.014 \text{ kA}$$

$$I''_k = I_k = I_a = 18.014 \text{ kA}$$

The fictitious magnitude of the initial symmetrical short circuit current is:

$$S''_k = \sqrt{3} \cdot 20 \text{ kA} \cdot 18.014 \text{ kA} = 624 \text{ MVA}$$

For the peak short circuit current:

$$\frac{R_k}{X_k} = \frac{14.24m\Omega}{705.1m\Omega} = 0.02019$$

$$\kappa = 1.02 + 0.98e^{-3 \cdot 0.02019} = 1.94$$

$$I_p = 1.94 \cdot \sqrt{2} \cdot 18.04kA = 49.5kA$$

Stability of operational equipment against short circuits:

For the short circuit strength of operational equipment we must calculate the dynamic (i_p) and thermal (I_{th}) stresses.

For far-from-generator short circuits:

$$\frac{I''_k}{I_k} = 1 \text{ and therefore } n = 1.$$

In accordance with DIN VDE 0102 we obtain for the thermal effect of the DC aperiodic component m:

$$m = \frac{1}{2 f T_k \ln(\kappa-1)} [e^{4 f T_k \ln(\kappa-1)} - 1]$$

For fault location F3 we calculate m with $T_k = 1s$:

$$m = \frac{1}{2 \cdot 50Hz \cdot 1s \cdot \ln(1.94-1)} [e^{4 \cdot 50Hz \cdot 1s \cdot \ln(1.94-1)} - 1] = 0.162$$

This yields the thermal short-time current:

$$I_{th} = I''_k \sqrt{m+1} = 18kA \cdot \sqrt{0.162+1} = 19.4kA$$

For fault location F1 we calculate m with $T_k = 1s$:

$$I_{th} = I''_k \sqrt{m+1} = 27kA \cdot \sqrt{0.195+1} = 29.5kA$$

Dimensioning the operational equipment:

The calculations (Table 19.7) are summarized in this section in order to make these available for dimensioning. For the dimensioning, the following operating conditions are assumed (Table 19.8). The standard value of the network frequency is 50 Hz. The rated short circuit duration T_k is assumed to be 1 second. The protection technology must be designed and set up in accordance with this. The dimensioning of the circuit breaker is taken from IEC 282 (Table 19.9). The rated short circuit making current of the circuit breaker must be 2.5 times as large as the effective value of the rated short circuit breaking current. If the peak short circuit current above 2.5 times this value, the rated making current must have at least the value of the peak short circuit current.

Table 19.10 gives the rated currents of load interrupter switches. The rated steady state current of the load interrupter switch is dimensioned according to the steady state operating current.

The dimensioning of the disconnect switch and the grounding switch follows from IEC 282 (Table 19.11).

Table 19.7: Current carrying capacities for the 110/20 kV level

| Rated voltage | Rated steady state current | Initial symmetrical short circuit current | Steady state short circuit current | Peak short circuit current | Thermal short-time current |
|----------------------|-----------------------------------|--|---|-----------------------------------|-----------------------------------|
| U_r kV | I_r A | I_k'' kA | I_k kA | i_p kA | I_{th} kA |
| 123 | 420 | 27 | 27 | 75 | 30 |
| 24 | 2200 | 18 | 18 | 50 | 20 |

Table 19.8: Rated voltages for the 110 kV/20 kV level

| Highest voltage for operational equipment | Rated short duration AC voltage | Rated lightning impulse voltage |
|--|--|--|
| U_m kV | U_{RW} kV | U_{rB} kV |
| 24 | 50 | 95 |
| 123 | 230 | 550 |

Table 19.9: Selection values and rated values for load interrupter switches in accordance with IEC 282

| Rated voltage kV | Rated short circuit breaking current kA | Rated operating current A | | | |
|----------------------------|---|----------------------------------|------|------|------|
| | | 800 | 1250 | 1600 | 2000 |
| 123 | 12.5 | x | x | | |
| | 20 | | x | x | x |
| | 25 | | x | x | x |
| | 40 | | | x | |

Table 19.10: Selection values and rated values for load interrupter switches in accordance with IEC 282

| Rated steady state current A | Rated short-time current kA | Rated peak current kA |
|--|---------------------------------------|---------------------------------|
| 630 | 31.5 | 78.75 |

Table 19.11: Selection values and rated values for disconnect switches and grounding switches in accordance with IEC 282

| Rated voltage kV | Rated initial symmetrical short circuit current kA | Rated peak short circuit current | Rated steady state current A | | | |
|------------------|--|----------------------------------|------------------------------|------|------|------|
| | | | 800 | 1250 | 1600 | 2000 |
| 123 | 12.5 | 32 | x | x | | |
| | 20 | 50 | | x | x | x |
| | 25 | 63 | | x | x | x |
| | 40 | 100 | | | x | x |

Dimensioning of the overvoltage surge arrester:

The dimensioning of the overvoltage surge arrester is accomplished with the help of IEC 99–1. The use of a silicon carbide surge arrester is preferred in ground fault neutralizer grounded systems and is connected for the transformer between the conductors and ground. The required quenching voltage and its rated discharge current must be considered during dimensioning. With the load rejection factor $\delta_L = 1.1$ the quenching voltage is:

$$U_L \geq \delta_L \delta \frac{U_m}{\sqrt{3}} = 1.1 \cdot \sqrt{3} \cdot \frac{123kV}{\sqrt{3}} = 135.3kV.$$

In accordance with IEC 99–1 the quenching voltage 138kV is chosen. For the choice of arresters according to the rated discharge current, for networks with above 60kV a 10kA arrester is recommended. The stability against short circuits must be dimensioned so that the short circuit strength remains ensured at currents higher than the expected initial symmetrical short circuit current.

Dimensioning the current inverter:

The dimensioning of the current inverter follows from the short circuit current to be expected, in order to ensure that the transformer does not become quickly saturated and the protection relays are no longer able to correctly sense the short circuit current. The standard values in accordance with IEC 44–1 are: 10, 15, 20, 30, 50, 75 and their decimal multiples or divisions. Here the standard value 30 is chosen.

Dimensioning the voltage transformer:

The standard values are given in IEC 44–2. The information applies to inductive and capacitive transformers. The rated network voltage is the essential parameter for dimensioning. For conductor-conductor voltage transformers, 110 kV and a conductor-ground voltage transformer $\frac{110kV}{\sqrt{3}}$ must be selected. The rated voltage factors are taken from IEC 44–2.

Dimensioning the 20 kV switchgear:

1. Dimensioning the supply line:

- For the dimensioning of the conductors the three-pole short circuit is used as the basis.
- For the loading of the shielding the neutral point connection and the asymmetrical short circuit currents are of greatest importance. The maximum short circuit current is calculated as the double ground fault.

2. Dimensioning the circuit breakers:

The electrical data for the circuit breakers from the manufacturers' catalogs are compared with the data measured (Table 19.12).

Table 19.12: Dimensioning the circuit breakers

| | <i>Values from data sheet</i> kA | <i>Measured values</i> kA |
|--|-------------------------------------|------------------------------|
| Rated short-duration power frequency withstand voltage | 50 | 50 |
| Rated lightning impulse withstand voltage | 125 | 125 |
| Rated short circuit breaking voltage | 25 | 18 |
| Rated short-time current 1s | 25 | – |
| Thermal short-time current 1s | – | 18 |
| Rated short circuit make current | 63 | – |
| Rated short-time current | 25 | – |
| Rated current of bus bar | 2500 A | 2200 A |
| Rated current of branches | 2000 A | – |
| Rated peak current | – | 50 |

At this point an example will be given for the dimensioning of the circuit breakers (Table 19.13) at different connection points to the bus bar (Figure 19.22).

Table 19.13: Dimensioning the circuit breakers

| | <i>Input field</i> kA | <i>Coupling field</i> kA | <i>Load field</i> kA |
|--|--------------------------|-----------------------------|-------------------------|
| Rated current of transformer is 1000 A | | | |
| Rated current of vacuum circuit breaker 1250 A | | | |
| Rated short-duration power frequency withstand voltage | 50 | 50 | 50 |
| Rated lightning impulse withstand voltage | 125 | 125 | 125 |
| Rated short circuit breaking voltage | 16 | 20 | 20 |
| Rated duration of short circuit | 3s | 3s | 3s |
| Rated short circuit make current | 40 | 50 | 40 |
| Rated current | 1250 A | 2000 A | 1250 A |

The dimensioning parameters are the:

- rated short circuit breaking capacity
- rated operating current and
- short circuit current determined by measurement

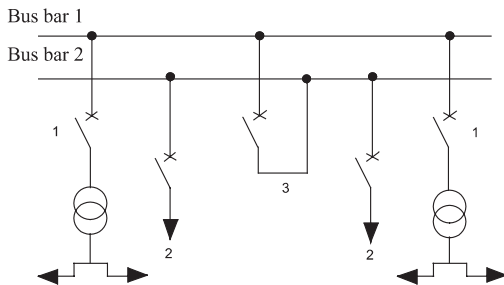


Fig. 18.22: Dimensioning the circuit breakers
1) input field 2) load field 3) coupling field

18.16

Example 16: Calculation for short circuit currents with impedance corrections

Given a 220 kV network with the data for the operational equipment as in Figure 19.23

Calculate the short circuit currents and the impedance corrections.

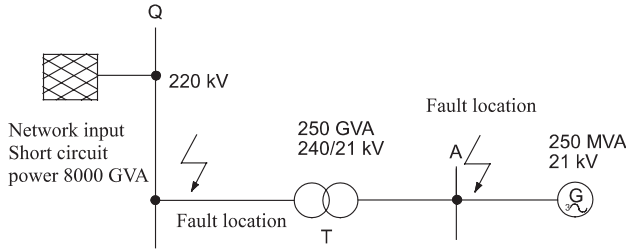


Fig. 18.23: Example 16: Calculation of short circuit currents with impedance corrections

Network:

$$Z_Q = \frac{c \cdot U_{nQ}^2}{S_{kQ}} = \frac{1.1 \cdot (220 \text{ kV})^2}{8000 \text{ MVA}} = 6.65 \Omega$$

Generator:

$$Z_G = \frac{x_d'' \cdot U_{rG}^2}{100\% \cdot S_{rG}} = \frac{17 \cdot (21 \text{ kV})^2}{250 \text{ MVA}} = 0.30 \Omega$$

Correction factor:

$$K_{G,KW} = \frac{c}{1 + x_d'' \cdot \sin \varphi_{rG}} = \frac{1.1}{1 + 0.17 \cdot 0.63} = 0.994$$

Corrected generator impedance:

$$Z_{G,KW} = K_{G,KW} \cdot Z_G = 0.994 \cdot 0.30 \Omega = 0.298 \Omega$$

Block transformer:

$$Z_{THV} = \frac{u_{kr}}{100\%} \frac{U_{rTHV}^2}{S_{rT}}$$

$$Z_{THV} = \frac{15\%}{100\%} \frac{(240 \text{ kV})^2}{250 \text{ MVA}} = 34.56 \Omega$$

$$Z_{TLV} = \frac{u_{kr}}{100\%} \frac{U_{rTLV}^2}{S_{rT}}$$

$$Z_{TLV} = \frac{15\%}{100\%} \frac{(21 \text{ kV})^2}{250 \text{ MVA}} = 0.26 \Omega$$

$$Z_{T,KW} = c \cdot Z_{TLV} = 1.1 \cdot 0.26 \Omega = 0.286 \Omega$$

Calculation of currents in Q:

$$I_k'' = I_{kQ}'' + I_{kKW}''$$

$$I_{kQ}'' = \frac{c \cdot U_{nQ}}{\sqrt{3} \cdot Z_Q} = \frac{1.1 \cdot 220 \text{ kV}}{\sqrt{3} \cdot 6.65 \Omega} = 21 \text{ kA}$$

$$Z_{KW} = K_{KW} \cdot (t_r^2 \cdot Z_G + Z_{THV})$$

$$K_{KW} = \left(\frac{t_f}{t_r}\right)^2 \cdot \frac{c}{1 + (x_d'' - x_T) \cdot \sin \varphi_{rG}}$$

$$K_{KW} = \left(\frac{220kV}{21kV}\right)^2 \cdot \left(\frac{21kV}{240kV}\right)^2 \cdot \frac{1.1}{1 + (0.17 - 0.15) \cdot 0.63} = 0.913$$

$$Z_{KW} = 0.913 \cdot \left[\left(\frac{240kV}{21kV}\right)^2 \cdot 0.30 + 34.56\Omega \right] = 67.32\Omega$$

$$I''_{kKW} = \frac{1.1 \cdot 220kV}{\sqrt{3} \cdot 67.32\Omega} = 2.07kA$$

$$I''_k = 21kA + 2.07kA = 23.07kA$$

Calculation of currents in A:

$$I''_k = I''_{kG} + I''_{kT}$$

$$I''_{kG} = \frac{c \cdot U_{rG}}{\sqrt{3} \cdot Z_{G,KW}} = \frac{1.1 \cdot 21kV}{\sqrt{3} \cdot 0.298\Omega} = 44.75kA$$

$$I''_{kT} = \frac{c \cdot U_{rG}}{\sqrt{3} \cdot (Z_{T,KW} + \frac{1}{t_f^2} \cdot Z_Q)}$$

$$I''_{kT} = \frac{1.1 \cdot 21kV}{\sqrt{3} \cdot (0.286\Omega + (\frac{21kV}{220kV})^2 \cdot 6.65\Omega)} = 38.48kA$$

$$I''_k = 44.75kA + 38.48kA = 83.23kA$$

18.17

Example 17: Calculation with per-unit magnitudes

Given $U_B = 6kV$, $U_B = 20kV$, $S_B = 100MVA$

Calculate Example 13 using per-unit magnitudes.

$$*U = \frac{U}{U_B}$$

$$*I = \frac{I \cdot U_B}{S_B}$$

$$*Z = \frac{Z \cdot S_B}{U_B^2}$$

$$*S = \frac{S}{S_B}$$

Transformation ratio of transformer as per-unit magnitude:

$$*t_r = \frac{U_{rTHV}}{U_{rTLV}} \cdot \frac{U_{B,6kV}}{U_{B,20kV}} = \frac{20kV}{6.3kV} \cdot \frac{6kV}{20kV} = 0.9524$$

Network feed-in:

$${}^*Z_{Qt} = \frac{c \cdot {}^*U_{nQ}^2}{{}^*S''_{kQ}} \cdot \frac{1}{{}^*u_r^2} = \frac{1.1 \cdot (1 \cdot pu)^2}{10pu} \cdot \frac{1}{0.9524^2} = 0.1212pu$$

Transformer:

$${}^*Z_T = \frac{u_{krT}}{100\%} \cdot \frac{U_{rTLV}^2}{S_{rT}} \cdot \frac{S_B}{U_{b,6kV}^2} = \frac{13\%}{10\%} \cdot \frac{(6.3kV)^2}{25MVA} \cdot \frac{100MVA}{(6kV)^2} = 0.5733pu$$

Impedance:

$${}^*Z_k = {}^*Z_{Qt} + {}^*Z_T = 0.6883pu$$

${}^*I''_k$ without motors:

$${}^*I''_k = \frac{c \cdot {}^*U_n}{\sqrt{3} \cdot {}^*Z_k} = \frac{1.1 \cdot 1pu}{\sqrt{3} \cdot 0.6883pu} = 0.923pu$$

Current in kA:

$$I''_k = {}^*I_k \cdot \frac{S_B}{U_{B,6kV}} = 0.923pu \cdot \frac{100MVA}{6kV} = 15.38kA$$

Impedances of motors:

$$\begin{aligned} {}^*Z_{m1} &= \frac{1}{2} \frac{\eta \cdot \cos\varphi}{I_{an}/I_{rm}} \cdot \frac{U_{rm}^2}{U_{B,6kV}^2} = \frac{1}{2} \frac{\eta \cdot \cos\varphi}{I_{an}/I_{rm}} \cdot \frac{S_B}{P_{rm}} \\ &= \frac{1}{2} \cdot \frac{0.86 \cdot 0.97}{5} \cdot \frac{100MVA}{2.3MVA} = 3.63pu \end{aligned}$$

$${}^*Z_{m2} = \frac{1}{2} \cdot \frac{0.87 \cdot 0.98}{5.5} \cdot \frac{100MVA}{0.36MVA} = 21.5pu$$

Transferred currents:

$${}^*I''_{km1} = \frac{c \cdot {}^*U_n}{\sqrt{3} \cdot {}^*Z_{m1}} = \frac{1.1 \cdot 1pu}{\sqrt{3} \cdot 3.63pu} = 0.175pu$$

$$I''_{km1} = 292kA$$

$${}^*I''_{km1} = 0.0295pu$$

$$I''_{km1} = 0.492kA$$

The results are identical with both methods.

Appendices

Calculation Tools for Electrical Engineering

1

The Elaplan Program

Power Networks

With this *Elaplan*-Modul you are able to calculate electrical power networks according DIN VDE 0102 and report them graphically. After doing the corresponding short-circuit calculation the recorded Network Graphic allows you to show the results of any symmetrical and unsymmetrical fault as well as data of the containing elements. In order to review the security in operation of the network you can check the selectivity and calculate the load flow.

Introduction

Login

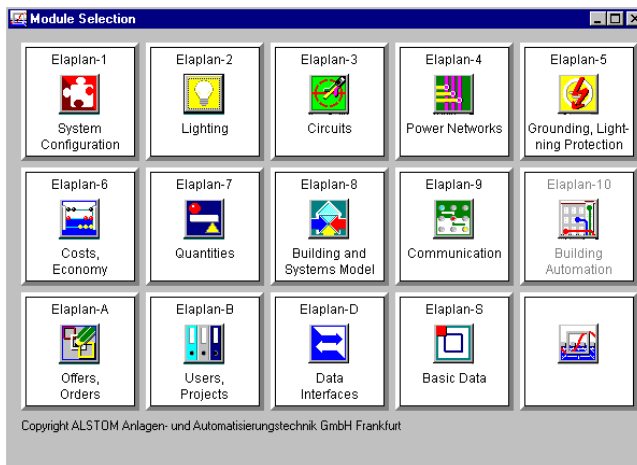
After installation of the software you get entry to the *Elaplan* user platform with the user-ID as follows:

Name: **SYSTEM**

Password: **PASS**

Please note, that there is a difference in use of capitals and small letters at the input.

After selection of the user name you have to change into the input area 'Password' by pressing TAB or by using the mouse. You log on by pressing OK or Enter. The window 'Module Selection' will be shown.



Elaplan-B Users, Projects

Add a Project

You are in the Module Selection of *Elaplan*. Please click onto the Module '*Elaplan-B: Users, Projects*' and then onto the icon 'Project Administration'. With the input area 'Add project' you can create the new project. By pressing OK the project will be saved to your hard disk.

The sub-directory in `\\Elaplan\pro\` has the name of the field 'Project':

Subsequently you can leave the module '*Elaplan-B*', open the desired module, e.g. '*Elaplan-4: Power Networks*' and select the added project.

In the 'Project Administration' you can also copy and delete projects, change their description etc.

There is the possibility to protect a project from unauthorised access and the definition of co-owners of the project, too. Besides common data of a project can be put in.

Do you wish to make changes of the user name described before (user-ID), you have to do this in the program 'User Administration'. Here you can add and change users with the corresponding access rights.

Names and access rights of **standard users** are defined as follows:

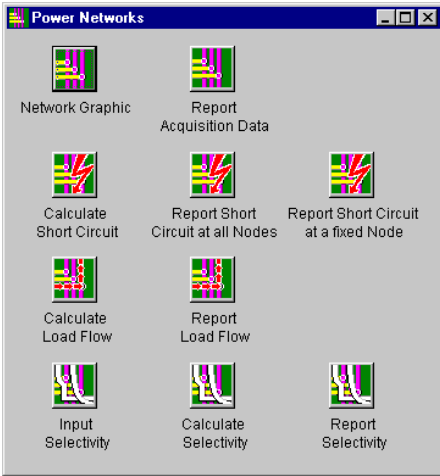
| Name | Password | Access right |
|---------|----------|--|
| Elaplan | PASS | user |
| Daten | PASS | basic data administrator + user |
| System | PASS | basic data administrator + user + user administrator |

You can change the password of a user, too.

With this software several sample-projects of the module are delivered. You can copy them, use them as an example for your first steps with the program module *Elaplan-4: Power Networks* and create some listings, typical for output.

Program Selection Power Networks

In the Module Selection (shown above) double click on the *Elaplan-4* icon. You open the *Elaplan-4* Program Selection, where you can choose the desired program by double click. Now the project you have create in the module 'Users, projects' will be shown for selection.



Program Selection Elaplan-4

The following chapters will describe the working with each of the tasks.

Network Graphic

With the program 'Network Graphic' all elements of the network will be recorded. The chosen arrangement of the elements and their connections will be provided for the output on screen, printer or plotter. By means of the available element symbols this method makes the design of the network graphic simple and easy to survey. Simultaneously the single elements will be connected with the nodes and the busbars of the network.

Graphic recording will be controlled with the menu bar. Additionally the function of the menus 'Edit', 'Element' and '' can be selected by means of symbol bars.

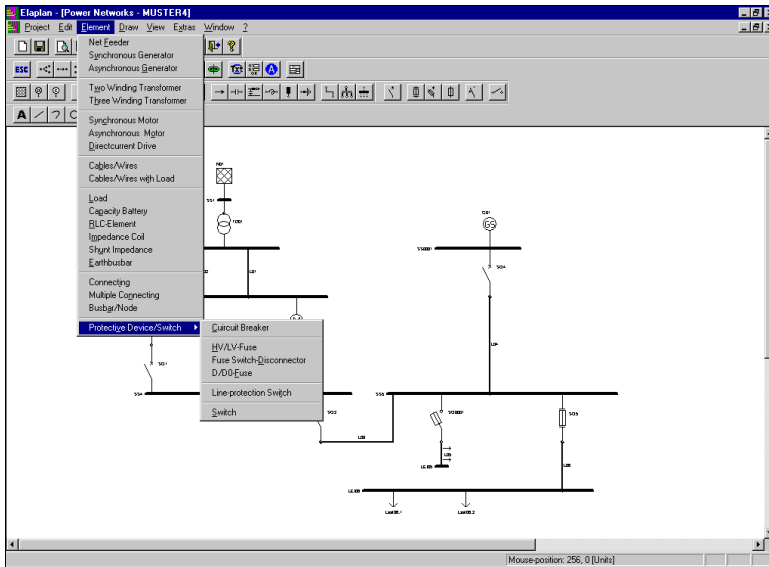
In the status bar of 'Network Graphic' you can see the current position of the mouse in the graphic window. You can change the defaults for position indication in 'Extras/Options' at the register 'General Options'.

Element

In the menu item 'Element' all types of elements are shown, which can be used in the network graphic.

Following types of elements are available: Net feeder, synchronous generator, asynchronous generator, two winding transformer, three winding transformer, synchronous motor, asynchronous motor, directcurrent drive, cables/wires, cables/wires with load, load, capacity battery, RLC-element, impedance coil, shunt impedance, earth busbar and busbar/node. For protective devices you can choose between HV/LV-fuse, line protection switch, circuit breaker, fuse switch-disconnector and D/D0-fuse. For connecting the single element you can use 'Connecting' or 'Multiple Connecting'.

With these elements you can design and output your network graphic.



Elements

The chosen type of element can be selected by clicking the icon in the symbol bar or with help of the menu.

With the mouse you can move the element at any position and confirm the position with the left mouse button.

The shown type of element nearby the mouse position indicator is a little help for the positioning of the element. After a click on the left mouse button the element will be inserted at that position it currently is - next to that grid unit which is the nearest by.



If you want to connect **transformers to earth busbars** the earth busbars must be positioned in the network graphic, but they don't need any **connection** to the network. Connection to the transformers will be made at the input of the network data. This method avoids confusing connection lines in the network graphic, if a lot of transformers will be connected to an earth busbar.



In the network graphic a **switch** kann be set in order to switch on or off parts of network or parts of a project.



Protective devices, switches and busbars will be positioned in the network graphic just like other elements. But their both connecting points must not end at **impedanceless connections**.

With the menu item 'Multiple Connecting' you have a tool to connect various elements to a common busbar quick and easy. After activating of the symbol you click the common busbar at first. Subsequently you click the connecting points of the single elements one after another. This function ends with a double click at the last connecting point.

Die connection lines from the busbar to the connecting points of the chosen elements will be drawn from the program.



With the menu item '**Connecting**' you have the possibility to connect or to lengthen the connection of elements at busbars.

By clicking the right mouse button the object will be rotated. Every mouse click rotates the object on 90°. This allows you an individual design of the network graphic.

A superposition of two elements will be avoided of the program and is signalled by an acoustic signal.



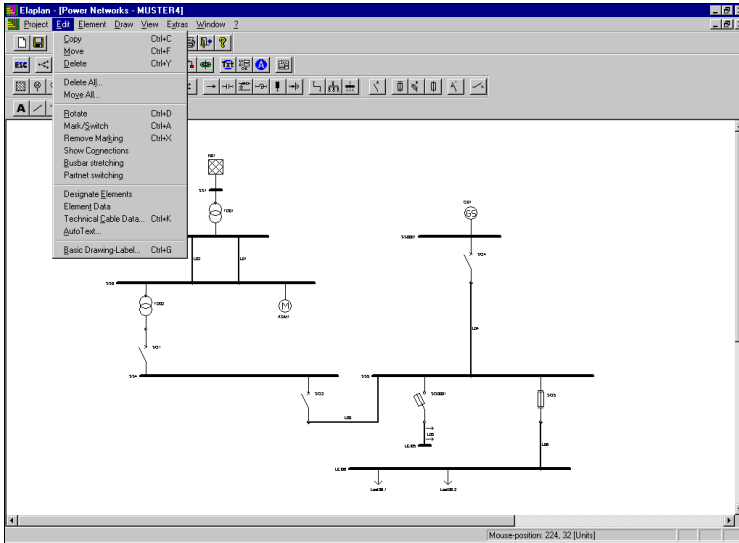
If you change from one symbol to another without making an endpoint at a connetion from a busbar to an element the current connection will be interrupted.



Every connection point of an element (except switches and protective devices) must end at a busbar.

Edit

In the menu item 'Edit' you can copy, move, delete, mark/switch und rotate the elements contained in the network graphics. Besides you can show the element data and input the designation of the elements.



Edit



The function 'Copy' is available for elements with one connecting point only (net feeder, synchronous generator, asynchronous generator, synchronous motor, asynchronous motor, directcurrent drive, load, capacity battery, shunt impedance and earth busbar). With copying the elements the relevant element data will be copied also. But the element data will be shown not before they were exported to the input of the network. The copied element needs a new designation; therefore a new input window opens automatically, which asks for the new designation. You must input a designation, which is not yet used. Otherwise the program interrupts the copy procedure without inserting the new object.



With the function 'Move' in the network graphic single elements with their connections and busbars including their connected elements can be arranged in a new way. After moving the connection lines must be drawn in a new way also, if necessary.



With the function 'Busbar stretching' you can change the length of a busbar. Please note, that only the second point (end point) of a busbar can be stretched or reduced. This symbol corresponds with the menu item 'Busbar stretching'.



With 'Delete' you can delete elements in the network graphic. Double clicking the symbol removes the element from the network graphic.

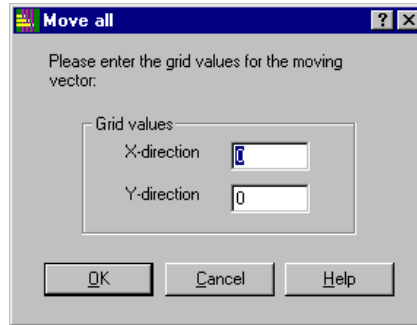
With the menu item 'Delete All' you have the possibility to replace the content of the network graphic with a new empty graphic window. For security you will be asked once more whether you are sure to delete all. Now you can design a new network graphic.



After selecting the menu item 'Delete All' and confirming the security check your network graphic cannot be restored.



With the menu item 'Move All ...' the whole network graphic can be moved on the worksheet.



Move All

The input of the moving vector has to be in **grid values**, only integer values are allowed. In order to move the network graphic to the top and/or to the left the desired value must be negative.

After confirming with the 'OK'-button the network graphic will be moved according the input values (in grid units).

With the menu item 'Move All ...' not only the elements of a network graphic will be moved, but the free drawing objects as well as the textes (all based on the entered grid values), too.



The function 'Rotate' turns single-pole elements on 90°. The direction is according the arrow in the symbol.



With the menu item 'Mark/Switch' and a double click on the switch symbol in your network graphic the switch will be operated (on/off). With this function you can mark single elements or busbars also.



The menu item 'Remove Marking' deactivates all elements and busbars marked in the network graphic.



With the function 'Show connections' you can get an overview in larger networks, which connections and elements belong to a busbar.

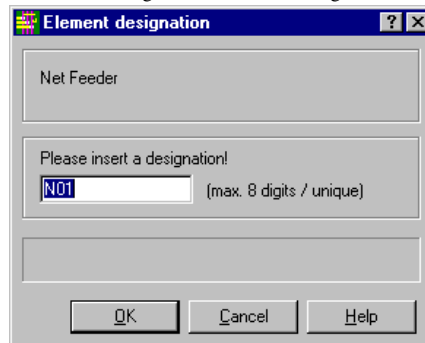
They will be marked red in the network graphic.



With the function 'Partnet switching' you can switch protective devices, which are placed in the network graphic. Besides you can use this function to operate switches for the selection of part networks. This symbol corresponds with the menu item 'Partnet switching'.



After inserting new elements in the network graphics you must designate them. Therefore you have to select the menu item 'Designate Elements'. Click on the relevant element and input the element designation. Maximum length of the element designation is 8 digits.



Element Designation



If more elements must be designated it can be done from the program also. Use the menu item 'AutoText...'. Please find more information to this item later in this chapter.



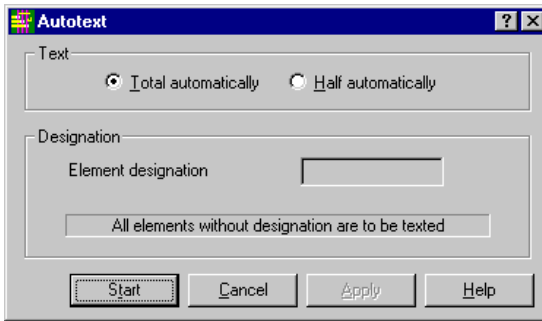
With the menu item **‘Element Data’** the related technical data of the elements can be shown on the screen and recorded. Please find more information in the chapter **‘Acquisition of Technical Data’**.

You get a message when you click on an element, which has no technical data related. If you save the network graphic, now the technical data for the new added element will be shown also. For example:

Technical Data: Load

With the function **‘Basic drawing label’** you can input data for modification remarks and name as well as date, company and the drawing number. When printing the network graphic these data will be shown in the drawing label.

The menu item **‘AutoText’** offers you the possibility to designate your elements supported by *Elaplan*. As default values *Elaplan* uses the standard values for the elements defined in *‘Options’*. *Elaplan* assigns the designations to the single elements in the modes *‘Total automatically’* or *‘Half automatically’* according to users intention.



Autotext

If you choose **‘Total automatically’** all elements which actually have no designation get denominated with standard values defined in ‘Extras/Options’ without any further request.

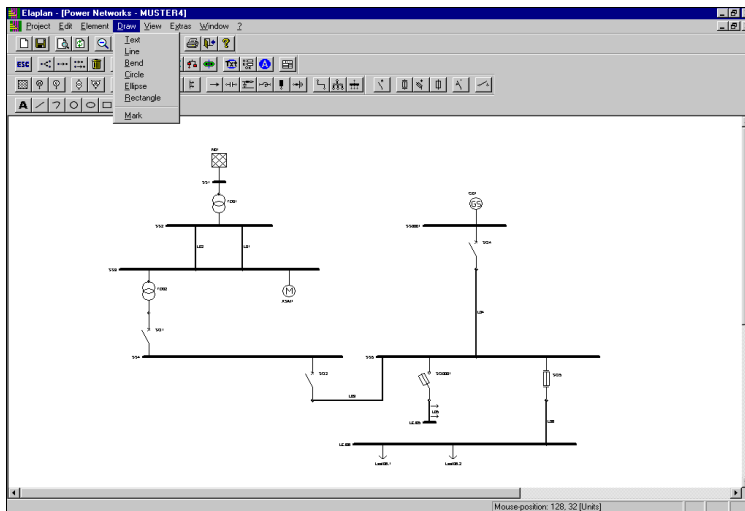
In the mode **‘Half automatically’** all elements which actually have no designation are shown in the dialog mask ‘Automatic Text’ one after another. At ‘Designation/Element designation’ you can input your favourite denomination for the element.

The next element will be shown after clicking the button ‘Start’. If all elements have their designation, the button ‘Start’ gets deactivated and you can leave the dialog mask with the button ‘Cancel’ only.

Draw

Under the menu item **‘Draw’** you are able to position free drawing objects in your network graphic. They are not in relation to the elements and can be put at the worksheet in order to denominate e.g. orientation points (buildings, streets etc.). *Elaplan* always fits them in the network drawing gridded according the so-called units. It is not possible to show these grid lines.

Therefore ‘Text’, ‘Line’, ‘Bend’, ‘Circle’, ‘Ellipse’ and ‘Rectangle’ are available. After positioning these free drawing objects in the network graphic they cannot be moved on the worksheet.



Menu item ‘Draw’



With the menu item **‘Text’** a free text can be placed in the network graphic. Now move the mouse indicator to that place where the free text should be inserted. After click with the left mouse button the free text will be inserted.



The menu item **‘Line’** inserts a straight line in your network graphic. Click with the left mouse button to that point where the line should start. Now move the mouse to that point where the line should end and click the left mouse button once more, you’ve got a straight line in the network graphic.



With the menu item '**Bend**' a bent line can be placed in your network graphic. Select the position where the bend should be inserted.

With the first mouse click the position, where the bend should be placed, will be set. Now you can choose the size of the bend. The circle shown on the screen is a little help for the size of the bend. The second click with the left mouse button will confirm the size of the bend. Subsequently you can determine the start point of the bend by moving the mouse. After the third click with the left mouse button you can determine the end point of the bend by moving the mouse. By clicking the left mouse button the bend will be inserted in the network graphics.



The menu item '**Circle**' inserts a circle in your network graphic. The circle is defined by input of the centre and the radius.

Choose the position where the circle should be set. The first click with the left mouse button sets the centre. Now you can determine the radius by moving the mouse. The second click with the left mouse button inserts the circle into the network graphic.



With the menu item '**Ellipse**' you can place an ellipse into your network graphic. The ellipse shown on the screen is a little help for the size of the ellipse.

Select the start point where you want to place the ellipse by means of the left mouse button. Now you can determine the size of the ellipsoid by moving the mouse. The second click with the left mouse button will insert the ellipse into your network graphic.



With the menu item '**Rectangle**' there's the possibility to insert a rectangle into your network graphic. Two opposite points define the size.

Choose a point in the network graphic where the start point for the rectangle should be set by means of a click with the left mouse button. Now the size of the rectangle can be determined by setting the opposite point. Therefore you move the mouse to that point where the opposite point should be placed. The second click with the left mouse button inserts the rectangle into your network graphic.



The menu item '**Mark**' activates single free drawing objects. The right mouse button shows the pop up menu for the selected object.



In order to change colors, size of text or line width of a free drawing object subsequently select the menu item 'Select' and click with the left mouse button on that object which attributes you want to change. If it is now marked as active click with the right mouse button on the selected object and choose the desired command from the opened pop up menu.



All changes made with the pop up menu will be saved as default settings by the program and given to new drawing objects when inserting them.

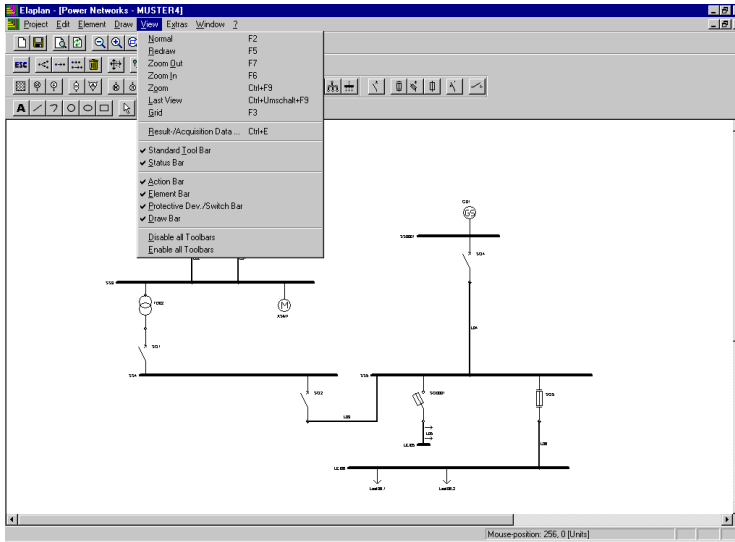
With the command '**Color**' you can change the default color for the active object. With this command the selected drawing object will be drawn once again in this color and the selected color gets the default color. All new inserted free drawing objects will be shown with the color select at last.

With the command '**Line**' you can change the line width of drawing objects (circle, ellipse, bend, line and rectangle). This item has no effect on 'Text'. With this command the selected drawing object will be drawn once again with this line width and the selected line width gets the default line width for the drawing objects.

With the command '**Text**' you can change height and width of the text as well as the text itself. This item has no effect on other free drawing objects. With this command the selected text object will be drawn once again with this changes. All changes that were done will get the new standard settings.

With the command '**Delete**' the active 'drawing object' will be removed from the network graphic.

With the menu item '**Normal**' you have the possibility to reset a view of the network graphic changed by **Zoom** into the default view. The default view depends on the system settings of your PC. *Elaplan* tries to show elements on the screen as much as possible according to the defined minimum size of the element symbols.



View

With the submenu item **'Redraw'** you can build up your network graphic once more because sometimes parts of elements remain on the screen after deleting. The background with the new Windows default color will be built up at first. Then the grid points will be drawn if the function 'Extras/Raster' is active. Subsequently all active elements of the network graphic will be redrawn. This function actualizes the content of the active window only. This function is valid for the display on the screen only. Afterwards you can keep on working with your network graphic as usual.



You always should use the menu item 'Redraw' when you have inserted several elements into your network graphic or you deleted some.



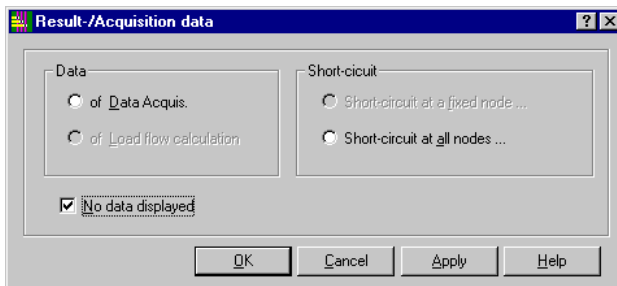
With the menu items **'Zoom In'** or **'Zoom out'** the section of the network graphic on the screen can be enlarged or reduced.

With the menu item **'Zoom'** you can zoom a window in order to display a detail of the network graphic enlarged.

If you gave the elements their technical data previously or you did short-circuit or load flow calculations before you are able to report the network graphic with the acquisition or result data at the elements and busbars.

The menu item **'Grid'** shows the grid dots on the screen where the elements are aligned. If you want to switch on the display of the grid for an existing project, you have to actualise the display of the graphic by pressing the function key 'F5'.

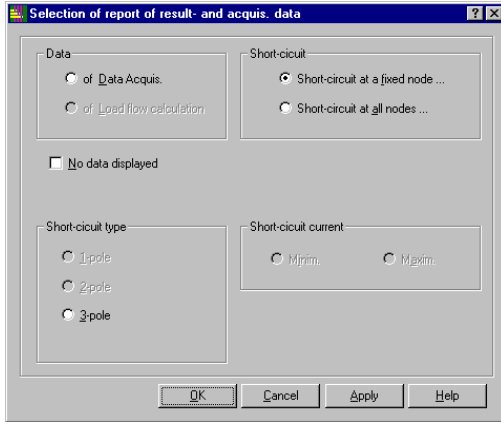
With the menu item **'Result-/Acquisition Data ...'** of 'View' you can select what kind of data should be shown.



Selection of report modus

You can select of following data: acquisition data, results of short-circuit calculation at all nodes (according **Takahashi**) or at a fixed node (according **Gauß**) or results of load flow calculation. Selection is only possible for items data were calculated for.

A further selection of individual types of short-circuits is possible. Only already calculated types of short-circuits can be selected.



After finishing your selection data are viewed in the network graphic and can be printed or plotted.

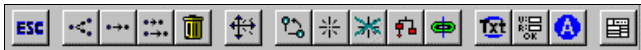
For a better reading of data you can reduce the section on the screen by means of the function 'Zoom In' in order to enlarge the elements in the section on the screen.

In the menu item 'View' you can activate or deactivate the symbol bars also. The arrangement of the symbol bar can be set by the user individually. It will be saved when you exit the program.

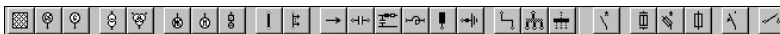
Standard Tool Bar:



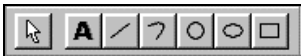
Action Bar:



Element Bar:



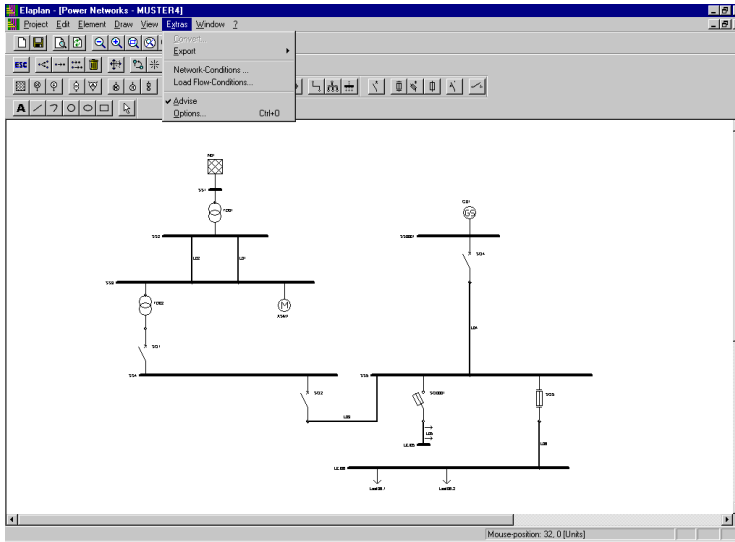
Draw Bar:



In the same way the 'Status Bar' (with display of the mouse position) can be activated or deactivated.

Extras

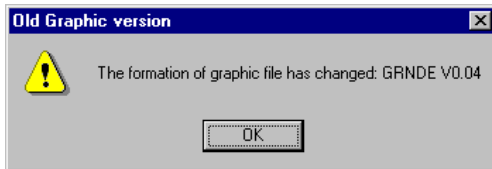
In the menu item 'Extras' all settings can be done necessary for displaying and printing the network graphics.



Extras

The sub item **'Convert ...'** you only should use if you want to open a network graphic, made with a former version than 3.1x, with the actual *Elaplan* version the first time.

In this case a dialog window appears on the screen with the message that you want to open a network graphic made in a former *Elaplan* version and you have to convert it into the actual version at first. This message must be confirmed.

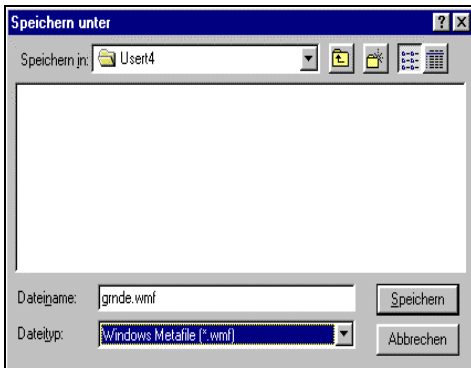


Old version of network graphic



This command you should only use, if you have opened a network graphic made in a former *Elaplan* version and the program references you to select the item **'Extras/Convert ...'** at the start.

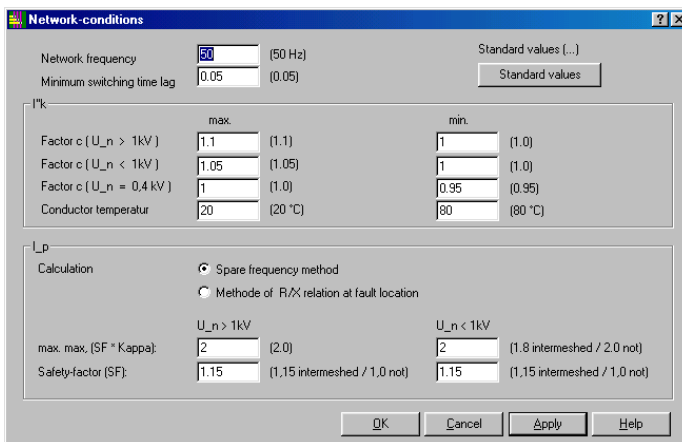
With the sub item **'Export'** you are able to export your network graphic to another graphic software, which can read a Windows-Meta-File. WMF-export is optimized for the software AutoCAD 14, AutoCAD LT 97 and CorelDRAW 7. This option uses the default settings in the item **'Extras/Options'** register card **'WMF-Output'** for generating the Windows-Meta-File. The Windows dialog **'Save As'** opens now.



Save as

After selecting the path and touching the button 'Save As' the WMF-file will be written with the name you have chosen. WMF-file of the network graphic will be performed without drawing label, legend and frame.

With the menu item 'Network-Conditions ...' you can change the periphere conditions for the short-circuit calculation. So you can intervene in the program and influence the result. The calculation method for the short-circuit peak current i_p is selected by means of the corresponding buttons.



Network conditions

The input areas are previously occupied with the standard values according VDE. On the right side of the input area the standard values are shown fixed once again. Meaning and effect of the single area will be described below.

The frequency of the network is used for the calculation of the impedance of the elements.

For calculation of the **breaking current** I_b the **minimum switching time lag** is essential. This is the minimum period from start of the short-circuit until the first separation of a pole of the circuit breaker.

For calculation of the short-circuit peak current in intermeshed networks the factor Kappa is needed. For determination of factor Kappa VDE gives different types of calculation. Default is type C; input a 0 in the area 'I_p calculation type' you will use calculation type B according VDE 0102.

Type B: ratio R/X at the short-circuit location factor Kappa = Kappa B * safety margin (value for FACT)

Kappa B = value from the diagram acc. VDE 0102 for the ratio R/X.

The value for the safety margin depends on the voltage level and must be recorded in the area 'value for FACT'.

For the product FACT * Kappa B in the input area 'max. value for FACT * KAPPA' the upper level acc. VDE will be determined.

Input of 1 in the area 'I_p calculation type' the program selects calculation type C acc. VDE 0102 (default).

Type C: Equivalent frequency calculation type factor Kappa = Kappa C

Kappa C = value from the diagram acc. VDE 0102 for the ratio R/X

$$R/X = (R_c / X_c) * (f_c / f)$$

This calculation type C is permitted for calculation of a short-circuit in intermeshed networks.

Calculation Type B is used for calculation of a short-circuit in radial networks.

The factor c for voltage (factor c) determines the ratio of the voltage of the equivalent voltage source (equivalent generator) to the rated voltage divided by $\sqrt{3}$ ($U_n / \sqrt{3}$). VDE 0102 states different factors for different voltage levels. For every voltage level an input area is available.

In order to get the most critical results for the maximum and minimum subtransient short-circuit currents I''_{kmax} and I''_{kmin} they are calculated at different temperatures of the conductor. I''_{kmax} occurs at the minimum resistance of the conductor. The minimum subtransient short-circuit current I''_{kmin} happens when in the moment of the short-circuit the conductor has already reached its maximum admissible temperature.

With the menu item 'Load Flow-Conditions ...' the parameters for a load flow calculation can be set, described as follows:

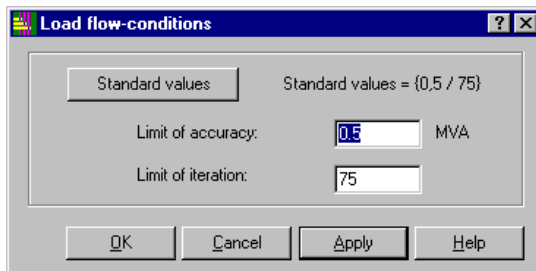
The network, a load flow calculation should be done for, must be recorded graphically at first. Via network graphic the element designations as well as the input and output nodes are determined.

Then the technical data of the network elements must be recorded by means of the menu item 'Edit' / 'Element Data'.

Please note, that during first input the data for short-circuit calculation must be recorded also.

Before starting the calculation program you can set up the parameters for the computation by means of the program 'Input of Load Flow Requirements'.

With the area 'Limit of accuracy' and 'Limit of iteration' you can set the break-off criteria for the load flow calculation.



Load flow-conditions

With every step of iteration the load flow calculation program checks the computed deviations of power in accordance to the calculation step before at all nodes. If the deviation of power at every node is less than the required accuracy, the computation will be stopped. Otherwise the program continues computation until the maximum number of steps (limit of iteration) is reached. In this case the load flow calculation programs lists an error protocol. The required limit of accuracy is not yet reached. For further information please refer to Section 'Report Load Flow Calculation' / Load Flow Statistic.

The standard values are deduced from the experience, when the load flow calculation of a medium-voltage network, which elements are recorded correctly, converges. For pure low-voltage networks the limit of accuracy must be selected smaller; an approximate value is 10 % of the sum of all consumers (loads) in the network.

The menu item 'Advise' turns on or off the display of a window, which warns you from the superposition of several elements. If this advise-function is turned off you will get an acoustic signal indeed but there is no advice for superpositioning elements by means of a dialog window.

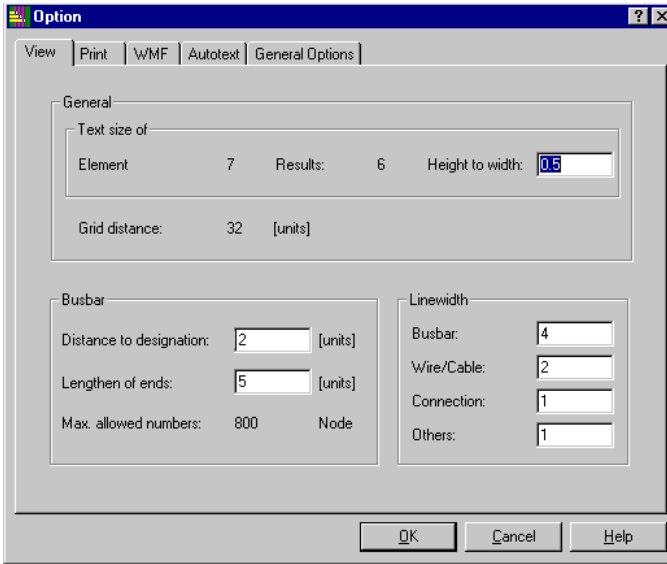
The menu item 'Options...' opens a dialog window with 5 register cards: 'Views', 'Print', 'WMF-Output', 'Autotext' and 'General Options'.

Panels with grey background color are display panels with default values of the program and cannot be edited.

The register cards 'Views', 'Print' and 'WMF-Output' modify the various kinds of output.

'Views' controls the display on the screen, 'Print' controls the print output including print preview, 'WMF-Output' controls the generation of WMF-files.

Identical inputs on different register cards have the same reactions but have no effect at other outputs e.g. line width on 'Views' / 'Print' / 'WMF-Output'.



Register card 'Views'

In the register card 'Views' the area 'General' / 'Text size of' shows you the text size of element designations and result data. The values cannot be changed. The relation between heights to width you can change has an effect on the display of designation of elements and result data.

Elaplan will subdivide the grid distance in further equidistant sections. The number of units per grid distance, here 32, defines the length of a section. The elements can be positioned on these grid points only. Free drawing objects can be positioned between these raster points also. The number of units per grid distance cannot be changed. The distance of grid points can be changed in the menu 'Project/Worksheet Setup ...' in the panel 'Millimeter per grid'.

In the area 'busbar' the horizontal distance of the designation to the busbar can be changed.

You can determine the lengthening of the ends of a busbar (input in units). Only positive numbers are allowed. With this function you can change the image of the busbar on the screen. A lengthening of the ends of a busbar of 8 units means a lengthening of $\frac{1}{4}$ grid distance.

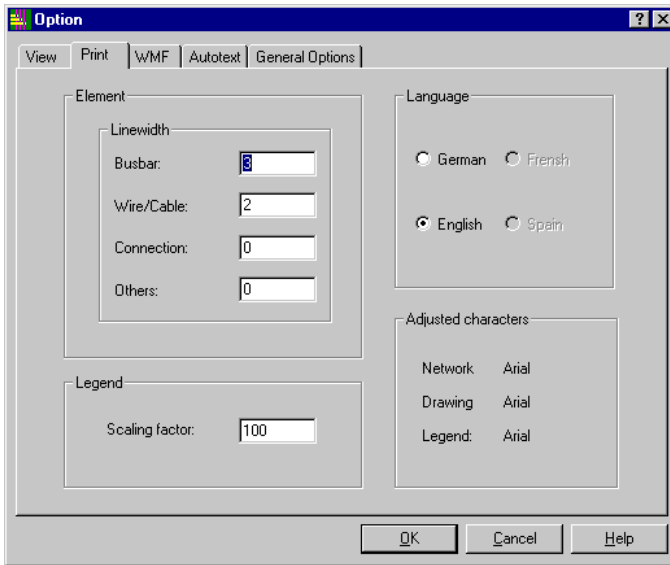
In addition the number of busbars / nodes you can place into the network graphic is displayed. This is a default value from the program and cannot be changed.



If you are interested in the number of nodes you have placed in your network graphic open the menu 'Project/Project...'; here you can see the number of nodes and elements in the network graphic.

In the area 'Linewidth' you can set the line width of different elements in the network graphic.

On the register card 'Print' you have the possibility to influence the image of the output on a printer or plotter and the print preview also.

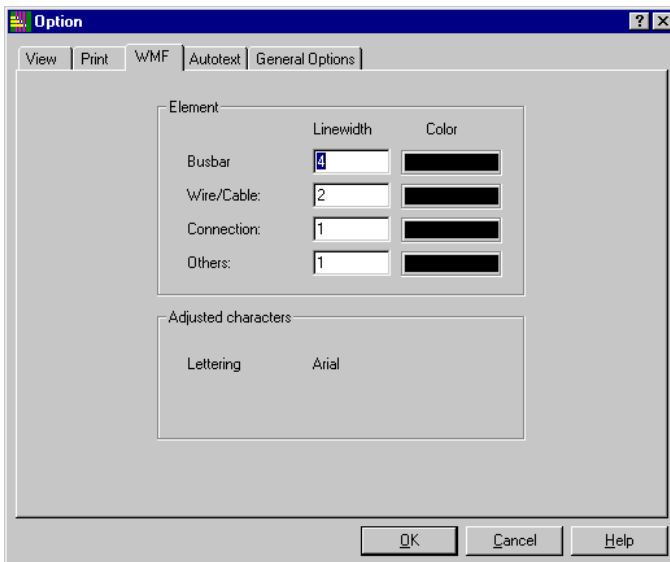


Print

Besides the line width of different elements you can set the language for the output of the network graphic on a printer or plotter also. The selection of the language has influence to the terms in legend and basic drawing label used by *Elaplan*.

In addition you can set the scaling factor for the legend. The font for the output of the network graphic, drawing label und legend is set at 'Arial' by the program. It cannot be changed

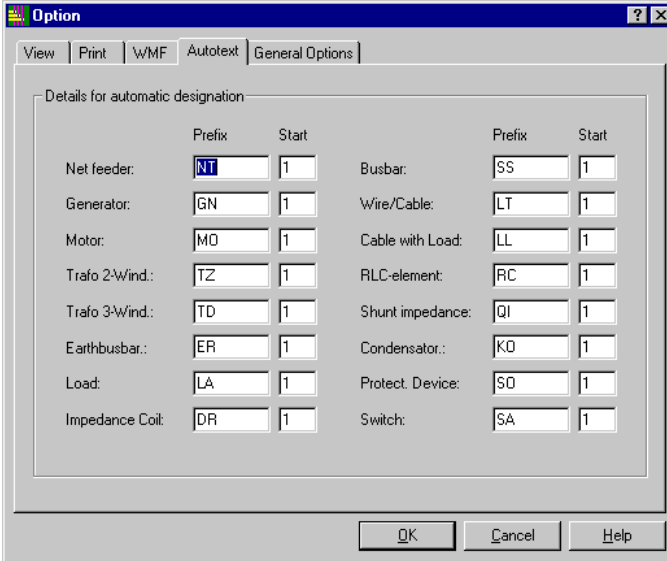
On the register card 'WMF' settings will be done for the output in a WMF-file. You can set the line width of different elements and the color for the display of elements and busbars. The default font for the generation of a WMF-file is 'Arial' set by the program and cannot be changed.



WMF

In the area 'Linewidth' the input of positive numbers between 1 and 100 is allowed only. Clicking on one of the color symbols opens the dialog window 'Color'. You can select the color and confirm with the button 'OK'. Subsequently the element symbol will be displayed in the chosen color.

By means of the register card '**Autotext**' you can determine your favourite designation for single elements the program will use if the menu item 'Edit/AutoText...' is set.



Autotext

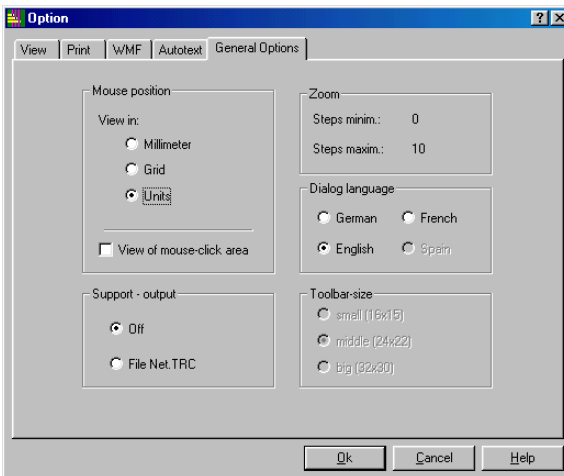
The setting consists of two parts:

The first part, the so-called prefix, is a body text with a maximum length of 4 symbols. You can use less than 4 symbols also.

The second part is a numeric array with a maximum length of 4 digits. All numbers the program generates have a fixed length of 4 digits; the program fills up with leading zeros automatically. Only positive numbers are allowed.

With these settings the program generates the complete designation of new elements inserted in the network graphic if the menu item 'Edit/AutoText...' is active, e.g. 'NT0001' for the first net feeder.

In the register card '**General Options**' you can set the type of view of the mouse position in the 'Status bar': Select between millimeters, grid and units.



General Options

In addition you have the possibility to view the **mouseclick area**; this is the area the element can be activated with the mouse. Every element is surrounded with a blue quadrangle symbolizing the mouseclick area.

In the area 'Zoom' the maximum number of zoom steps is viewed for both directions ('Zoom In' and 'Zoom Out'). They are set by the program and are not subject to change.

In the area 'Support - output' there are options for the kind of support by phone. They are not subject to change.

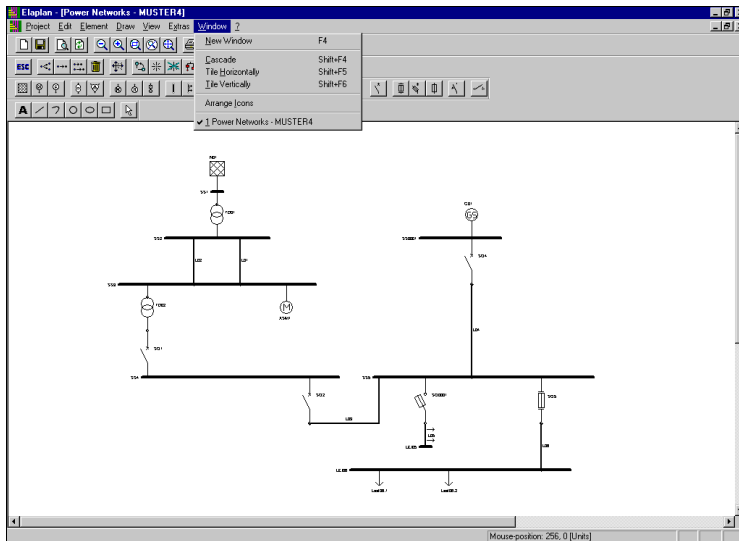
In the area 'Dialog language' you can select the language of the user surface. At the moment you can choose between German and English; French and Spanish is available at a later time. For activation the adjusted language you have to restart the program.

In the area 'Toolbar-size' the size of the toolbars is displayed in a dimmed mode only, because it cannot be changed.

In the area 'Support - output' you can select to create the file 'Net.TRC'. It can help the support in any case of program errors.

Window

In the sub menu item '**New Window**' you can open your network graphic as a copy in a further window. You can insert new elements in all windows.



Window

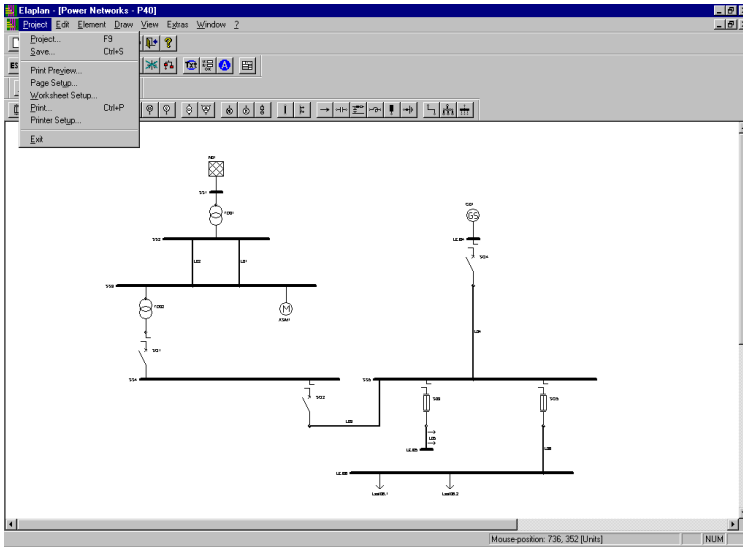


The use of more windows is usefull when results of load flow calculation, short-circuit calculation and/or acquisition data should be shown on the screen simultaneously. You can set the selection what kind of report should be shown with the menu item 'View / Result-/Acquisition Data ...' for each active window.

Additionally you can arrange your windows in the manner 'Cascade', 'Tile Horizontally' or 'Tile Vertically'. With the command 'Arrange Icons' you can rearrange the minimized windows on the screen.

Project

In the sub menu item '**Project...**' you can see the path where your project is saved. Besides the number of elements and nodes used in your network graphic is viewed.

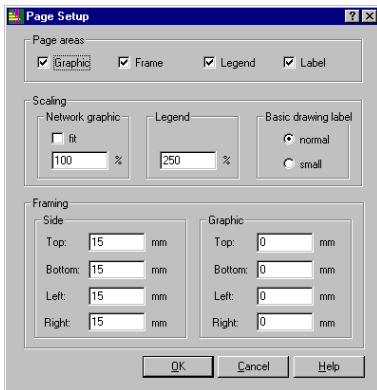


Menu item 'Project'

With the sub menu item 'Save...' the network graphic can be saved and exported for further working with the element data without leaving the module 'Network Graphic'. After saving you can continue working in your network graphic as usual.

With the sub menu item 'Print Preview ...' you have the possibility of a preview of the printed output on the screen.

In the sub menu item 'Page setup ...' you can prepare the image of your network graphic for printing basically.



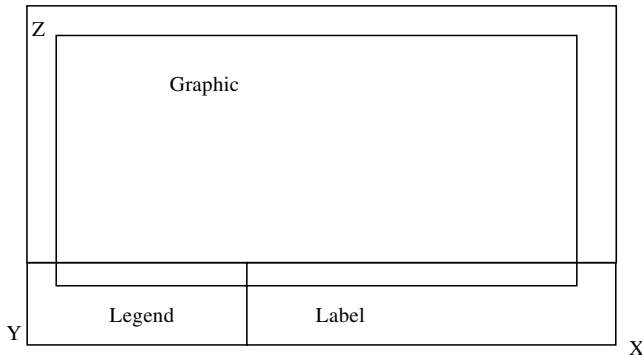
Page Setup

The size of the paper to print is optionally. It will be divided in four areas (network graphic, frame, legend and drawing label), which have different information. These areas you can switch on or off for the print individually.

The extension of the frame is defined by the margins. The printing area for the drawing label is spread from the lower right corner of the margin (point 'X' in the graphic) to the left and to the top. You have the possibility to display the size of the drawing label as 'normal' (according DIN 6771) or 'small' (i.e. the drawing label is smaller by the factor $\sqrt{2}$).

At the lower left corner of the frame (point 'Y' in the graphic) the area starts which is available for the print of the legend. It will be drawn centered with respect to the available space. The legend is scaleable in the menu item 'Extras/Options...', register card 'Print'.

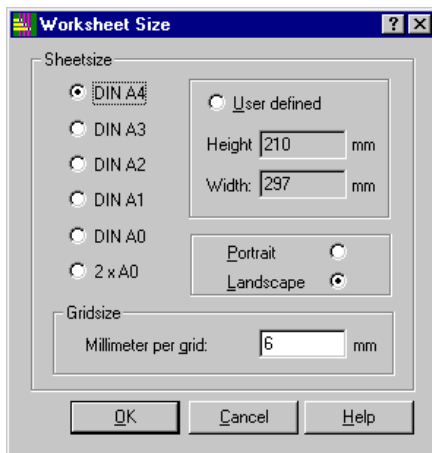
The area of the network graphic can overlap with the area for the drawing label and the legend as shown in the example.



Work Sheet

Here all objects (elements and free drawing objects) are shown recorded within the graphic area. If it is not possible to display all recorded elements in the printing area, you are able to scale the content of the network graphic area. The part of the network graphic to print will always be built up from the upper left corner (point 'Z' in the graphic). Simultaneously the X- and the Y-axis of the network graphic will be scaled also in order to avoid distortion.

The sub menu item '**Worksheet Setup ...**' opens a dialog with the possibility to set size and orientation of the worksheet as well as the grid size.



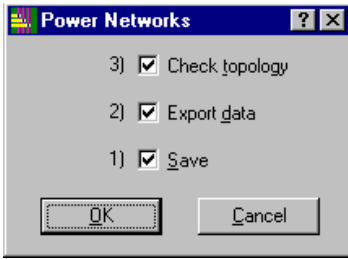
Worksheet Setup

The worksheet size is selectable from the defined DIN-sizes or free of choice. You can scroll within the defined worksheet size only. The elements will be arranged on grid points always. The distance of grid points is definable in the area 'Gridsize' by the user (in millimeters). Since elements will be saved because of the grid points the display and print of elements can be changed afterwards by variation of the grid size. Depending on the chosen grid size it is possible that elements will be positioned one upon the other (very low grid size) or outside of the worksheet. The change of the grid size has influence on the print output and the print preview of the network graphic; it has no effect for the display on the screen.

With the sub menu item '**Print ...**' you can output the network graphic to a plotter or printer. The print dialog opens. After pressing the button 'OK' your network graphic is given out to the selected plotter or printer. Default is the standard printer of the system settings.

With the sub menu item '**Printer Setup ...**' the standard Windows dialog opens for the setup of the printer. Here you can select and setup another printer.

With the sub menu item '**Exit**' you leave the module 'Network Graphic'. You will be asked whether the network graphic should be saved, data of the network graphic should be exported or the topology should be checked. These items can be selected by a click onto the relevant control element.



Save, Export data and Check topology

Now the program closes your network graphic automatically and finishes the module 'Network Graphic'

Acquisition of Technical Data

Display and input of technical element data as well as of protective devices occurs in the program module 'Network Graphic' by means of the icon in the symbol bar or the menu item 'Edit / Element Data'. The dialog windows will be described afterwards.



Acquisition and view of Element Data.

With the menu item 'Extras' you can select whether the acquisition of data for short-circuit and load flow should happen combined or separated.

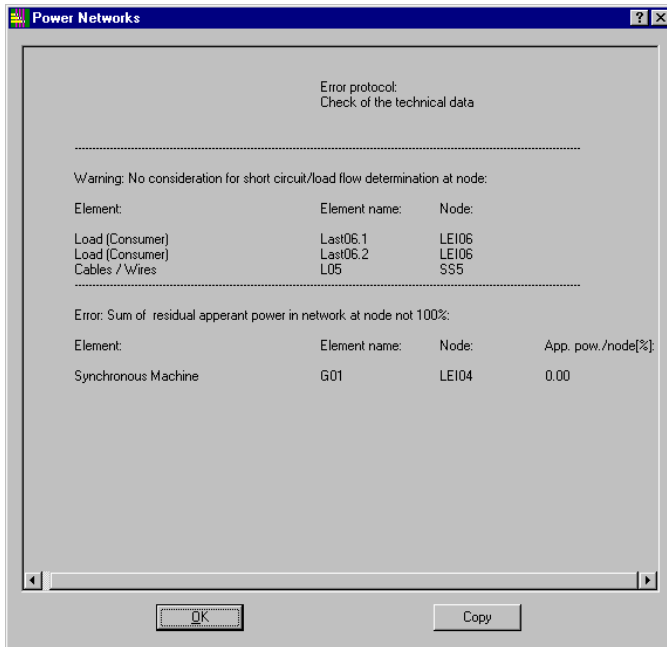
Following dialog windows and descriptions refer to the acquisition of data in the mode 'short-circuit and load flow'.

The functions for the single elements will be described very detailed in the following chapters.

If you have finished the definition of the elements please close the acquisition mode. At the end of the data acquisition *Elaplan* checks that in the acquired data for short-circuit both element and node voltage correspond and the relation of the earth busbars is correct. At the acquisition of load flow data *Elaplan* checks that real power and reactive power per node is 100 %.

If there is any error a protocol will be given out on the screen. This makes possible a systematic debugging when coming back to the data acquisition.

Example for an error protocol:



All elements recorded in the network graphic must have technical data assigned. Otherwise no calculation can be done.

The protective devices recorded in the network graphic get assigned their technical data by means of the item 'Input Selectivity'.

Net Feeder

Select the menu item 'Element Data' or the corresponding icon and click to the net feeder placed and designated in your network graphic before.

Net feeder for short-circuit and load flow calculation

With the function '?' for 'Direct help' you get detailed information to every input- or selection-/display area. Context help with connections to the online-help is not yet available.

The element designation is given from the system. With the selection area 'Consideration' you can choose for which kind of calculations the element should be considered. Following selections are possible:

- not considered
- general considered
- considered only for I^kmin
- considered only for I^kmax.

The rated voltage on the output of the node (U_n) must be defined. It will be given for every further element connected to this node. Elements connected to the node of the net feeder must have the same rated voltage (U_n). This is the voltage which the subtransient short-circuit power S^k delivered from the network at rated voltage refers to.

The input of minimum and maximum value has influence on the short-circuit calculation. The maximum values are for calculation of I^kmax and the minimum values for calculation of I^kmin.

After acquisition of rated voltage and subtransient short-circuit power the resistance and reactance in the positive sequence system [R₍₁₎ and X₍₁₎] will be calculated. You are able to input the values for R₍₁₎ and X₍₁₎ also and the program calculates the subtransient short-circuit power S^k.

The input of the ratio of the impedances is necessary only in case of deviation from VDE standard values. Otherwise the program calculates with a value of 10 % for the ratios R/X in the positive and the zero sequence system. As default setting *Elaplan* assumes a network with no earthing.

If the network has impedance earthing the ratio of the reactances X in zero to X in positive sequence system must be acquired.

At net feeders always PV node elements must be given for load flow calculations; defined by real power P and terminal voltage U_{KL}. Parallel net feeders must have same terminal voltage. If there are parallel net feeders the total input reactive power must be split to the single net feeders (just like parallel generators).

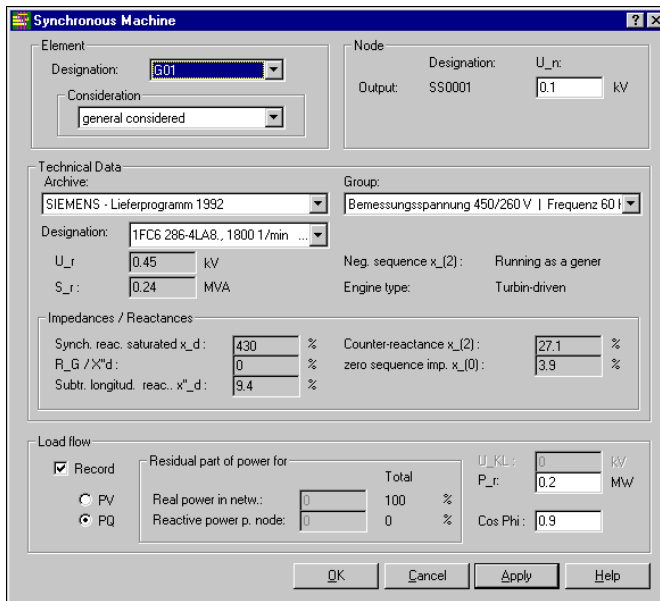
This happens with the input area 'Reactive power per node'. The sum of the single reactive power must be 100 % for every input net feeder.



Elements not active for calculation must not be considered for the division of the residual power parts.

Synchronous Machine

Select the menu item 'Element Data' or the corresponding icon and click to the synchronous machine placed and designated in your network graphic before.



Synchronous machine for short-circuit and load flow calculation

With the function '?' for 'Direct help' you get detailed information to every input- or selection-/display area. For detailed information to the area 'Element designation' and 'Consideration' please refer to explanations in Section **net feeder**.

For load flow calculations only the values for the maximum case of operation are considered. In other words: In the area 'Consideration' the selection 'considered only for I"kmmin' gives the same result as the selection of 'not considered'.

The mode of operation shows whether the synchronous machine operates as motor or generator because the same dialog window will be used for a synchronous motor also.

The rated output voltage of the node U_n is necessary for calculation of short-circuit current and must be defined. For all elements connected to this node also this value is valid and will be given in the relevant input dialog. It can be changed max. +/- 20% of the node voltage.

The input of the element data of the synchronous machine is possible manual or with the selection 'Archive / Group' from a root database. In case of manual input take care that the rated voltage U_r deviates max. 20% of the output voltage of the node. The input of the engine type has influence to the default values of the machine reactances.

The saturated synchronous reactance is the reciprocal value of the saturated no-load/short-circuit ratio. The default values of the ratio R to X for short-circuit depend on U_r and S_r and are different for high voltage and low voltage machines. For detailed information please refer to the booklet 'Networks'. The subtransient reactance x''_d is the effective reactance of the machine at the moment of short-circuit. If there is no input for the negative sequence reactance x_2 *Elaplan* sets x_2 equal to x''_d . The zero sequence reactance has a default value also defined by the program and is subject to change. It will be assumed that the housing of the generator is solid earthed.

For load flow calculation the synchronous machine can be defined as PV-node element (input of feeding real power P_r and terminal voltage U_{KL}) or as PQ-node element (input of feeding real power P_r and power factor $\cos \phi$, no input of terminal voltage U_{KL}). You have to select the relevant element within the item 'Record' at input area 'Load flow'. The input area will allow you the input of the relevant data according your selection.

PV-Generators

Input are real power P and terminal voltage U_{KL} , reactive power and phase angle of the voltage ϕ will be calculated. Parallel PV-generators (and net feeders) must have same terminal voltage. Since *Elaplan* in its calculation comprehends parallel generators to a equivalent generator the total feeding reactive power of the node will be split to single generators and net feeders after finishing calculation.

This happens with the input area 'Reactive power per node'. The sum of the single reactive power must be 100 % for every input net feeder.

Example:

One generator at the node: Reactive power per node = 100 %.

Several generators at one node: Reactive power per node must be split to the single generators, e.g. according to the ratio of the feeding real power. This is equal to an identical power factor per machine. A splitting according to the rated power of the machines gives an identical utilization of the machines. According to the need of operation other types of splittings are possible also.

PQ-Generators

Input are real power P and power factor $\cos \varphi$, terminal voltage U_{KL} will be calculated with scalar value and phase angle of the voltage.

The PQ-generator will not be considered at the division of the residual power. The program sets the acquired residual part of power to zero. You have the possibility to split the residual part of the power manually. Otherwise the feeding power at the slack node takes the residual power. In this case the program gives a message on the screen.



PQ- and PV-generators at one node can cause physical problems. A solution for the load flow calculation is not possible in any case.



Elements not active in the calculation must not be considered at the division of the residual power.

Two Winding Transformer

Select the menu item 'Element Data' or the corresponding icon and click to the two winding transformer placed and designated in your network graphic before.

Two winding transformer p. 1/2 for short-circuit and load flow calculation

With the function '?' for 'Direct help' you get detailed information to every input- or selection-/display area. For detailed information to the area 'Element designation' and 'Consideration' please refer to explanations in Section **net feeder**.

For load flow calculations only the values for the maximum case of operation are considered. Other selections have the same meaning just like 'not considered' and 'general considered'.

Input and output voltage of the node will be taken for the calculation of the short-circuit current and therefore they must be recorded. Are there any definitions of voltages for those nodes made before they will be shown as default values. A change of them has influence to all elements connected to this node.

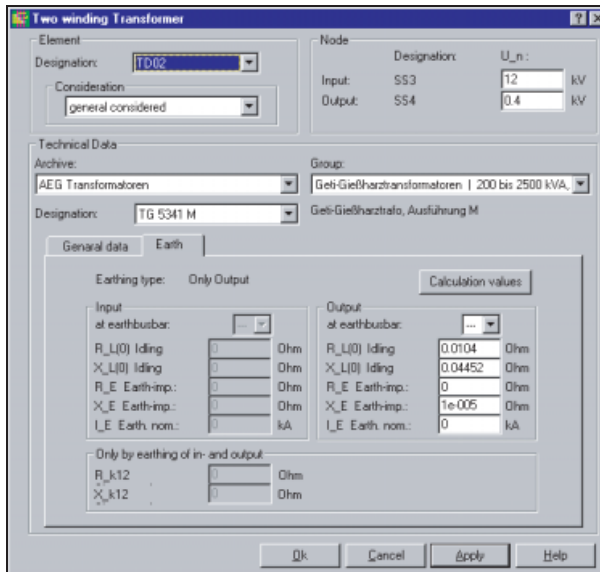
By means of the root database you have a quick access to the desired two winding transformer. Please input the relevant numbers at the area 'Archive' and 'Group'.

If you have selected a transformer type all relevant data of the transformer just like vector group, rated voltages, rated power, phase rotation, losses of the windings and impedance voltage u_{kr} will be shown and are not subject to change.

If you want to record the data manually input 0 at 'Archive'. With the vector group the phase rotation between high and low voltage winding is determined. Simultaneously the possibility of earthing is set.

With the register card 'Earth' you can input data for earthing..

The kind of earthing is given with the recorded data. This determines the flow of the input in the shown dialog.



Two winding transformer p. 2/2 for short-circuit and load flow calculation

If you want to connect the two winding transformer to an earth busbar note the sign. This sign (A to Z) you have to relate to a designated earth busbar in the network graphic when recording their element data. Additionally the earthing impedance X_E must be determined.

Transformators are elements, which can compensate voltage deviations in the network caused by load variations. This is the reason why a variable voltage ratio of the transformer is realized, typically on its high voltage side. The voltage can be varied in small steps by means of on-load or off-load tap changers.

The vector group of transformers will not be considered for load flow calculations basically because all transformers between voltage levels must have the same vector group.

Two winding transformers are built as transformers with in-phase and phase-angle regulation. It is assumed that high-voltage side (side 1) is regulated only.

With input of the staging range ΔU on the input side and the phase angle ϕ of this voltage referring to the input voltage every voltage ration can be adjusted.

The voltage ratio is defined by:

$$X = U_{rt_output} / U_{rt_input} * (1 + \Delta U * \cos \phi + j (\Delta U * \sin \phi))$$

Elaplan will use this formula if no number of steps is acquired. If there is recorded a value for the maximum adjustable number of steps m Elaplan interprets ΔU as staging range $\pm \Delta U$ (in both directions). ΔU must be given in % of input voltage. If positive and negative staging ranges are different referring to the main tap position the larger value must be given.

The maximum number of steps m will be counted from the main step position. From the adjusted tap position $\pm n$ the actual voltage ratio will be calculated

$$\Delta U = \Delta U * (+/- n) / m$$

for further use in the formula for \dot{u} .

Example:

The transformer has a maximum number of steps in the positive staging range of 5 steps and in the negative range of 10 steps. The total staging range is 20 %.

In order to increase the voltage on the output side the number of windings must be decreased on input side. A negative number of steps must be adjusted.

The adjusted staging of -10 gives a maximum increase of voltage on the low voltage side of the transformer.

Vice versa an increase of the number of windings on the input side enlarges the voltage ratio and decreases the voltage on the output side.

Three Winding Transformer

Select the menu item 'Element Data' or the corresponding icon and click to the three winding transformer placed and designated in your network graphic before.

Three winding transformer p. 1/2 for short-circuit and load flow calculation

With the function '?' for 'Direct help' you get detailed information to every input- or selection-/display area. For detailed information to the area 'Element designation' and 'Consideration' please refer to explanations in Section **net feeder**.

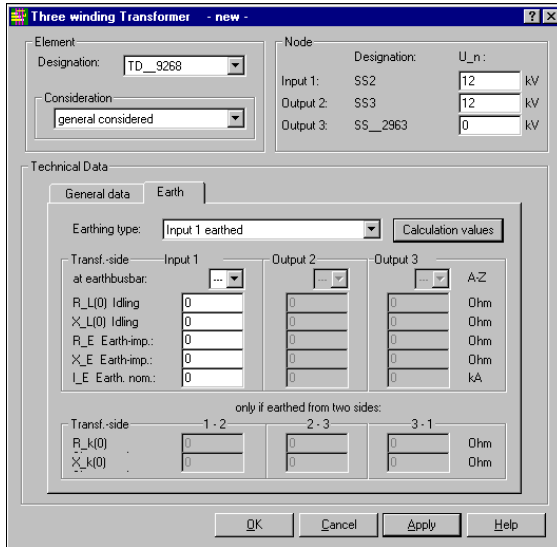
For load flow calculations only the values for the maximum case of operation are considered. This is why the selection 'considered only for I^{max}' is interpreted as not considered.

Input and output voltage of the node will be taken for the calculation of the short-circuit current and therefore they must be recorded. Are there any definitions of voltages for those nodes made before they will be shown as default values. A change of them has influence to all elements connected to this node.

Since three winding transformers are a special design the manufacturer has to deliver detailed information of rated voltages, phase rotations, rated power, losses of windings and impedance voltages.

Transformers are elements, which can compensate voltage deviations in the network caused by load variations. This is the reason why a variable voltage ratio of the transformer is realized, typically on its high voltage side. The voltage can be varied in small steps by means of on-load or off-load tap changers.

Three windings transformers can be built with in-phase regulation in every winding. This occurs with input of the additional voltage or the maximum number of steps m and the adjusted staging $\pm n$.



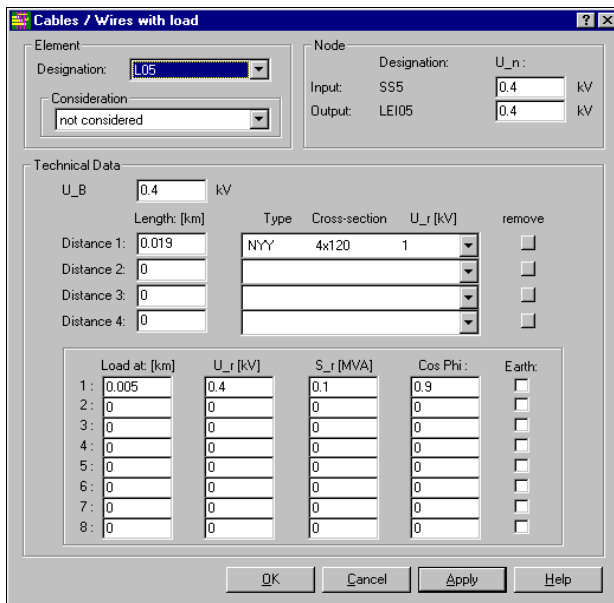
Three winding transformer p. 2/2 for short-circuit calculation

If the transformer is earthed, you are able to set the kind of earthing by means of the register card 'Earth'. The flow of input is determined by the kind of earthing.

With the button 'Calculation values' required data for earthing are calculated for the short-circuit computation.

Cables / Wires and Cables / Wires with Load

Select the menu item 'Element Data' or the corresponding icon and click to cables / wires placed and designated in your network graphic before.



Cables / Wires with load for short-circuit and load flow calculation

With the function '?' for 'Direct help' you get detailed information to every input- or selection-/display area. For detailed information to the area 'Element designation' and 'Consideration' please refer to explanations in Section *net feeder*.

For load flow calculations only the values for the maximum case of operation are considered. Other selections have the same meaning just like 'not considered' and 'general considered'.

Input and output voltage of the node will be taken for the calculation of the short-circuit current and therefore they must be recorded. Are there any definitions of voltages for those nodes made before they will be shown as default values. A change of them has influence to all elements connected to this node.

Between input node and output node the cable can consist of maximum four partial distances with different types of cables. Short circuit point is not assumed between two partial distances but on the nodes only.

By means of the cable designation in the root database the definition of cable type and cross-section gets easier. The rated voltage U_n determines the voltage level the cable should be in.

The acquisition of loads between partial distances considers the loads according their connection points.

The cable with loads between partial distances is modelled as π -equivalent. The loads will be converted into impedances with the rated voltage as reference value.

With successive star-delta-transformation the loads will be shifted to the end nodes. This transformation reduces the number of nodes in the network and accelerates the load flow calculation especially in medium and low voltage networks.

Maximum eight loads can be connected to a cable, which can consist of four partial distances. The definition of a load covers the record of the point of connection (load at km), rated voltage, rated power and power factor. It is important for the load flow calculation whether the connected consumer has a star-point coming out and if it has whether it is earthed.

Input of data to cables / wires without load happens in the same way as described but without information to loads.

| Distance | Length: [km] | Type | Cross-section | U _r [kV] | remove |
|-------------|--------------|---------|---------------|---------------------|--------------------------|
| Distance 1: | 2 | NAEKEBY | 3x240 | 20 | <input type="checkbox"/> |
| Distance 2: | 0 | | | | <input type="checkbox"/> |
| Distance 3: | 0 | | | | <input type="checkbox"/> |
| Distance 4: | 0 | | | | <input type="checkbox"/> |

Cables / Wires for short-circuit and load flow calculation

Asynchronous Machine

Select the menu item 'Element Data' or the corresponding icon and click to the asynchronous machine placed and designated in your network graphic before.

The screenshot shows the 'Asynchronous Machine' dialog box with the following data:

| Section | Parameter | Value |
|--------------------|-------------------------------------|--------------------|
| Element | Designation | ASM1 |
| | Consideration | general considered |
| Node | Designation | U_n: |
| | Input | SS3, 12 kV |
| Technical Data | Archive | Manual |
| | Group | |
| | Designation | |
| | Operating type | Running as a motor |
| | U _r | 12 kV |
| | Pair of poles | 1 |
| | P _r (Output power) | 5 MW |
| | Cos Phi | 0.8 |
| | ETA (efficiency) | 0.9 |
| | I _a / I _r | 6 |
| Impedance-relation | R ₍₁₎ / X ₍₁₎ | 10 % |
| | X ₍₂₎ / X ₍₁₎ | 0 % |

Asynchronous machine for short-circuit calculation

With the function '?' for 'Direct help' you get detailed information to every input- or selection-/display area. For detailed information to the area 'Element designation' and 'Consideration' please refer to explanations in Section **net feeder**.

The operating type shows whether the machine is in motor or in generator operation.

Input voltage of the node will be taken for the calculation of the short-circuit current and therefore it must be recorded. Is there any definition of voltage for this node made before it will be shown as default value. A change of it has influence to all elements connected to this node.

For load flow calculations asynchronous machines have no influence.

By means of the root database you have a quick access to the desired asynchronous machine. Please input the relevant numbers at the area 'Archive' and 'Group'.

When selected a type of machine all relevant data of the machine will be shown and are not subject to change.

If you want to record the data manually input 0 at 'Archive'.

In case of a short-circuit asynchronous machines contribute to the delivery of short-circuit energy especially they have large rated power.

U_r is the rated voltage the asynchronous machine delivers its output rated power P_r.

For determination of impedances efficiency, power factor, ratio of starting current to rated current and the number of pole pairs is important.

If there is no input at the ratio of R to X in the positive sequence system as well as X in the negative sequence system to X in the positive sequence system the program calculates with standard values.

RLC-Element

Select the menu item 'Element Data' or the corresponding icon and click to the RLC-element placed and designated in your network graphic before.

Element: Designation: RC_3955
Consideration: general considered

Node: Designation: U_n:
Input: SS2 12 kV
Output: SS3 12 kV

Technical Data: U_r: 12 kV, L_r: 0 kA

Positive sequence system: R_(1) Real: 0 Ohm, X_(1) App.: 0 Ohm, C_Operat.: 0 μF

Zero sequence system: R_(0) Real: 0 Ohm, X_(0) App.: 0 Ohm, C_Earth: 0 μF

Buttons: OK, Cancel, Apply, Help

RLC-element for short-circuit and load flow calculation

With the function '?' for 'Direct help' you get detailed information to every input- or selection-/display area. For detailed information to the area 'Element designation' and 'Consideration' please refer to explanations in Section **net feeder**.

For load flow calculations only the values for the maximum case of operation are considered. Other selections have the same meaning just like 'not considered' and 'general considered'.

Input and output voltage of the node will be taken for the calculation of the short-circuit current as well as for the load flow calculation and therefore they must be recorded. Are there any definitions of voltages for those nodes made before they will be shown as default values. A change of them has influence to all elements connected to this node.

Besides data for rated voltage and rated current for the RLC-element resistances and reactances for positive and negative sequence system must be recorded.

Data of the zero sequence system are required for calculation of unsymmetrical short-circuits; data of the positive sequence system are needed for calculation of symmetrical short-circuits.

Informations of capacitances are needed in order to consider the shunt impedance of the RLC-element in load flow calculations.

RLC-elements are always used when elements in the network cannot be defined by means of standard elements, e.g. capacitors, switches or arbitrary complex impedances.

The RLC-element is realized as equivalent π -network.

Impedance Coil

Select the menu item 'Element Data' or the corresponding icon and click to the impedance coil placed and designated in your network graphic before.

Element: Designation: DR_3939
Consideration: general considered

Node: Designation: U_n:
Input: SS2 12 kV
Output: SS3 12 kV

Technical Data: U_r: 12 kV, L_r: 0 kA, P_kr: 0 kW, u_kr: 0 %

Buttons: OK, Cancel, Apply, Help

Impedance Coil

With the function '?' for 'Direct help' you get detailed information to every input- or selection-/display area. For detailed information to the area 'Element designation' and 'Consideration' please refer to explanations in Section **net feeder**.

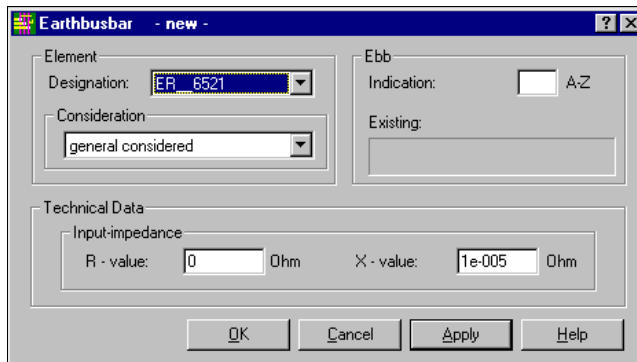
Input and output voltage of the node will be taken for the calculation of the short-circuit current and therefore they must be recorded. Are there any definitions of voltages for those nodes made before they will be shown as default values. A change of them has influence to all elements connected to this node.

By means of the root database you have a quick access to the desired impedance coil. Please input the relevant numbers at the area 'Archive' and 'Group'.

When selected a type of impedance coil all relevant data of the impedance coil will be shown and are not subject to change.

Earth Busbar

Select the menu item 'Element Data' or the corresponding icon and click to the earth busbar placed and designated in your network graphic before.



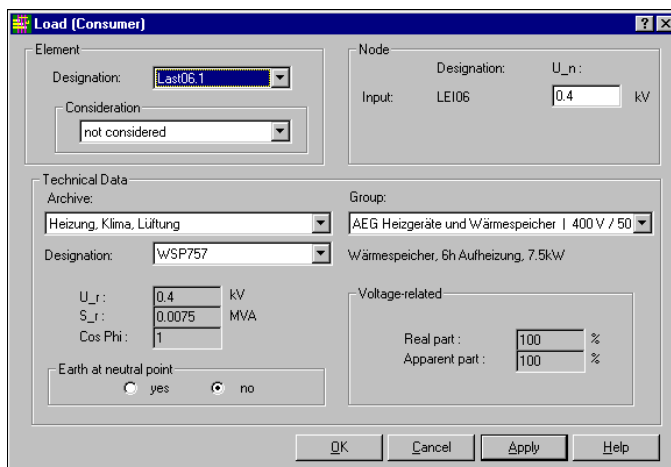
Earth busbar for short-circuit calculation

With the function '?' for 'Direct help' you get detailed information to every input- or selection-/display area. For detailed information to the area 'Element designation' and 'Consideration' please refer to explanations in Section **net feeder**.

Input of resistance and reactance will be considered at the calculation of single-phase and double-phase short-circuits. Earth busbars have no influence to load flow calculations.

Load (Consumer)

Select the menu item 'Element Data' or the corresponding icon and click to the load (consumer) placed and designated in your network graphic before. Loads are non-motive consumers and will be considered for load flow calculations only because they have no influence on the magnitude of the short-circuit current.



Load for load flow calculation

With the function '?' for 'Direct help' you get detailed information to every input- or selection-/display area. For detailed information to the area 'Element designation' and 'Consideration' please refer to explanations in Section **net feeder**.

The selections for minimum and maximum short-circuit are not applied and are equal to 'not considered' or 'general considered'.

With the selection of a consumer from the root database all input area will be fed with the relevant technical data except the values for earthing.

Power factor $\cos \varphi$ is required in order to determine real and reactive power of the given apparent power.

The load of a consumer can be divided in a part, which is independent of the voltage (constant load) and a part with quadratic dependence of the voltage. The part with the quadratic dependence of the voltage will be recorded in % in order to consider the influence of the variation of the voltage in the calculation.

| Kind of Load | Real Part A_p [%] | Reactive Part A_q [%] |
|--------------------|---------------------|-------------------------|
| Constant power | 0 | 0 |
| Constant current | 55,55 | 55,55 |
| Constant impedance | 100 | 100 |

Shunt Impedance

Select the menu item 'Element Data' or the corresponding icon and click to the shunt impedance placed and designated in your network graphic before.

Shunt Impedance for short-circuit and load flow calculation

With the function '?' for 'Direct help' you get detailed information to every input- or selection-/display area. For detailed information to the area 'Element designation' and 'Consideration' please refer to explanations in Section **net feeder**.

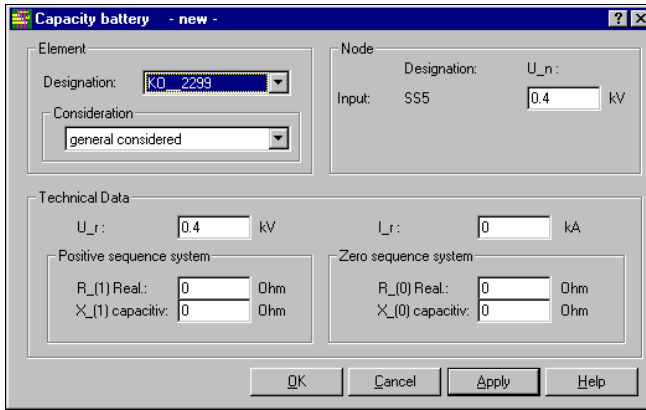
For load flow calculations only the values for the maximum case of operation are considered. Other selections have the same meaning just like 'not considered' and 'general considered'.

Input voltage of the node will be taken for the calculation of the short-circuit current as well as for the load flow calculation and therefore it must be recorded. Is there any definition of voltage for this node made before it will be shown as default value. A change of it has influence to all elements connected to this node.

Besides data for rated voltage and rated current for the shunt impedance resistances and reactances for positive and zero sequence system must be recorded.

Capacity Battery

Select the menu item 'Element Data' or the corresponding icon and click to the capacity battery placed and designated in your network graphic before.



Capacity Battery for short-circuit and load flow calculation

With the function '?' for 'Direct help' you get detailed information to every input- or selection-/display area. For detailed information to the area 'Element designation' and 'Consideration' please refer to explanations in Section **net feeder**.

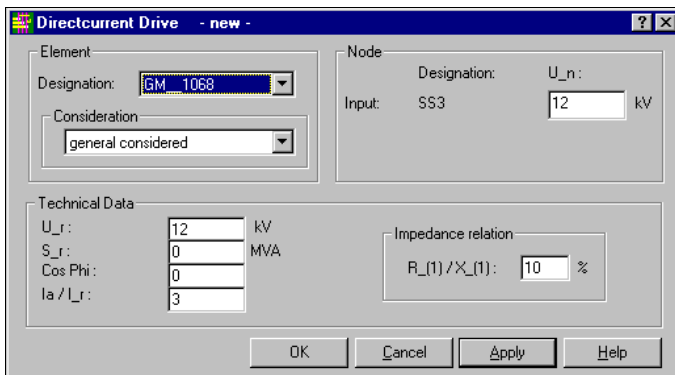
For load flow calculations only the values for the maximum case of operation are considered. Other selections have the same meaning just like 'not considered' and 'general considered'.

Input voltage of the node will be taken for the calculation of the short-circuit current as well as for the load flow calculation and therefore it must be recorded. Is there any definition of voltage for this node made before it will be shown as default value. A change of it has influence to all elements connected to this node.

Besides data for rated voltage and rated current for the capacity battery resistances and reactances for positive and zero sequence system must be recorded.

Direct Current Drive

Select the menu item 'Element Data' or the corresponding icon and click to the direct current drive placed and designated in your network graphic before.



Direct Current Drive

With the function '?' for 'Direct help' you get detailed information to every input- or selection-/display area. For detailed information to the area 'Element designation' and 'Consideration' please refer to explanations in Section **net feeder**.

For load flow calculations only the values for the maximum case of operation are considered. Other selections have the same meaning just like 'not considered' and 'general considered'.

Input voltage of the node will be taken for the calculation of the short-circuit current as well as for the load flow calculation and therefore it must be recorded. Is there any definition of voltage for this node made before it will be shown as default value. A change of it has influence to all elements connected to this node.

In case of a short-circuit direct current drives contribute to the delivery of short-circuit energy especially they have large rated power.

U_r is the rated voltage the direct current drive consumes its rated power S_r .

For determination of impedances power factor and ratio of starting current to rated current is important.

If there is no input at the ratio of R to X in the positive sequence system as well as X in the negative sequence system to X in the positive sequence system the program calculates with standard values.

Circuit Breaker

Activate the icon 'Show \Enter Technical Data' and click onto the circuit breaker in the network graphic, which was placed and denominated in the network graphic before.

Circuit breaker

With the function '?' for 'Direct help' you get detailed information to every input- or selection-/display area. Context help with connections to the online-help is not yet available. Regarding the area 'Designation' please refer to explanations of section **Net feeder**.

With the check box 'Switching Condition' you can turn on or off the circuit breaker. It displays its status, too.

The default value of the nominal input voltage U_n of the node, where the circuit breaker is connected, is shown or can be defined here.

The technical data will be taken from the protective device data base and set to the smallest type of protective device, which is available, at first. A change of the technical data is possible with a selection from the data base (Archive and Designation). Technical data for circuit breakers are required as follows: Rated current, selection of range, bimetal- and short-circuit release and a time-delay, if applicable.

Fuse Switch-disconnector

Activate the icon 'Show \Enter Technical Data' and click onto the fuse switch-disconnector in the network graphic, which was placed and denominated in the network graphic before.

Fuse Switch-Disconnector

With the function '?' for 'Direct help' you get detailed information to every input- or selection-/display area. Context help with connections to the online-help is not yet available. Regarding the area 'Designation' please refer to explanations of section **Net feeder**.

With the check box 'Switching Condition' you can turn on or off the fuse switch-disconnector. It displays its status, too.

The default value of the nominal input voltage U_n of the node, where the circuit breaker is connected, is shown or can be defined here.

The technical data will be taken from the protective device data base and set to the smallest type of protective device, which is available, at first. A change of the technical data is possible with a selection from the data base (Archive and Designation). Technical data for circuit breakers are required as follows: For fuse switch-disconnectors, fuses and line-protection switches only the input of the rated current is necessary.

The input dialogue for the technical data of the remaining types of protective devices stated above is identical to that of the fuse switch-disconnector.

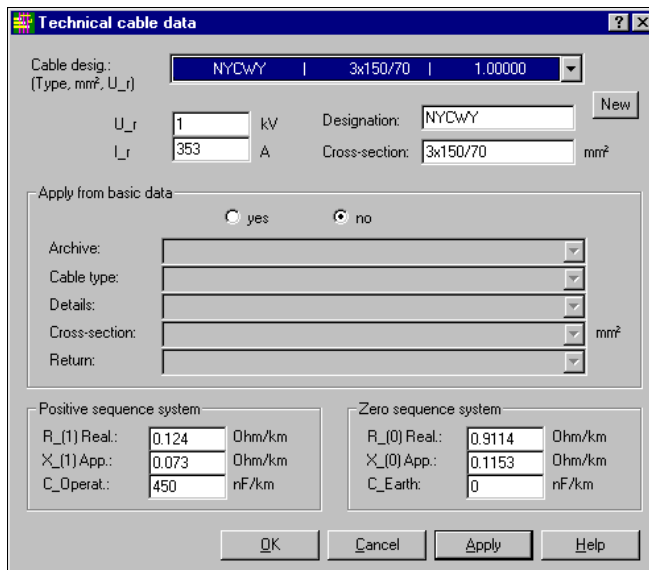
Independent (Definite) Time Overcurrent Protection

For the calculation of medium-voltage networks the independent (definite) time overcurrent protection was added to the protective device data base and integrated into the computation.

In the protective device data base the independent (definite) time overcurrent protection is modelled as circuit breaker. The characteristic of the bimetal release, which is necessary for computation but does not exist in this case, is acquired in the data base simultaneously to the short-circuit release. This requires at the input, that the settings for the bimetal release and the short-circuit release are set to the same value in order to ensure a switch-off from the short-circuit release. If there is an input for a time-delay, it is valid for the whole range of the characteristic. That means if the independent (definite) time overcurrent protection will release in the undelayed range, the time delay must be reset to zero.

Acquisition of Technical Cable Data

In addition to the element data of your network you can record further technical cable data also. Therefore you have to select the menu item 'Edit' / 'Technical Cable Data'.



Technical cable data for short-circuit and load flow calculation

With this menu item you can record detailed cable data, which will be used in your network.

In the window 'Cable desig.' you can choose an existing cable to inform yourself about the recorded data or to change these data.



Every change of these system data has only effect in the current project. At every new project you will find the unchanged system data again.

If you want to use the extended system cable data for further projects you have to use that project where the system cable data were changed or extended as basic project. From this basic project new projects will be generated by copying.

You can define a new cable by pushing the button 'New'. Cable designation as well as cross section describes the cable type. If a required cable type is already defined in the common root data base for cables its cable data can be taken from there for short-circuit and load flow calculations.

With the area 'Archive' and 'Cable type' you can select the relevant cable. Data for 'Details', 'Cross-section' und 'Return' are selectable also. Existing technical cable data of the selected cable, which will be needed for the calculations, will be shown in the relevant area. If the required cable doesn't exist you have to record its data manually. Therefore you have to transfer the necessary data into the relevant area (rated voltage, rated current, reactances and capacities for the positive and zero sequence system from the leaflet of the cable manufacturer). If a cable should be operated at a higher voltage you can record U_m in the area for U_r (e.g. in a three-phase system a 30kV cable can be operated up to max. $U_m = 36$ kV).



Cable data for short-circuit calculations will be saved with the current project because further cable data are needed i.e. capacity of operation and earth capacity. They both can vary for different projects.

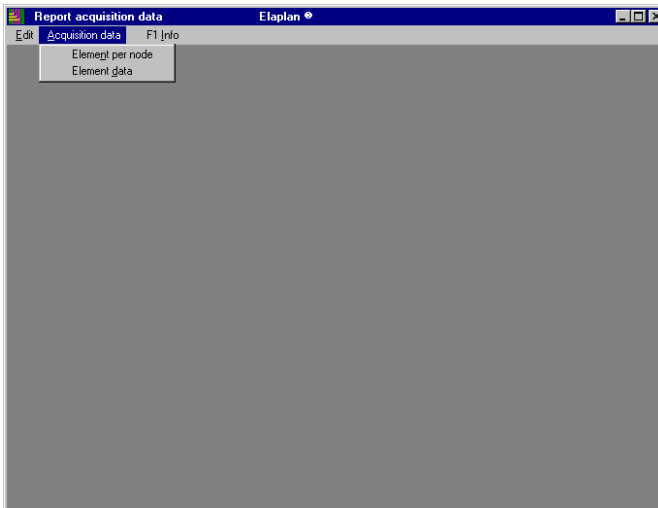


For load flow calculations the capacity of operation of the cable must be recorded in the positive sequence system.

Report Acquisition Data

All recorded data can be given on screen and printer.

The output of the element data is without calculation and is needed for the check of the recorded values.



Report Acquisition Data

You can select between the output of the elements per node or the output of the whole data of every single element.

Typicals for different output listings, e.g. for the output of the recorded elements per node, for the output of the recorded data per element etc., can be made by means of sample-projects, which are scope of the software delivery. With the function 'Copy Sample-Project' in the module *Elaplan-B* you can select one of the sample-projects and add it as an actual project. You can print or display the different kinds of output listings and illustrate yourself their differences and uses.

Short-Circuit

Elements installed in electrical switchgear are designed and selected according to the VDE regulations. Besides the continuous load all stresses and consequences in any cases of short-circuit must be considered. Since short-circuit currents can reach a multiple of the rated current high thermal and mechanical stress is expected. Inadmissible voltages arising possibly can cause damaging of elements and endangering of persons. This is why the expected stresses in case of a short-circuit must be evaluated for safety reasons. Therefore the knowledge of the short-circuit currents in the network is needed.

The module *Elaplan-4* uses two different kinds of mathematical algorithms. For short-circuit at one node the method according to **Gauß (short-circuit location at one node)** is used for the calculation of the fault current at the short-circuit location and the partial short-circuit currents in the complete network. The method according to **Takahashi (short-circuit location at all nodes)** considers the location of the short-circuit at every node of the network one after the other. This method calculates the total short-circuit current at all nodes of the network as well as the partial short-circuit currents flowing in the direction of the fault location immediately.

Initial Short-circuit Current I''_k

For the three-phase short-circuit only the impedances of the positive sequence network will be used. The calculation occurs according to the method of the **equivalent voltage source** where the one and only voltage source is effective at the fault location.

It is a precondition for using the method of the equivalent voltage source at the fault location that shunt impedances of lines and transformers as well as loads must not be considered.

That means:

- No-load losses and magnetizing current of transformers will not be considered.
- Capacities of lines will be neglected.
- Shunt impedances and loads will be neglected.
- Asynchronous motors, synchronous generators and net feeders are the only shunt impedances.

The calculation of unsymmetrical faults

- single-phase – earth fault
- double-phase fault
- double-phase fault with ground touch
- double earth fault

occurs with the method of Symmetrical Components (Fortescue Components). Impedances of the original system will be transformed into components of the positive sequence system (index 1), negative sequence system (index 2) and zero sequence system (index 0). The method of Symmetrical Components is based on the fact that any arbitrary unsymmetrical three-phase system can be divided in components in a way that several new but symmetrical three-phase systems and one single-phase system are generated. The intermediate results will be superposed to the total solution afterwards (synthesis).

Short-circuit Peak Current i_p

VDE 0102 gives three methods for calculation of the short-circuit peak current:

- Type A: Unique ratio of R/X or X/R.

Only applicable, if no extended precision is required. This is why this method is not used in *Elaplan*.

- Type B: Ratio R/X at the fault position.

This method is allowed for intermeshed networks, but gives more inexact results than the equivalent frequency calculation. This is why VDE 0102 deals with a safety margin the result must be multiplied by. Default this value is set to 1,15. In radial networks this safety margin can be set to 1,0. A splitting of this factor makes it possible to calculate intermeshed in high-voltage networks and radially in low-voltage networks.

$$i_p = \text{Fakt1} * \epsilon * \sqrt{2} * I''_k \text{ (high-voltage)}$$

$$i_p = \text{Fakt2} * \epsilon * \sqrt{2} * I''_k \text{ (low-voltage)}$$

According to VDE 0102/1.90 the product $\text{Fakt} * \epsilon$ is limited to 2,0 in the high-voltage network when calculation type B is used. For low-voltage networks the product $\text{Fakt} * \epsilon$ is limited to 1,8. Other limits can be set in *Elaplan* also.

- Type C: Equivalent frequency calculation

According to VDE 0102 this method is always allowed for calculation of short-circuits in intermeshed networks. It gives the smallest deviations between calculated and real short-circuit peak current. This is the standard method of *Elaplan*.

Breaking current I_a

The breaking current at the fault location consists of the partial breaking currents of synchronous generators, net feeders and asynchronous motors. The fading away to the breaking current is considered by the factor μ .

$$I_a = \mu * I''_k$$

The factor μ depends on the **min. switching time lag** t_{min} and the ratio $I''_{k_generator} / I_{r_generator}$.

Continuous short-circuit current I_k

The value of the continuous short-circuit current depends on saturation effects and on the variation of the switching situation in the network. In practice both items are not known. VDE 0102 states a method of calculation which delivers a sufficient result for the maximum and minimum continuous short-circuit current for that case where a generator or a synchronous machine feeds the short-circuit. The calculation of the minimum and maximum continuous short-circuit current happens according the λ_{min} - and λ_{max} -curves. They depend on the ratio $I''_{k_generator} / I_{r_generator}$ and $x_{d, saturated}$. $x_{d, saturated}$ is the reciprocal value of the saturated no-load/short-circuit ratio.

$$I_k = \lambda * I''_k$$

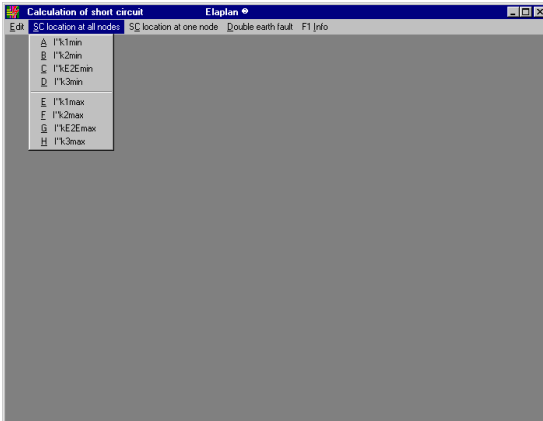
After acquisition of the network graphic the single elements get related to their technical data. After executed short-circuit calculation you can output the results on screen or printer.



Besides network data for the short-circuit calculation the data for load flow calculation can be acquired also. For description of the relevant dialog windows and input area refer to Section 'Load Flow'.

Calculate Short Circuit

When you have related technical data to all elements in the network graphic you can start calculation of short-circuit currents.



Calculate Short Circuit

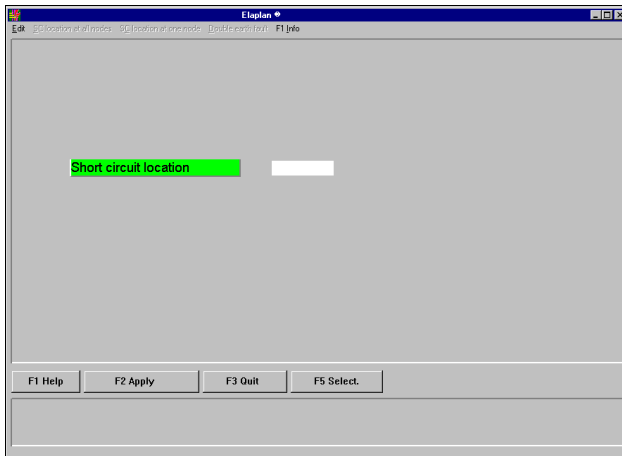
You have the possibility to calculate short-circuit currents for different types of faults. There are the two methods of calculation available. The selection items of the menu are identically of both methods.

With the method according **Takahashi** (menu bar 'SC location at all nodes') the initial short-circuit current at all nodes will be calculated. The result of the calculation with this algorithm is the total short-circuit current at all nodes of the network as well as the partial short-circuit currents flowing in the direction of the fault location immediately.

With the method according **Gauß** (menu bar 'SC location at one node') the fault currents will be calculated only for the selected node. The result of the calculation with this algorithm is the total short-circuit current at the selected node as well as the partial short-circuit currents flowing through all branches of the network.

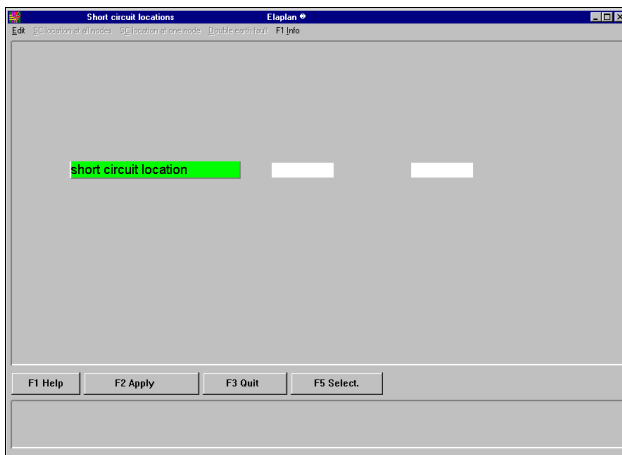
When using the method according **Gauß** (**short-circuit location at one node**) you have to determine a **fault location**. Beginning from this node all partial short-circuit currents flowing through the branches of the network will be calculated.

When you put in the chosen fault location the calculation starts. At this method the result data of the node calculated at last will be kept for every type of fault.



Calculate Short-Circuit, Short-Circuit location at one node

For calculation of double earth fault you have to determine two fault locations at different nodes.



Registration of Short-Circuit Locations

Both short-circuit locations must be part of the same voltage level, e.g. 0,4 kV and 10 kV are not permissible. Short-circuit will be assumed between phase L1 and earth at the first fault location and between phase L2 and earth at the second fault location.

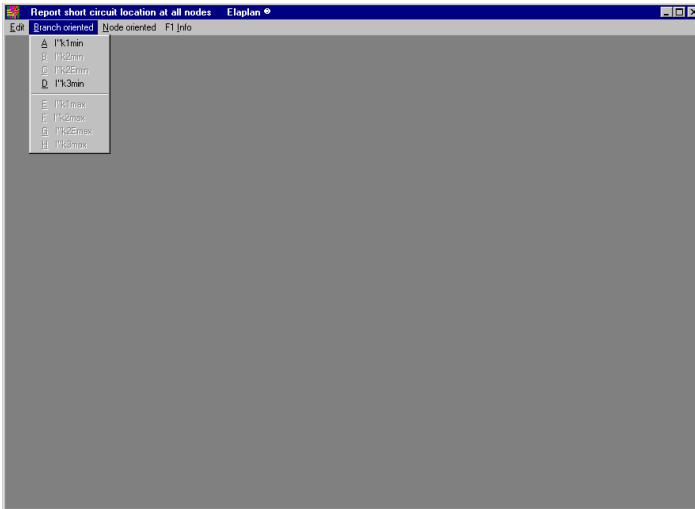
As result after executed calculation you receive the short-circuit data at both fault locations.

If the program detects an error during calculations an error protocol can be given on screen or printer.

Are all necessary results of calculation ready you can put them out on screen or printer.

Report Short Circuit at all Nodes

When calculating the short-circuit currents at all nodes (according **Takahashi**-algorithm) you can put them out on screen or printer.



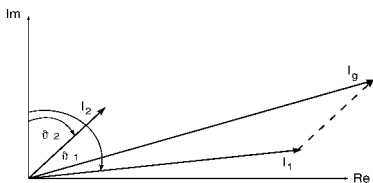
Report Short Circuit at all Nodes

The results of the calculation can be shown completely (branch oriented) or for chosen short-circuit locations (node oriented).

The presentation of a result with a '*' in the output lists means that this results exceeded the maximum presentable value (e.g. 9999 Ω). This presentation is permissible because larger values don't affect the total result and its evaluation.

Typicals for different output listings, e.g. for the report of calculation of a minimum single-phase short-circuit, for the report of calculation of a maximum three-phase short-circuit etc., can be made by means of sample-projects, which are scope of the software delivery. With the function 'Copy Sample-Project' in the module *Elaplan-B* you can select one of the sample-projects and add it as an actual project. You can print or display the different kinds of output listings and illustrate yourself their differences and uses.

The diagram below shows the meaning of the angle of the current θ at branch oriented short-circuit currents calculated according the Takahashi algorithm (short circuit at all nodes):



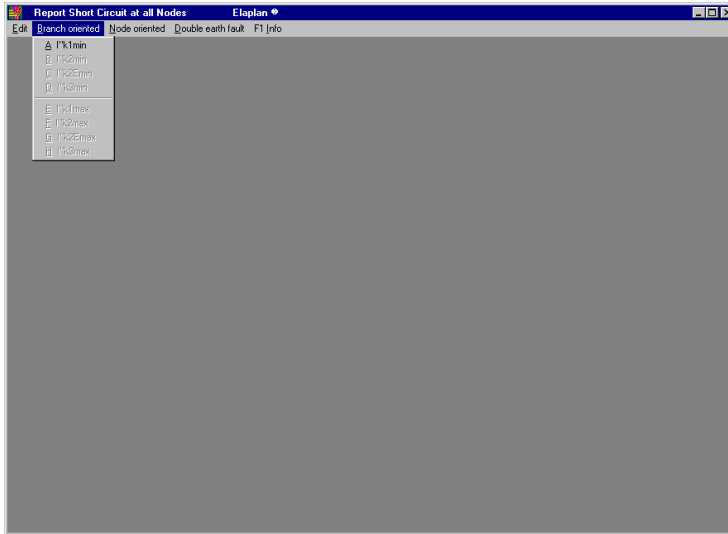
$$I_g = I_1 + I_2$$

$$I_1 = (I_1) * (\cos \varphi_1 - j \sin \varphi_1)$$

$$I_2 = (I_2) * (\cos \varphi_2 - j \sin \varphi_2)$$

Report Short Circuit at a Fixed Node

When calculating the short-circuit currents at a fixed node (according **Gauß**-algorithm) you can put them out on screen or printer.



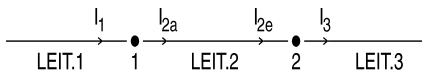
Report Short Circuit at a fixed Node

The results of the calculation can be shown completely (branch oriented) or for chosen short-circuit locations (node oriented).

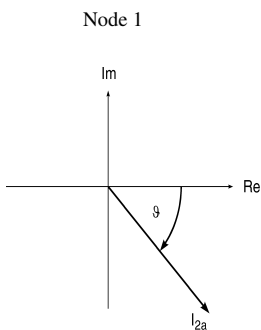
The presentation of a result with a * in the output lists means that this results exceeded the maximum presentable value (e.g. 9999 Ω). This presentation is permissible because larger values don't affect the total result and its evaluation.

Typicals for different output listings, e.g. for the report of calculation of the maximum three-phase short-circuit current at a fixed node etc., can be made by means of sample-projects, which are scope of the software delivery. With the function 'Copy Sample-Project' in the module *Elaplan-B* you can select one of the sample-projects and add it as an actual project. You can print or display the different kinds of output listings and illustrate yourself their differences and uses.

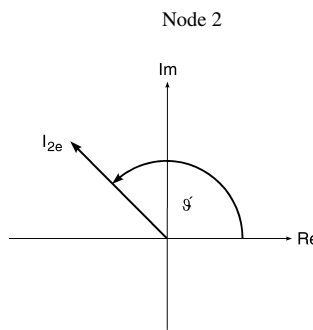
The diagram below shows the meaning of the angle of the current ϑ at branch oriented short-circuit currents for a fixed node:



- I_1 Current at the end of line LEIT.1 (node 1)
- I_{2a} Current at the beginning of line LEIT.2 (node 1)
- I_{2e} Current at the end of line LEIT.2 (node 2)
- I_3 Current at the beginning of line LEIT.3 (node 2)



$$\vartheta = \arctan \left(\frac{I_{Im}}{I_{Re}} \right)$$



$$\vartheta' = \arctan \left(\frac{I_{Im}}{I_{Re}} \right) * (-1)$$

ϑ clockwise:

negative value

→ Assumed direction of current flow: out from element into node

ϑ ' counter-clockwise:

positive value

→ Assumed direction of current flow: into element out from node

The 1st Kirchhoff's law (node theorem) is effective: $\Sigma I = 0$ at one node.

Node 1:

$$I_1 - I_{2a} = 0$$

$$I_1 = I_{2a}$$

Node 2:

$$I_{2e} - I_3 = 0$$

$$I_{2e} = I_3$$

Rule of sign:

Current, which flows into an element, has an angle with negative value.

Load Flow

The load flow calculation program is used for determination of the voltages at all nodes of the network (scalar value and phase angle), the load flows and the losses in the elements of the network.

A **load flow calculation** requires that the consumption of all loads in the network is well known by means of measurements or estimates. Additionally the voltage and the real power at feeders from prior networks or power plants must be known.

Feeders and generators must power the consumption of the loads and the losses in the network caused by the load flow in the network.

For balancing the total load in the network one generator, the so-called slack generator, must feed the difference power to the assumed feeding powers (residual power). The slack generator is situated at the reference node, the so-called slack node. The slack node has a phase angle of 0 deg by definition and is determined as the node of that net feeder, which was put in at first. If there is no net feeder the node of that generator, which was put in at first, is chosen. The residual power can be split to various arbitrary feeders also. The sum of the split residual power must be 100 % in any case.

The assumed direction of the power flow is defined in the load reference arrow system: Real power and inductive reactive power (lag) flowing into an element will have positive value. The load reference arrow system will be used for the output of the results of generators and net feeders also.

At an overexcited generator that feeds real power and inductive reactive power (lag) into the network the real and reactive component have a negative sign because they both flow against the defined direction of the positive power flow.

This rule for the sign will be used in the output listings also.

At the nodes of a network feeders (net feeder, synchronous generators) and loads (asynchronous motors, consumers, cables and lines) can be connected. Nodes without any connection are permissible also.

The kind of the connected elements determines the type of the node:

- **PQ-node**
- **PV-node**
- **Slack-node**
- **PQ-node**

PQ-nodes are nodes without feeders and nodes with generators without determination of the terminal voltage U_{KL} . Real power P and power factor $\cos \varphi$ must be stated, terminal voltage U_{KL} will not be recorded. There exist:

- nodes with constant load (record of P, Q)
- nodes with constant impedance (powers have quadratic dependence of the voltage), i.e. reactive part with dependence of the voltage = 100 % real part with dependence of the voltage = 100 % ($\underline{S} = P + jQ = U^2/\underline{Z}$)
- node with mixed load (constant part and impedance part)
- node without load

At PQ-nodes the voltage will be calculated with scalar value and phase angle. The phase angle is related to the reference node (slack node), which has a phase angle of 0 deg by definition.

PV-node

PV-nodes are nodes with feeders (net feeders, generators). Real power P and terminal voltage U_{KL} must be stated. Reactive power Q and phase angle of the node voltage will be calculated.

Slack-node

The slack node is the reference node. It must contain minimum one feeder which voltage is given. The phase angle of the voltage will be kept to 0 deg during load flow calculation.

The slack node can deliver the residual power of the network. But this is not a requirement. It is also possible to state the real power P , which is fed at the slack node, and to split the residual power to several generators at other nodes. The percentage of the residual power, delivered by the single generators, can be set for every generator.

Etaplan determines the slack node according the rule as follows:

The node of that net feeder, which was put in at first, is selected as the slack node. If there is no net feeder the node of that generator, which was put in at first, is chosen.

Calculate Load Flow

The load flow program makes possible the calculation of the distribution of real and reactive power flows, the losses in the network elements as well as in the whole network and the voltage at all nodes.

In many cases it is not possible to find a solution of the load flow calculation for the given conditions. In such case an error protocol will be given which indicates that the iteration was cancelled. The user has to detect the physical incompatibilities in the given data systematically.

Possibilities are as follows:

1. Reducing of loads in the network

until a solution is possible (motors, loads, cables with load).

2. Changing of constant loads into impedance loads.

For larger loads the real part A_p and the reactive part A_q for real and reactive power should be set to 100 %. This is equal to pure impedance loads. Afterwards a new load flow calculation has to be made. If this calculation converges, the loads, which are too large, probably are situated at those nodes with the smallest voltages.

3. Changing of PV- into PQ-nodes

This change is only possible for generators but not for net feeders. If necessary the net feeders must be changed into generators before. If the program calculates a high terminal voltage for several generators after this changing, this is an indication that the given feeding power of the net feeder was too high. Either the power for transmission is lower or element data are incorrect e.g. lengths of cables are too large or impedance voltages are too high. If the calculated generator voltages will be given than terminal voltages and the generators will be changed back into PV-elements a solution of the load flow calculation is possible. Starting from this solution you can vary the network data as long as a realistic solution can be found.

4. Set limit of accuracy to appr. 10 % of the total power.

Reduce the limit of accuracy for further calculations down to the smallest load if necessary.

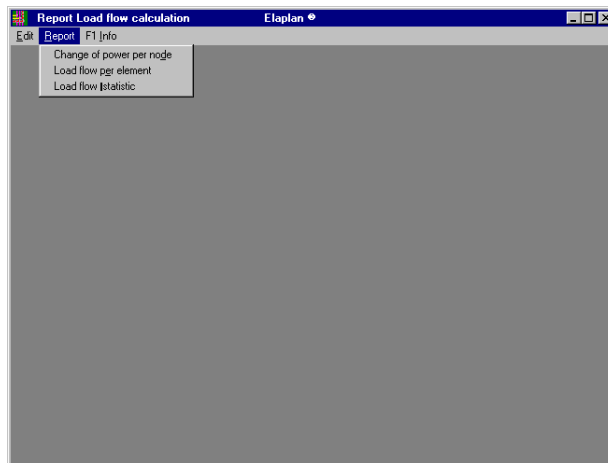
5. Enlarge the number of iterations up to the limit of iteration

Results of the load flow calculation can be given graphically or as listing on screen as well as on the printer.

Report Load Flow Calculation

The results of the load flow calculation can be put out on screen or printer. By means of the network graphic the output of data related to every network element is possible on the plotter additionally.

The listings with the results can be put out even at cancelled iteration.



Report Load Flow Calculation

The result of a load flow calculation consists of three parts:

- **Change of voltage per node**
Output of voltage at all nodes.
- **Load flow per element**
Output of the current in all branches of the network, the loading and the flow of real and reactive power for every element.
- **Load flow statistic**
Output of those nodes with the highest and lowest voltage. For every kind of network element the generated and consumed real and reactive power will be balanced.

In order to ensure that a practical solution was computed you should check the listings of results referring to criteria as follows:

Typicals for different output listings, e.g. for the change of voltage per node etc., can be made by means of sample-projects, which are scope of the software delivery. With the function ‚Copy Sample-Project‘ in the module *Elaplan-B* you can select one of the sample-projects and add it as an actual project. You can print or display the different kinds of output listings and illustrate yourself their differences and uses.

Normally the angle of voltage has a value between -20° and 0°.

The slack-voltage U_{Slack} is located at the real axis by definition (in the example the adequate node is SS1: angle $\vartheta = 0^\circ$).

In the listings the voltages at all other nodes are shown as scalar value of the node voltage and with an angle between the voltage of the slack-node (real axis) and the relevant node voltage:

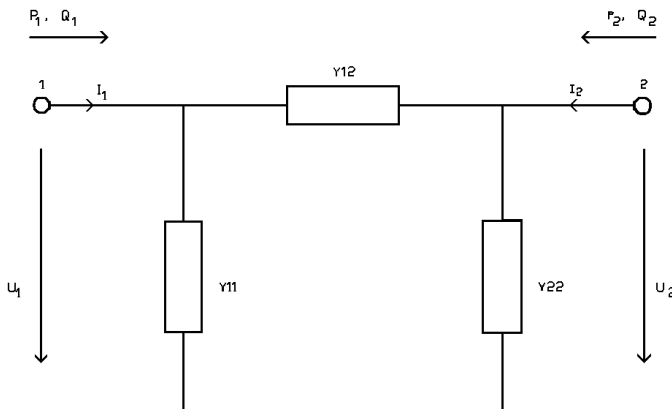
$$\tan \vartheta = \frac{U_{\text{IM}}}{U_{\text{RE}}} \quad \vartheta = \arctan \left(\frac{U_{\text{IM}}}{U_{\text{RE}}} \right) \quad |U| = \sqrt{U_{\text{RE}}^2 + U_{\text{IM}}^2}$$

For cables / wires the loading in [%] is the ratio of operating current to rated current (rated current without consideration of reducing factors for accumulation and laying according VDE 298). For all other elements the loading is computed as the ratio of operating apparent power to rated apparent power. The operating apparent power is calculated according the formula $S_{\text{operating}} = \sqrt{3} * U_{\text{operating}} * I_{\text{operating}}$.

Typicals for different output listings, e.g. for the load flow per element etc., can be made by means of sample-projects, which are scope of the software delivery. With the function ‚Copy Sample-Project‘ in the module *Elaplan-B* you can select one of the sample-projects and add it as an actual project. You can print or display the different kinds of output listings and illustrate yourself their differences and uses.

Please note at all feeders, that the expected values for generators and net feeders will appear. You should check whether the power would be transported through the network (note the sign in the listings). Series losses (P_{SER} , Q_{SER}) between nodes of the network are caused by the voltage drop, which occurs at the series impedance of the element. Transmission lines are modelled as series impedances. Shunt losses (P_{SHUNT} , Q_{SHUNT}) result from the voltage drop between a node and earth. Loads are pure shunt impedances. Transmission lines with loads are modelled as π -equivalent. The sum of series losses and shunt losses makes the **total losses** (P_{INT} , Q_{INT}) of the elements between two nodes of the network.

Calculation of the losses:



$$\begin{aligned}
 P_{INT} &= P_1 - P_2 & Q_{INT} &= Q_1 - Q_2 \\
 S &= U * I^* \\
 S_{SHUNT} &= (U_1)^2 * Y_{11}^* + (U_2)^2 * Y_{22}^* \\
 P_{SHUNT} &= (U_1)^2 [\text{Re}(Y_{11}) + \text{Re}(Y_{22})] \\
 Q_{SHUNT} &= -(U_2)^2 [\text{Im}(Y_{11}) + \text{Im}(Y_{22})] \\
 P_{SER} &= P_{INT} - P_{SHUNT} \\
 Q_{SER} &= Q_{INT} - Q_{SHUNT}
 \end{aligned}$$

The loading in % specifies the ratio of operating current to rated current.

Typicals for different output listings, e.g. for the load flow statistic etc., can be made by means of sample-projects, which are scope of the software delivery. With the function 'Copy Sample-Project' in the module *Elaplan-B* you can select one of the sample-projects and add it as an actual project. You can print or display the different kinds of output listings and illustrate yourself their differences and uses.

The load flow statistic is needed for verification of the accuracy of the calculation. If the sum of the real power is not zero, the user must criticize whether the accuracy of the calculation is sufficient enough. The user has to decide how many percent deviation in power related to the feeding power is allowed.

If the deviation is too high, the limit of accuracy must be reduced. If the iteration will be cancelled, the maximum number of iteration cycles must be increased. The load flow calculation will be stopped, if the deviation in power at every node between the calculation steps n-1 and n is less than the limit of accuracy. But it doesn't mean, that this is the real solution. It is possible, that the calculation step n is far away from the real solution, although the deviation in power from calculation step n-1 to n is less than the limit of accuracy.

Selectivity

Protective devices in networks protect electrical elements against undue strain because of short-circuit and overload.

Electrical elements are net feeders, transformers, lines, busbars, switchgear, loads and consumer etc.

If there are any fault conditions failure should be limited to that element it concerns. If this comes true and if all other elements can continue in operation without any disturbance it is called selectivity, also called discrimination.

Conditions of selectivity:

- Overcurrent protective devices must cut off that element with a fault (short-circuit or overload) from the network immediately.
- Current peaks under service conditions, e.g. starting currents of motors, must not switch off.
- Sometimes a third requirement is raised:
If the protective device of the element fails a back-up protection must cut off.

Selectivity by current in case of different short-circuit current levels at location of protective devices

Since in a distribution network the rated currents of protective devices get smaller from transformer to consumer, their magnetic short-circuit trips, also called instantaneous elements or high-set elements, are set to smaller values also resp. their tripping characteristics are lower. Due to the fact, that short-circuits which occur get smaller with increasing distance of the fault location from the transformer, there is an inherent selectivity. Selectivity between protective devices of different distribution levels is ensured if the short-circuit levels at a fault location on every protective device are different enough.

Complete selectivity in case of a short-circuit is given if the maximum short-circuit current behind the downstream protective device is lower than the tripping current of the upstream (line-side) protective devices.

Elaplan calculates the relevant short-circuit currents at the location of the protective devices and compares their tripping characteristics resp. their heat losses due to current (I^2t -values) with each other.

Selectivity by current in case of approximately equal-sized short-circuit current levels at location of protective devices

If in the distribution network the length of lines between upstream and downstream protective device are only small, the maximum short-circuit currents at the location of upstream and downstream protective device are not different enough because of the less attenuation. In this case a complete selectivity of the upstream protective device cannot be reached without time delay of its high-set element.

For determination of selectivity *Elaplan* compares the tripping characteristics. In the field of the overcurrent trip positive selectivity is usually given because of the high operating times. In the field of the short-circuit trip positive selectivity only occurs, when the short-circuit current behind the downstream protective device is smaller than the tripping current of the high-set element of the upstream protective device. This current indicates the limit of selectivity.

Selectivity by time

Positive selectivity is obtained if the total clearing time of the downstream protective device is shorter than the minimum command time of the upstream protective device. The total clearing time of a protective device consists of following times, shown at the example of a circuit-breaker:

| | | |
|---|---|-------------|
| | high-set element, (minimum command time = time between begin of the fault and the releasing of the spring energy store; | appr. 5 ms |
| | breaking process cannot be interrupted after forwarding of the command) | |
| | + release of the locked spring energy store | appr. 5 ms |
| | ----- | |
| = | tripping time (begin of contact separation) | appr. 10 ms |
| + | breaker mechanism with trip-free mechanism, (operating time = time to clearance between open contacts) | appr. 10 ms |
| + | contact system and arcing chamber (arcing time) | appr. 10 ms |
| | ----- | |
| = | total clearing time | appr. 30 ms |

For circuit breakers with selectivity by time this condition can be expressed alternatively:

The delay time of the upstream breaker must be sufficient longer than the total clearing time of the downstream breaker. The delay time consists of the minimum command time and the time delay, set on the time-delay mechanism. Minimum delay time between two breaker levels, which can be reached, are 60 or 100 ms.

If circuit breakers are discriminated by time, the minimum command time of the upstream protective device can be extended when the magnetic short-circuit trip will not release the breaker mechanism directly but delayed.

The delay can be obtained either with a mechanical delay mechanism, which releases the breaker mechanism, or with a electrical device, which trips the shunt release or the undervoltage release. The delay time, which is set at these devices, is not influenced by the level of the short-circuit current.

Selectivity between breakers and fuses

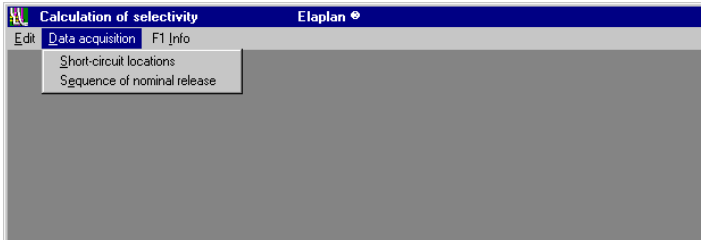
Determination and check of selectivity between breakers and fuses happens by comparison of

their tripping characteristics. Positive selectivity is ensured, if the tripping characteristic of the downstream breaker lies below the tripping characteristic of the upstream breaker. In practical operation a time gap of 60 ms between the characteristics is sufficient.

The adjustment can be set by variation of the tripping current (shifting the tripping characteristic in the overcurrent/time-diagram in horizontal direction, current axis) or by variation of the tripping time (shifting the tripping characteristic in the overcurrent/time-diagram in vertical direction, time axis).

Input Selectivity

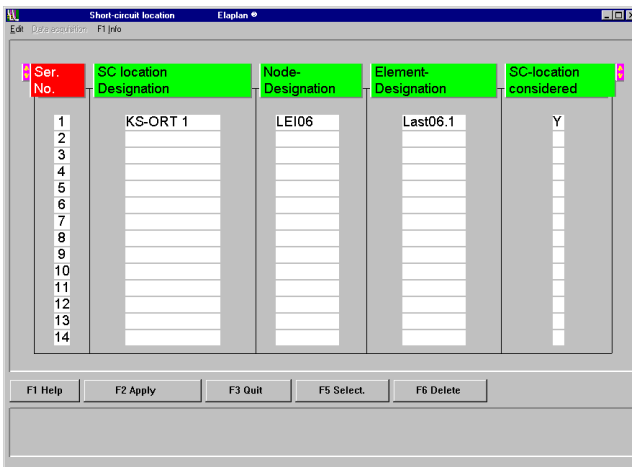
Before starting the check of selectivity, network and data of elements must be recorded for the short-circuit calculation. This happens by means of the programs Network Graphic and Acquisition of Technical Data as stated in the relevant sections before. Protective devices must be positioned and recorded in the network graphic. A manual input of protective devices, which are not positioned in the network graphic, is not possible.



Calculation of Selectivity

Data Acquisition: Short-Circuit Locations

With this dialogue you determine the short-circuit (SC) location(s) and consequently the switching condition of the network for the check of selectivity.

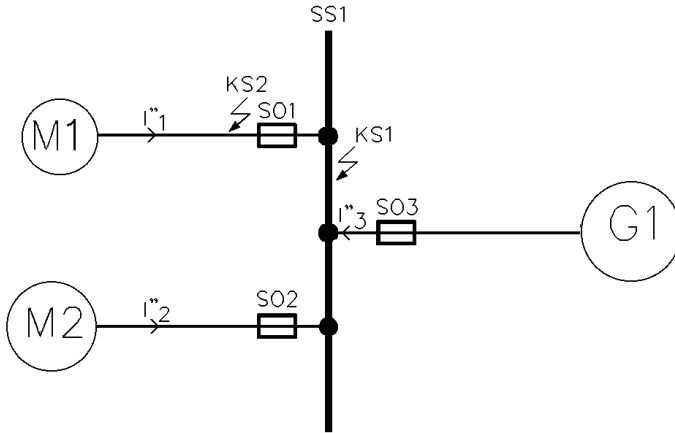


Short-circuit location

Every short-circuit location, where a short-circuit shall be assumed for the check of selectivity, gets a free definable designation of the SC location.

The short-circuit can occur at a busbar or at an element. The short-circuit location for short-circuit at an element is determined unique by input of the node (busbar) and the designation of the element. The location of a short-circuit at a busbar is determined by input of the node.

Example:



- KS1 Short-circuit at busbar SS1
- KS2 Short-circuit at element M1

In case of consideration the short-circuit location KS1 the partial short-circuit current I''_1 flows through the protective device SO1.

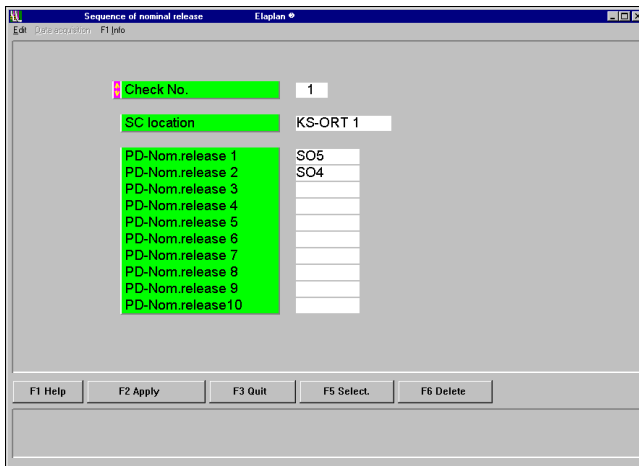
In case of consideration the short-circuit location KS2, the partial short-circuit current $I''_2 + I''_3$ flows through the protective device SO1.

There is the possibility to execute the check of selectivity for several short-circuit locations within one calculation. Every short-circuit location, which shall be considered in the calculation, has to be designated with a "Y". If individual short-circuit locations should be excluded from the calculation, they have to be designated with a "N".

Data Acquisition: Sequence of Nominal Release

The definition of a desired sequence is meaningful, if only a part of protective devices, e.g. a single branch, shall be considered.

In intermeshed networks the desired sequence of release can be different according to the fault location. In this case the definition of a sequence of release is meaningful also.



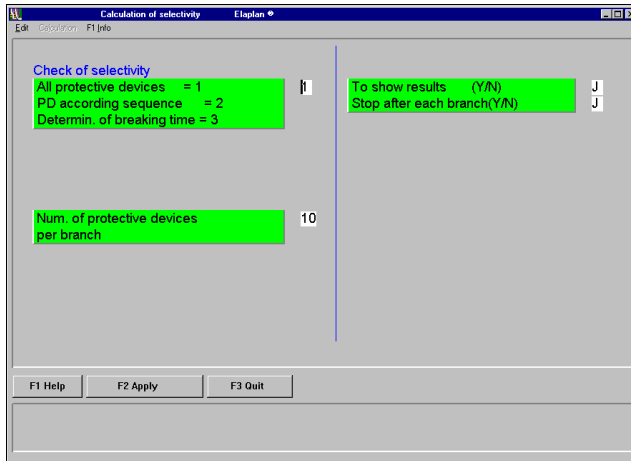
Sequence of nominal release

The assumed short-circuit location is assigned to the stated check number. Starting with this short-circuit location you arrange the protective devices in that sequence they shall release. The protective device stated in the field 'PD-nominal release 1' shall release at first and that one stated in field 10 at last.

In the program you can select, whether you want to check all protective devices or the protective devices according sequence.

Calculation of Selectivity

Before starting the calculation of selectivity some conditions can be defined, which influence the way of calculation. The choices and their consequences will be described in this section.



Calculation of selectivity

With selecting „1“ in the first input area you specify, that a check of selectivity will be done for all recorded protective devices.

In this mode of calculation the program determines all branches of the network with protective devices and the nominal sequence of release related to the respective short-circuit location. That protective device, which is nearby the short-circuit location, gets rank 1 (highest rank), the next gets rank 2 etc. This procedure will be repeated in every branch up to the end node (net feeder, asynchronous motor, generator or end of lines). For checking selectivity the number of protective devices, located one behind the other in a branch of the network, can be limited.

With selecting „2“ in the first input area you specify, that only those protective devices should be calculated, which were selected in the program ‚Sequence of nominal release‘. You can limit the number of protective devices, located one behind the other in a branch of the network, in this mode also. If a branch of a network was defined with e.g. 6 protective devices and the calculation was limited to 3 protective devices, only those 3 protective devices with the highest rank will be considered.

With selecting „3“ in the first input area you specify, that only the tripping times of the defined protective devices will be calculated. The program will not check the selectivity. This mode is meaningful in intermeshed networks, since sometimes a positive selectivity is not possible.

The results of every check can be shown on the screen during calculation. Input a "Y" in the area 'To show results'.

If you select a stop after the calculation of each branch, the computation will be halted and the results keep displayed on the screen. The computation will be continued with the Enter key.

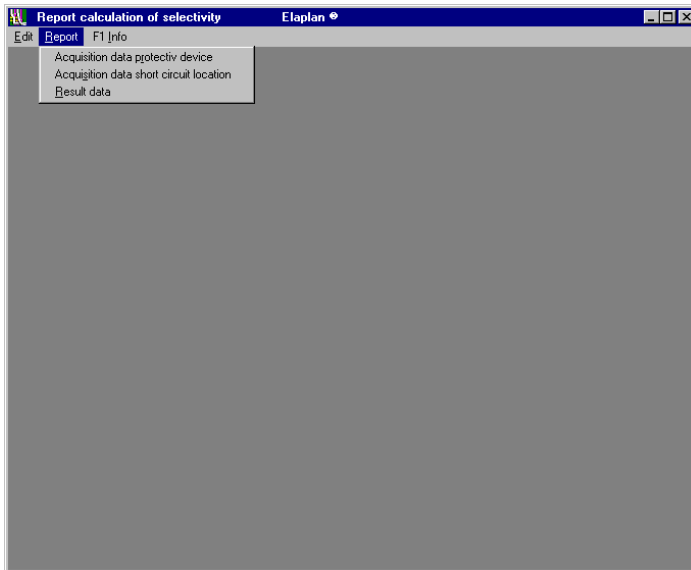
The program determines the minimum and the maximum sub-transient short-circuit currents at the locations of the protective devices. By means of these currents the tripping times of the protective devices will be calculated. A selectivity check of protective devices in rank 2 to n with the protective device in rank 1 gives the results of the calculation for this branch of the network.. Including a sufficient safety margin the protective device with rank 1 must trip before all other protective devices of this branch of the network. In this case a positive selectivity is obtained, and only that element where the fault occurred will be cut off. A further check for the protective device in rank 2 with the protective devices in rank 3 to n will not be done, since it is ensured that the protective device with the highest rank (rank 1) has tripped.

At first the tripping times will be compared with each other. If they are within one half-wave (less 10 ms at 50 Hz), a comparison of the tripping times will not give a reliable result. In this case the heat losses due to current (I^2t -values) of the protective devices will be compared. If there are current-limiting protective devices, a comparison of the tripping characteristics will be useless also. The I^2t -values of the protective devices will be compared additionally.

The program displays the result of the selectivity check of two protective devices with the remark "yes" oder "no" and a code number with the argument. At the last page of the print listings the code numbers will be explained (legend).

Report Selectivity

The output of acquisition data and results is possible on screen and printer.



Report calculation of selectivity

Acquisition data protective device

Listing of defined protective devices and their technical data.

Acquisition data short circuit location

Listing of defined short circuit locations.

Result data

For the calculated short-circuit locations the protective devices of all calculated branches with their tripping times resp. I^2t -values at the calculated short-circuit currents will be listed. The selectivity statement (Y, N) and the accompanying code number of the argument are related to the respective protective device.

Typicals for different output listings, e.g. for acquisition data protective elements, the list of defined short-circuit locations, the result data for a calculation of selectivity etc., can be made by means of sample-projects, which are scope of the software delivery. With the function 'Copy Sample-Project' in the module *Elaplan-B* you can select one of the sample-projects and add it as an actual project. You can print or display the different kinds of output listings and illustrate yourself their differences and uses.

If the selectivity check could be done by comparison of the tripping times of the protective devices, no I^2t -values will be displayed.

At the last page of the print listings the given code numbers for selectivity will be explained (legend).

List of Abbreviations and Symbols

| | |
|---------------------------------------|--|
| $\cos \varphi$ | Power factor |
| C_Operat. [μF] | Operating capacity [Microfarad] |
| C_Earth [mF] | Capacity to earth [Microfarad] |
| ETA | Efficiency |
| f [Hz] | Frequency [Hertz] |
| f_c [Hz] | Equivalent frequency [Hertz] |
| Fakt ₁ | Safety margin for the calculation of the short-circuit peak current (high-voltage) |
| Fakt ₂ | Safety margin for the calculation of the short-circuit peak current (low-voltage) |
| Faktor c | Factor for voltage |
| i_p [A] | short-circuit peak current [Ampere] |
| I^2t -Wert [A^2s] | heat losses due to current (I^2t -values) [Ampere ² second] |
| I_a [A] | Breaking current [Ampere] |

| | |
|--------------------------|--|
| I_{an} [A] | Motor starting current [Ampere] |
| I_{bi} [A] | Setting range of overload release [Ampere] |
| I_c [A] | Setting current of overload release [Ampere] |
| I_E [A] | Earth fault current [Ampere] |
| I_k [A] | Continuous short-circuit current [Ampere] |
| I_{ks} [A] | Setting range of high-set element [Ampere] |
| I''_k [A] | Sub-transient short-circuit current [Ampere] |
| I''_{k1max} [A] | Maximum 1-phase sub-transient short-circuit current [Ampere] |
| I''_{k1min} [A] | Minimum 1-phase sub-transient short-circuit current [Ampere] |
| I''_{k2max} [A] | Maximum 2-phase sub-transient short-circuit current with ground touch [Ampere] |
| I''_{k2emin} [A] | Minimum 2-phase sub-transient short-circuit current with ground touch [Ampere] |
| I''_{k2max} [A] | Maximum 2-phase sub-transient short-circuit current [Ampere] |
| I''_{k2min} [A] | Minimum 2-phase sub-transient short-circuit current [Ampere] |
| I''_{k3max} [A] | Maximum 3-phase sub-transient short-circuit current [Ampere] |
| I''_{k3min} [A] | Minimum 3-phase sub-transient short-circuit current [Ampere] |
| I''_{kmax} [A] | Maximum sub-transient short-circuit current [Ampere] |
| I''_{kmin} [A] | Minimum sub-transient short-circuit current [Ampere] |
| $I''_{k_generator}$ [A] | Sub-transient short-circuit current of a generator [Ampere] |
| I_m [A] | Setting current of the high-set element [Ampere] |
| I_n [Ampere] | Nominal current [Ampere] |
| I_r [A] | Rated current [Ampere] |
| I_{rM} [A] | Rated current of a motor [Ampere] |
| $I_{r_generator}$ [A] | Rated current of a generator [Ampere] |
| I_S [A] | short-circuit peak current [Ampere] |
| α | Factor for calculation of short-circuit peak current |
| λ_{max} | Factor for calculation of maximum continuous short-circuit current |
| λ_{min} | Factor for calculation of minimum continuous short-circuit current |
| μ | Factor for calculation of breaking current |
| P_{krT} [W] | Load losses [Watt] |
| P_n [W] | Nominal power [Watt] |
| P_{rG} [W] | Rated power of a generator [Watt] |
| P_{rM} [W] | Rated power of a motor [Watt] |
| R [Ω] | Ohmic resistance [Ohm] |
| $R_{(0)}$ [Ω] | Ohmic resistance in the zero sequence system [Ohm] |
| $R_{(1)}$ [Ω] | Ohmic resistance in the positive sequence system [Ohm] |
| R_C [Ω] | Ohmic resistance at equivalent frequency [Ohm] |
| R_E [Ω] | Ohmic resistance of earthing [Ohm] |
| R_G [Ω] | Ohmic series resistance [Ohm] |
| $R_{k(0)}$ [Ω] | Ohmic short-circuit zero sequence impedance at earthing of one side [Ohm] |
| R_{k12} [Ω] | Ohmic short-circuit zero sequence impedance at earthing of both sides [Ohm] |
| R_{k21} [Ω] | Ohmic short-circuit zero sequence impedance at earthing of both sides [Ohm] |
| $R_{L(0)}$ [Ω] | Ohmic no-load zero sequence impedance [Ohm] |
| S''_k [VA] | Sub-transient short-circuit power [Voltampere] |
| S_r [VA] | Rated power [Voltampere] |
| S_{rG} [VA] | Rated power of a generator [Voltampere] |
| S_{rT} [VA] | Rated power of a transformer [Voltampere] |
| t_a [s] | tripping time [Seconds] |
| t_{min} [s] | minimum switching time lag [Seconds] |
| t_v [s] | Time delay [Seconds] |
| u_{kr} [%] | Impedance voltage [Percent] |
| U_{KL} [V] | Terminal voltage [Volt] |
| U_n [V] | Nominal voltage [Volt] |
| U_n KnotenAusg. [V] | Nominal voltage at output node [Volt] |
| U_n KnotenEing. [V] | Nominal voltage at input node [Volt] |

| | |
|-------------------------|---|
| U_r [V] | Rated Voltage [Volt] |
| U_{rG} [V] | Rated Voltage of a generator [Volt] |
| U_{rM} [V] | Rated Voltage of a motor [Volt] |
| U_{rT} [V] | Rated Voltage of a transformer Volt |
| $x_{(0)}$ [%] | Reactance in the zero sequence system [Percent] |
| $x_{(2)}$ [%] | Reactance in the negative sequence system [Percent] |
| x''_d [%] | Sub-transient reactance in direct axis [Percent] |
| x_d [%] | Generator reactance in direct axis, saturated [Percent] |
| $x_{d_gesättigt}$ [%] | Reciprocal value of the saturated no-load/short-circuit ratio [Percent] |
| X [Ω] | Reactance [Ohm] |
| $X_{(0)}$ [Ω] | Reactance in the zero sequence system [Ohm] |
| $X_{(1)}$ [Ω] | Reactance in the positive sequence system [Ohm] |
| $X_{(2)}$ [Ω] | Reactance in the negative sequence system [Ohm] |
| X_C [Ω] | Reactance at equivalent frequency [Ohm] |
| X''_d [Ω] | Generator sub-transient reactance in direct axis [Ohm] |
| X_E [Ω] | Reactance of earthing [Ohm] |
| $X_{k(0)}$ [Ω] | Short-circuit zero sequence reactance at earthing of one side [Ohm] |
| X_{k12} [Ω] | Short-circuit zero sequence reactance at earthing of both sides [Ohm] |
| X_{k21} [Ω] | Short-circuit zero sequence reactance at earthing of both sides [Ohm] |
| $X_{L(0)}$ [Ω] | No-load zero sequence reactance at earthing of one side Ohm] |

2

The KUBS plus Program

The KUBS plus program is suited for the calculation of three-pole, single-pole and peak short circuit currents in low voltage radial networks. It can determine the backup protection, the selectivity and the voltage drop, and the permissible current loading of cables and conductors, as well as dimension circuit breakers. The program can process up to 250 outgoing electric circuits in any arbitrary arrangement of radial networks. In each outgoing electric circuit it is possible to choose the types of conductor (cables, bus bars and overland lines) and the conductor material (copper and aluminum). The high voltage can assume values of up to 100 kV. The characteristic data for transformers can be entered as user values or the values for standard transformers can be used. The program can also calculate with several (up to 10) transformers connected to a bus bar. The input data (transformer, medium voltage network or known I''_{1kmin} as well as rated currents for the individual outgoing electric circuits are entered. The program selects the cross-section and calculates the impedances of this cross-section as well as the short circuit currents.

The program divides the network calculation (Figure 1) into network feeder and network distribution. To the network feeder belong several transformers or defined input positions. Immediately thereafter follow a cable connection and then a circuit breaker with its cable or bus bar connection. The common input position is represented as a bus bar and has no impedance.

Installation/system requirements

System requirements

Hardware:

- IBM-compatible PC AT 80486 with 8 MByte RAM or higher
- VGA graphics card
- CD-ROM drive
- Minimum 3 MByte available hard disk storage
- Printer: HP Laserjet or similar type, HP Deskjet or similar type, Kyocera laser printer or compatible

Note: The program does **not** support mouse control.

System software: Windows 95 or higher, Windows NT 4.0
 Installation under Windows

- Start Windows
- Insert CD-ROM in drive

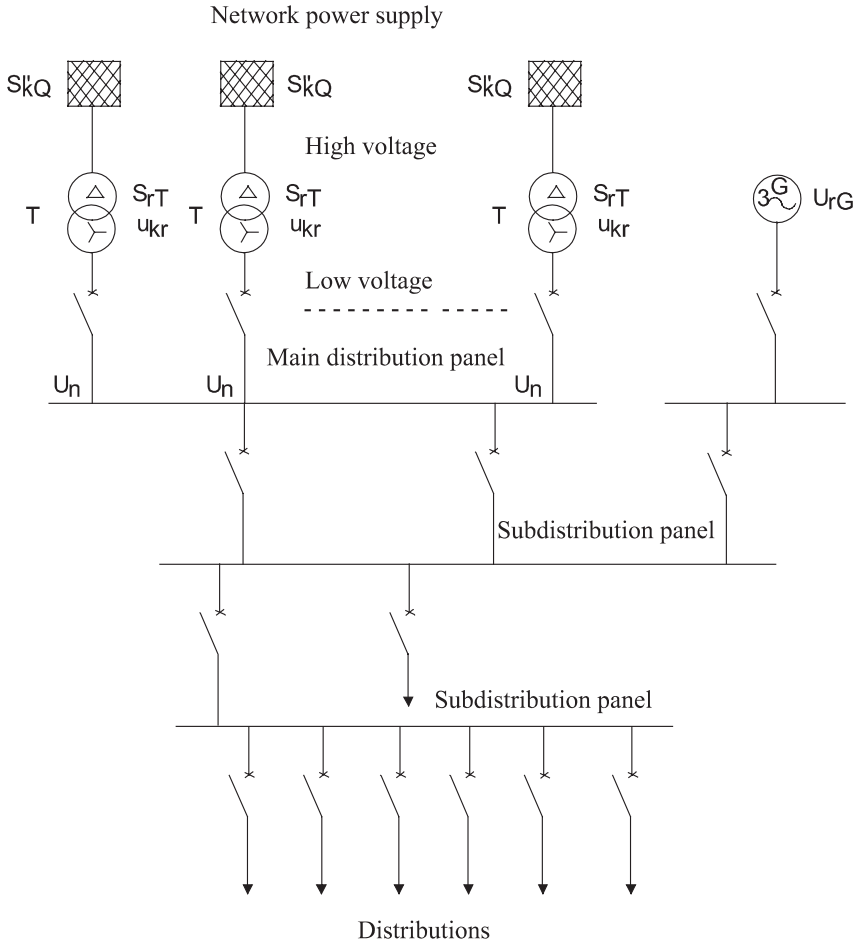


Fig. 1: Design of a network and calculation procedure

- Call File Manager and start the required file WININST.EXE from CD-ROM
- The required hard disk memory capacity is shown and the directories C:\KUBSPPLUS and C:\KUBSPPLUS\FILES are generated. Confirm all following windows with < OK >.

- Important: For installing under Windows 95, after unpacking the files (Decompressing Archive) you must close the window in which unpacking takes place
- The Kubs Setup program is started from the installation program. You can then start KUBS plus.

Setup

The Setup is called automatically following installation. It can also be called from the main menu of KUBS plus. The dialog language for the Setup program is English. With the Setup, presettings are defined; in the Setup program the dialog language for the main program in KUBS plus can be selected:

A selection menu showing the available printer drivers is displayed on the monitor screen. Select your printer or a similar one.

Note: Most printers have the possibility to select an emulation. This makes it possible to emulate a printer which can be operated with one of the printer drivers offered.

KUBS plus could, for example, determine a conductor of $3 \times 240 \text{ mm}^2$ for a current of 20 A. In practice, this of course makes little sense, because the conductor – while it would be adequately dimensioned – would presumably be too expensive. In order to prevent this, in the Setup program there is the possibility to enter two overdimensioning factors: “Minimum and Maximum”. For each current which you will enter later, KUBS plus then determines only conductors for which the permissible current lies within the limits defined by “Minimum and Maximum”.

Attention: A tolerance results in very few (or no) selection possibilities; a large tolerance could lead to a very large selection list.

The check of the contact voltage can be switched on or off.

Using KUBS plus

To start the program from the MS-DOS level type in *KUBS*. To start from Windows, double click on the icon. To start from the Windows file manager, double click on *Kubsplus.pif*.

The following regulations are included in the program file:

- Types of installation and bundling for cables and conductors in accordance with IEC 60364-5-523
- Permissible current loading of bus bars
- Calculation of short circuit currents in accordance with IEC 60 909

The following two diagrams (Figures 2 and 3) indicate the possibilities of the Main menu and the Project menu.

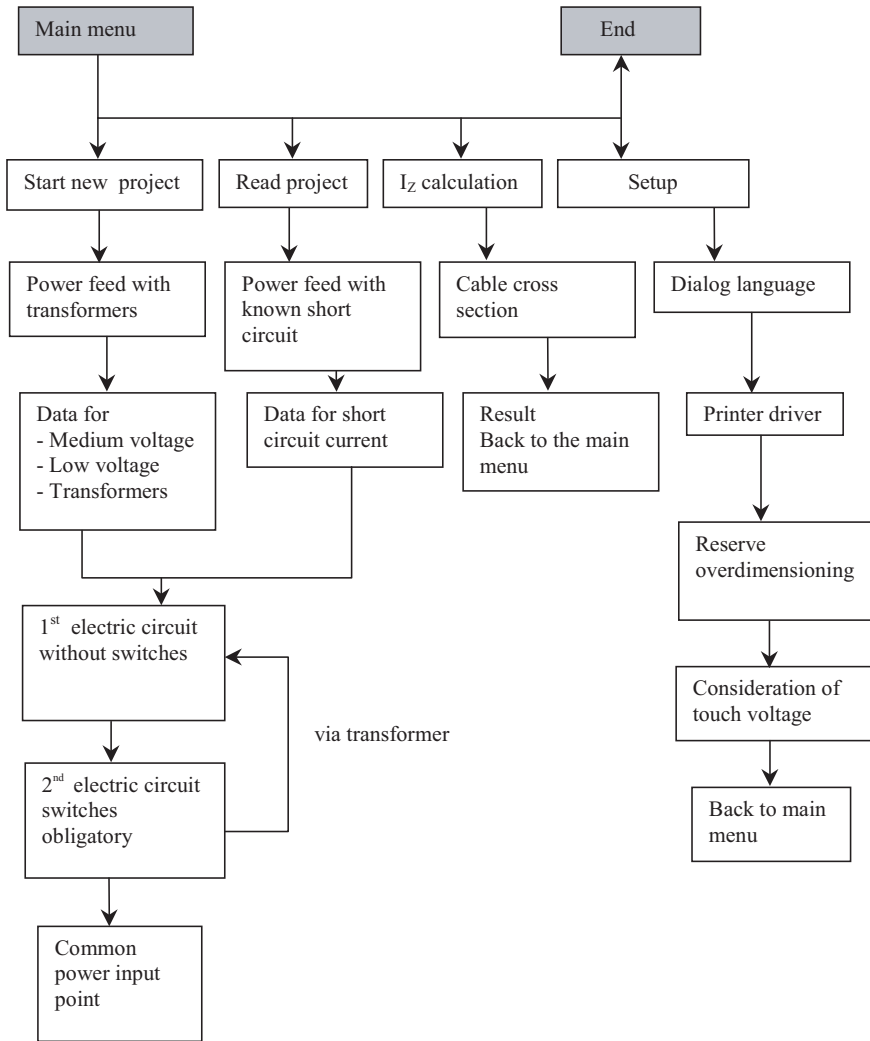


Fig. 2: Overview of the Main menu

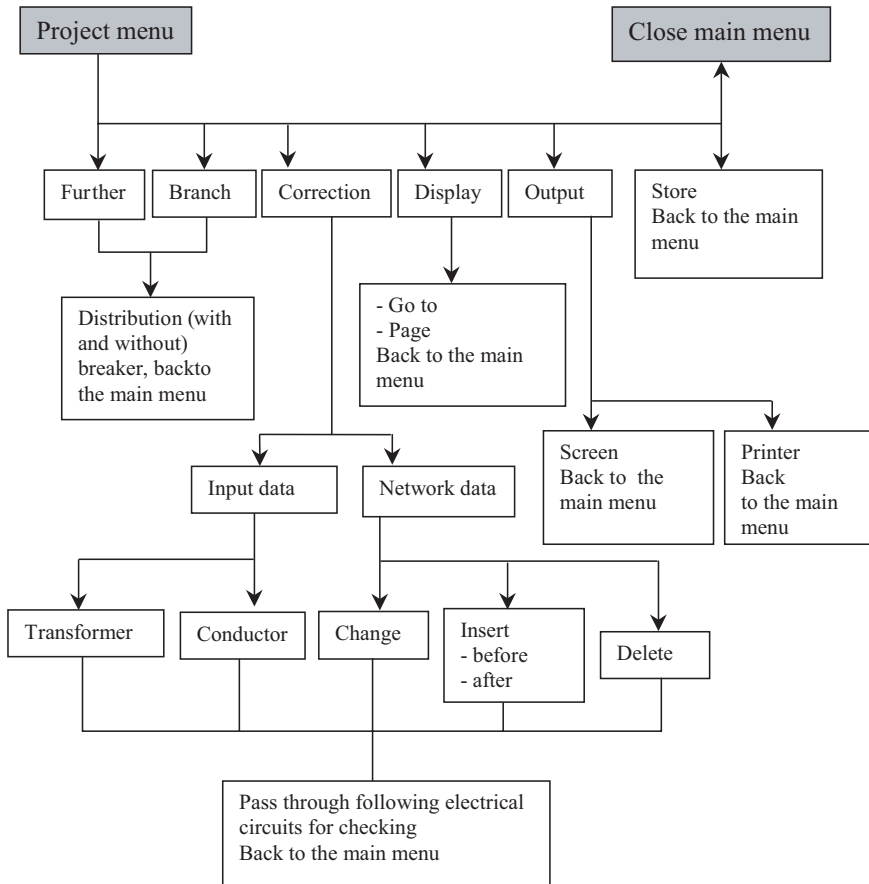


Fig. 3: Overview of the Project menu

Calculating Example 7 with KUBS plus

Example 7 was worked out with the KUBS plus program (Figure 4) and with a pocket calculator and the results compared. The results of the two procedures are in full agreement. The following remarks are relevant here:

1. Manual calculation (with pocket calculator)
 - The impedances of the circuit (outgoing and return lines) are added under operational conditions
 - The zero-sequence impedances of the cable and the conductor are not considered here
 - The zero-sequence impedance of the transformer is also not considered

2. Calculation with KUBS plus

- The impedances are added vectorially
- The zero-sequence impedances of the cable, conductor and transformer are taken into account

General project data:

Network form: TN-C-S system

N distributed?: yes

 U_L for: 50 V

Voltage: 400 V

Medium voltage network:

Voltage: 20.0 kV

Short-circuit power: 250 MVA

Frequency: 50 Hz

R: 0.0070 m Ω X: 0.070 m Ω *Feed-in to low voltage network: Transformer:*

Power: 630 kVA

Nominal current: 909 A

 u_z : 6 % u_r : 1.10 %

Short circuit losses: 7 kW

 u_x : 5.90 %

Connection symbol: Dy

R: 2.7937 m Ω X: 14.9898 m Ω *Transformer 1:*

Transformer terminals → Protection equipment

Branch a: Branch A → (1,1)I : 100 A I_{kmax1p} : 14.54 kA I_z : 129 A I_{kmin1p} : 12.33 kABreaker : None I_{k3p} : 14.24 kA: i_p : 30.41 kAcos φ : 0.90du : 0.04% R: 0.79m Ω X: 0.12m Ω dutot : 0.04% R_r : 0.79m Ω X_r : 0.12m Ω **Bus bars**

Material : Cu Ambient temperature : 25 °C

Treatment : Blank Temperature of conductor : 65 °C

| | |
|-----------------|--|
| Main conductor | : $3 \times 1 \times 12 \times 2 \text{ mm}^2$ |
| PE | : $1 \times 12 \times 2 \text{ mm}^2$ |
| N cross-section | : $1 \times 12 \times 2 \text{ mm}^2$ |
| Length [m] | : 1.00 m |

Protection equipment → Starting point of network

Branch 1A: Branch 1A → (1,3)

| | | | |
|-----------------|--|-------------------------|-----------------|
| I | : 100 A | I_{kmax1p} | : 2.17 kA |
| I_z | : 100 A | I_{kmin1p} | : 0.88 kA |
| Breaker | : 3VF32116DS7 | I_{k3p} | : 2.17 kA |
| | : | i_p | : 3.13 kA |
| $\cos \varphi$ | : 0.90 | | |
| du | : 4.68% | R: 96.50mΩ | X: 20.75mΩ |
| $dutot$ | : 4.72% | R_t : 97.29mΩ | X_t : 20.87mΩ |
| Cables | : | | |
| Material | : Cu | Ambient temperature | : 25 °C |
| Insulation | : PV | Type | : multi-strand |
| Armouring | : without | Number of cable systems | : 1 |
| Installation | : C | | : |
| Cable type | : NYY | I_r | : 100–160 A |
| Main conductor | : $3 \times 1 \times 150 \text{ mm}^2$ | | |
| PE | : $1 \times 50 \text{ mm}^2$ | I_i | : 150–2400 A |
| N cross-section | : $1 \times 50 \text{ mm}^2$ | I_{cu} (400V) | : 70 kA |
| Length [m] | : 250.00 m | | |
| | | Sel. (i) | |
| | | Sel. (t) | |
| | | Backup | not required |
| | | Correction factor | |

Remarks

Branch in order

Network data:

Branch2: Branch 2A → (1,5)

| | | | |
|----------------|-----------|-------------------------|-----------------|
| I | : 16 A | I_{kmax1p} | : 0.33 kA |
| I_z | : 24 A | | : |
| Breaker | : | I_{k3p} | : 14.24 kA |
| $\cos \varphi$ | : 0.90 | | : |
| du | : 1.83% | R: 255.36mΩ | X: 3.74 mΩ |
| $dutot$ | : 6.54% | R_t : 355.44mΩ | X_t : 39.59mΩ |
| Cables | : | | |
| Material | : Cu | Ambient temperature | : 25 °C |
| Insulation | : PV | Type | : multi-strand |
| Armouring | : without | Number of cable systems | : 1 |

| | | | |
|-----------------|--|-------------------|--------------|
| Installation | : B | | : |
| Cable type | : NYM | I_r | : 0 A |
| Main conductor | : $1 \times 1 \times 2.5 \text{ mm}^2$ | | |
| PE | : $1 \times 2.5 \text{ mm}^2$ | | |
| N cross-section | : $1 \times 2.5 \text{ mm}^2$ | I_{cu} (400 V) | : |
| Length [m] | : 35.00 m | | |
| | | Sel. (i) | Sel. (t) |
| | | Backup | not required |
| | | Correction factor | 1.00 |

Remarks

Branch in order

Branch 3A: Branch 3A → (2,5)

| | | | |
|-----------------|--|--|----------------|
| I | : 7 A | I_{kmax1p} | : 0.41 kA |
| I_z | : 17 A | I_{kmin1p} | : 0.31 kA |
| Breaker | : | | : |
| $\cos \varphi$ | : 0.90 | | : |
| du | : 0.57% | R: 182.40mΩ X: 1.60mΩ | |
| $dutot$ | : 5.29% | R _i : 282.48mΩ X _i : 37.45mΩ | |
| bf cables | : | | |
| Material | : Cu | Ambient temperature | : 30 °C |
| Insulation | : PV | Type | : Multi-strand |
| Armouring | : without | Number of cable systems | : 1 |
| Installation | : C | | : |
| Cable type | : NYM | I_r | : |
| Main conductor | : $1 \times 1 \times 1.5 \text{ mm}^2$ | | |
| PE | : $1 \times 1.5 \text{ mm}^2$ | I_i | |
| N cross-section | : $1 \times 1.5 \text{ mm}^2$ | I_{cu} (400 V) | |
| Length [m] | : 15.00 m | | |
| | | Sel. (i) Sel. (t) | |
| | | Backup | not required |
| | | Correction factor | 1.00 |

Remarks

Branch in order

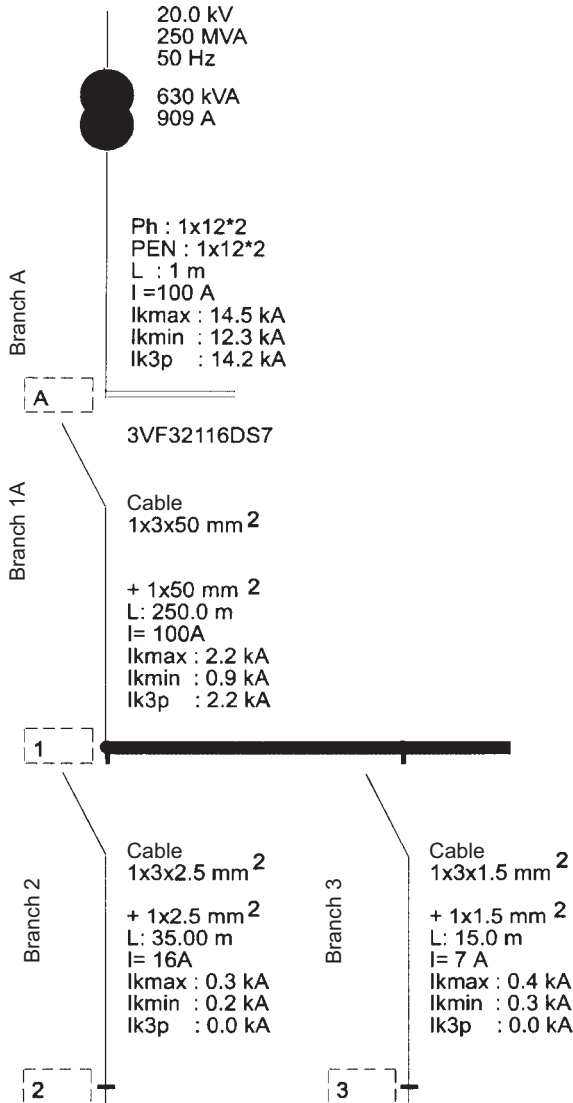


Fig. 4: Diagram of example and results

Preparations for the short circuit current calculation

1. Program (e.g. KUBS plus)
2. Form sheets
3. System forms in low voltage range in accordance with IEC 60 364, Part 30

4. Purpose of calculating short circuit currents:
 - Breaking conditions
 - Selecting bus bars
 - Breaking capacity of overcurrent protection equipment
 - Settings for overcurrent protection equipment
5. Network conditions:
 - High voltage and low voltage motors
 - Block or distribution transformers
 - External inputs (S''_{kQ})
6. Special properties of network and operational equipment:
 - Asynchronous motors
 - Transformers
7. Types of short circuit currents:
 - Largest short circuit current
 - Smallest short circuit current
 - Peak short circuit current
 - Two-pole short circuit current with or without contact to ground
 - Double ground fault
8. Required short circuit currents:
 - Largest short circuit current
 - Smallest short circuit current
9. Required component systems:
 - Positive-sequence impedance
 - Negative-sequence impedance
 - Zero-sequence impedance
10. Voltage sources:
 - Network power feeder
 - Motor feeder
 - Generator feed-ins
11. Network type:
 - Short circuit with simple input
 - Short circuit with several simple inputs
 - Short circuit in meshed network
12. Method of calculation to be used:
 - Equivalent voltage source