Ismail Kasikci

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Analysis and Design of Low-Voltage Power Systems

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ISBN: 3-527-30483-5

Analysis and Design of Low-Power Systems

An Engineer's Field Guide

Ismail Kasikci

WILEY-VCH Verlag GmbH & Co. KGaA

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Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data:
A catalogue record for this book is available from the British Library.

Bibliographic information published by Die Deutsche Bibliothek
Die Deutsche Bibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data is available in the Internet at <http://dnb.ddb.de>.

printed in the Federal Republic of Germany
printed on acid-free paper.

Composition Kühn & Weyh, Freiburg
Printing betz-druck GmbH, Darmstadt
Bookbinding Litges & Dopf Buchbinderei GmbH, Heppenheim

ISBN 3-527-30483-5

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Foreword

With each project, the planning engineer for electrical systems confronts the following questions:

- How can I design the electrical system?
- Which regulations must I observe?
- Which calculations must I perform?
- Which methods/CAD can I use?
- Which protective measures must I consider?
- Which requirements and conditions apply for project planning?
- How can persons and animals be protected against electrical shock?
- Which operational components shall I select?
- Are there special problems with regard to planning?

For calculation, dimensioning and evaluation of a system, in addition to extensive professional knowledge the planning engineer requires above all CAD experience and a knowledge of all relevant standards and regulations. Due to the great number of standards and their revision in regular intervals and also due to their increasing international harmonization, maintaining this knowledge is becoming more and more difficult.

For this reason the present book, intended as a help for the planning engineer in the solution of problems in low voltage networks, also presents a detailed discussion of the current situation in regard to standards.

Following the theoretical part and the discussion of regulations and standards, a wide range of examples taken largely from practice is worked out fully. The numerous tables and diagrams from which the planning values required for calculation can be taken make this book an indispensable reference. Each topic is given its own treatment.

For the calculations required in project planning, the CAD programs included on the accompanying CD-ROM are certain to be of great use to the planning engineer.

The idea of developing an easy to use project planning aid for practical planning activities arose during my many years spent in the area of power supply, above all during my period of teaching at VDE, at the Technical Academy in Esslingen and at the Master Trade School in Heidelberg.

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I wish to extend my heartfelt thanks to all my professional colleagues and acquaintances who supported me through their ideas, criticism and suggestions. I would like to express my gratitude to the ABB, Siemens, Dehn+Sons, Hager, Klöckner, Präzisa and Trilux companies for their readiness to support me with technical documentation, My special thanks go to Trilux, Siemens, MODL, ABB, TRABTECH and Phoenix Contact for placing software at my disposal.

I am also indebted to my publisher, Wiley-VCH, especially Dr. Bär and Mr. Schmitt 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, I wish to thank my wife for her great patience, without which this book could never have been written.

Weinheim, December 2003 Ismail Kasikci

Symbols

a	Center-to-center distance between bus bars, costs of electrical energy, room length, center-to-center distance between conductors, near-to-generator short circuit
a_i	Utilization factor for motors
$A_{W,D}$	Surface area of walls and ceiling
A	Acquisition price, floor area of room, air intake and exhaust opening, initial value of DC component
A_2	Area of circle
A_e	Effective cooling area of housing, equivalent collecting area of stand-alone structure
A_0	Individual surface areas of external side of housing
c_{max}	Voltage factor
c	Voltage factor, temperature distribution factor, specific heat capacity of conducting material, smallest power step
C_{str}	Phase capacitance
C_e	Environmental coefficient
C'_E	Ground capacitance
C	Capacitor power
C_p	Rated power
D	Separation distance
E	Light intensity
E_m	Average light intensity
E_n	Rated light intensity
f_1	Stator frequency
f_2	Rotor frequency
f_n	Network frequency
F	Electro-dynamic force between conductors
g_i	Coincidence factor
GD	Moment of inertia
h	Height difference, distance between lighting elements and evaluation level
H	Magnetic field strength, height of housing
i_{DC}	Decaying DC current component

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i_p	Peak short circuit current
I	Current, light intensity
I_0	No-load current
I_{thr}	Rated short time current
I_{an}	Starting current of motor
I_{rM}	Rated current for motors in a group
I''_{kQ}	Initial symmetrical short circuit current
I_a	Cut-off current of overcurrent protective equipment
I_A	Starting current
I_d	Leakage current
$I_{\Delta n}$	Rated differential current of RCD
I_f	Fault current (smallest short circuit current)
I_{an}/I_{rM}	Ratio of starting current to rated current for motor
I_n	Nominal current
I_e	Current setting
I_{rm}	Magnetic current setting
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 short circuit current
I_k	Steady state short circuit current
I_{th}	Thermal short circuit current
I_b	Load current
I_n	Rated current of protective equipment
I_z	Permissible current loading of cable or conductor
I_r	Rated current
I_Δ	Current for delta connection
I_Y	Current for star connection
I_2	Large test current
I''_k	Initial symmetrical short circuit current
J_L	Mass moment of inertia of load
J_{thr}	Rated short time current density
k	Housing constant, material factor or specific conductivity factor, transformation ratio of transformer, material coefficient, correction factor for operating conditions 1.06 for oil transformers, 1.2 for resin-encapsulated transformer
k_a	Costs of work
k_c	Current distribution coefficient, dependent on geometrical arrangement
k_L	Power costs
k_m	depends on material of isolation path
k_i	depends on lightning protection class
K_1	Costs of a light fixture, capacity costs for amortization and interest
K_2	Costs of installation and installation material
K_3	Price of a lamp

K_4	Costs of replacing a lamp
K_J	Annual costs
K_A	Proportionate acquisition costs
$K(P_0/P_k)$	Operating costs resulting from no-load and short circuit losses
K_u	Maintenance costs
$K_{W,D}$	Heat transfer coefficient
l	Length
l_h	Length of horizontal grounding electrode
l_v	Length of vertical grounding electrode
l_1	Minimum length of grounding electrode
m	Decaying DC component, thermal effect of DC component with three-phase AC current and single-phase AC current
M_M	Motor torque
$M_{M\Delta}$	Motor torque for direct startup
M_{MY}	Motor torque for star-delta startup
M_L	Load torque (counter-torque)
M_{L0}	Load breakaway torque\crM_N *Ratedtorque*
M_N	Motor rated torque
M_A	Pull-up torque
M_{acc}	Accelerating torque
M_S	Pull-up torque \crM_K *Breakdowntorque*
$M_L(M)$	Load moment relative to motor shaft
n	Speed of rotation, calculated number of lighting elements, thermal effect of AC current component with three-pole short circuit, number of internal horizontal partitions, number of transformers in parallel, decaying AC current component, amortization time in years, number of loads
n_1	Total number of lamps
n_2	Number of lamps per lighting element
n_S	Synchronous speed of rotation
n_M	Speed of rotation of motor
n_L	Speed of rotation of load
N	Number of windings
N_c	Permissible number of critical lightning strikes
N_d	Strike frequency of the structural installation
N_g	Lightning density
p	Rate of interest
P_n	Rated power
P_v	Transformer power loss, control gear power loss
P	Effective power, effective power loss of operational equipment installed in housing, power consumption of one lamp + control gear
P_L	Lamp power
P_k	Short circuit losses
P_{max}	Power requirement
P_i	Installed power
P_{input}	Power input

P_{output}	Power output
P_d	Output
P_0	No-load losses
P_{Vr}	Equipment power losses
P_{Fe}	Core losses
P_{Cu}	Load losses
P_{rM}	Rated power of motor
q	Factor for the calculation of breaking currents of asynchronous motors
Q	Reactive power
Q_v	Dissipated losses
$Q_{W,D}$	Losses dissipated through walls and ceiling
Q_{v1}	Proportion in natural air stream
Q_{v2}	Proportion through walls and ceiling
Q_{v3}	Proportion in forced air stream
Q_T	No-load reactive power of transformer
r	Average radius, percent capital costs from interest and amortization
R_A	Sum of resistances of grounding electrode and protective conductor
R_L'	Relative effective resistance of a conductor
R_E	Grounding resistance
R_l	Conductor resistance
R	Pure resistance, equivalent resistance, costs of cleaning per light and per year
R_Q, X_Q	Ohmic, inductive resistance of control gear network
R_T, X_T	Ohmic, inductive resistance of transformer
R_L, X_L	Ohmic, inductive resistance of network
R_{0T}, X_{0T}	Ohmic, inductive no-load resistance of transformer
R_{0L}, X_{0L}	Ohmic, inductive no-load resistance of network
R_G	Resistance of generator
s	Slip, protection ratio
S	Apparent power, cross-section of conductor
S_k''	Short circuit power
S_{rT}	Rated power of individual transformer
S_{st}	Load starting capability
$\sum P_{rM}$	Sum of rated effective powers
$\sum S_{rT}$	Sum of rated apparent powers
S_{kQ}''	Initial symmetrical short circuit apparent power
S_0	No-load apparent power of transformer
t	Time
t_{ab}	Cut-off time of overcurrent protection equipment
t_{zu}	Permissible cut-off time
t_L	Economic life of lamp
t_B	Yearly time in use
t_a	Cut-off time
T_B	Operating time in years
T_a	Starting temperature

T_e	End temperature
T_B	Operating time
Δt	Overtemperature of air in housing, general
$\Delta t_{0,5}$	Overtemperature of air, internal, at half height of housing
$\Delta t_{0,75}$	Overtemperature of air, internal, at three-quarters height of housing
$\Delta t_{1,0}$	Overtemperature of air, internal, at upper edge of housing
Δu	Percent voltage drop
ΔP	Power loss
ΔU	Spannungsfall
U_E	Ground potential rise
U_{B1}	Touch voltage without potential grading (on concrete-footing grounding electrode)
U_{B2}	Touch voltage without potential control (on concrete-footing grounding electrode + potential grading grounding electrode)
U_0	Line-to-ground voltage
U_L	Touch voltage
U_s	Step voltage
U_{nQ}	Rated voltage of network at connecting point Q
U	Rated AC voltage between external lines, charging voltage
U_n	Rated voltage of network
U_{rG}	Rated voltage of generator
U_{rM}	Rated voltage of motor
$\ddot{u}$	Transformation ratio
$\ddot{u}_f$	Fictitious transformation ratio
$\ddot{u}_r$	Rated value of transformation ratio for transformer with step switch at principal tapping
v	Depreciation factor
V_L	Amount of air
x	Exponent
X	Reactance, distance from concrete-footing grounding electrode
X_d''	Subtransient reactance
X_L'	Relative reactance of a conductor
Z	Impedance
Z_1	Positive-sequence impedance
Z_2	Negative-sequence impedance
Z_0	Zero-sequence impedance
Z_E	Impedance of grounding electrode system
Z_Q	Impedance of control network
Z_{PE}	Impedance of protective conductor
Z_T	Impedance of transformer
Z_v	Source impedance
Z'	Relative impedance
Z_F	Fault impedance
Z_k	Body impedance
Z_{st}	Site impedance

Z_S	Ground fault loop impedance
Z_S'	Ground fault loop impedance, consisting of neutral conductor and protective conductor of circuit
Z_{TUS}	Impedance of transformer (low voltage side)
Z_{TOS}	Impedance of transformer (high voltage side)
Z_{KW}	Corrected impedance of power plant block, relative to high voltage side
Z_G	Impedance of generator
Z_M	Short circuit impedance of a motor
Z_{GK}	Corrected impedance of generator
α	Temperature coefficient
δ	Loss factor
η	Efficiency of gear system
η_b	Lighting utilization factor
η_i	Utilization factor
η_B	Lighting utilization factor according to data sheet
ϑ	Temperature
$\Delta\vartheta$	Temperature rise
θ	Conductor temperature
Θ	Current linkage
Θ_{max}	Highest temperature attained
κ	Conductivity
ρ_m	Density of conductor material
φ_{rG}	Phase angle between $U_{rG}/\sqrt{3}$ and I_{rG}
$\cos\varphi$	Power factor
$\sin\varphi$	Reactive factor
Φ_n	Lumens per lamp per lighting element x 0.95 correction factor
μ	Factor for the calculation of the symmetrical short-circuit current

Abbreviations

A	Aluminum conductor
AC1	Non-inductive or weakly inductive load, resistance furnace
AC2	Slipring motors: starting, switching off
AC3	Squirrel cage motors: starting, switching off while running
AC4	Squirrel cage motors: switching on, breaking by plugging, jogging
ASM	Asynchronous motor
B	Mine-type installations
BHKW	Block heating power plant
CENELEC	European Committee for Electrotechnical Standards
CW	Wave-shaped concentric conductor
DIN	German Standards Institute
DKE	German Electrotechnical Commission
ED	ON period
EN	European standard
EPR	Ethylene-propylene-rubber insulation
FE	Concrete-footing grounding electrode
G	Rubber insulation or generator
HKS	Heating, climate, sanitary
HV	High voltage
IEC	International Electrotechnical Commission
L_1, L_2, L_3	External conductor
LEMP	Lightning Electromagnetic Pulse
LTO	Long time operation
LV	Low voltage
LVMD	Main low voltage distribution panel
M	Motor, switchgear
MDP	Main distribution panel
MGT	Main grounding terminal
MV	Medium voltage
N	Neutral conductor
OPE	Overcurrent protection equipment
PE	Protective conductor
PV	Primary voltage (transformer) or harmonics

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PVC	Polyvinyl chloride insulation
R	Semiconductor
RCD	Residual Current Protective Device
SEMP	Switching Electromagnetic Pulse
SE	Grading grounding electrode
STO	Short time operation
SV	Secondary voltage (transformer)
T	Transformer
TAB	Technical conditions for connection
UVV	Accident prevention regulations
VBG	Accident prevention regulations of the BG
VDE	Union of Electrotechnical, Electronics and Information Technology
VPE	Cross-linked polyethylene insulation
VdS	Union of Property Insurors
Y	PVC insulation

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1
Introduction

Terms and Definitions

- Electrical system
  is the combination of operational electrical equipment for the generation, further transmission, conversion, distribution and consumption of electrical energy with the purpose of performing work in the form of mechanical work, for the generation of heat and lighting or in electrochemical processes.
- Operational electrical equipment
  refers to all objects used in electrical systems and which serve to make use of electrical energy. These can be classified as permanently installed, fixed and mobile equipment, as well as hand-held appliances.
- Electrical operating areas
  are clearly defined rooms, areas and cabinets for electrical systems, which serve to accommodate operational equipment.
- Maintenance
  is an overall term which includes the inspection, servicing, repairs, replacement and monitoring of electrical systems.
- Trained electrical worker
  is a person who possesses a specialized electrical qualification (e.g. special training, several years assisting skilled electrical workers, knowledge and experience, knowledge of the applicable standards, and the ability to recognize hazards and to properly judge the tasks assigned) for the installation and operation of electrical systems and operational equipment.
- Electrotechnically instructed person
  is a person with less qualification than the trained electrical worker. Only knowledge and technically correct behavior, as well as the performance of tasks assigned, are required of this person.
- Electrotechnical layman
  is neither a trained electrical worker nor an electrotechnically instructed person. He is not responsible for the installation, modification and operation of electrical systems. He may work only under the continuous surveillance and leadership of a trained electrical worker.

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- Electrotechnical regulations
  are the “generally recognized rules of technology” found in the standards and to which the professional trade union refers. Such standards are parts of the accident prevention regulations and thus legally binding electrotechnical regulations. Compliance with these regulations is absolutely essential.

2
Planning and Project Management

2.1
Guidelines for the Remuneration of Architects and Engineers and Regulations for Contracting System Installations

For the planning and project management of public contracts, the Regulations for Contracting System Installations and the Guidelines for the Remuneration of Architects and Engineers are used exclusively. Invitations for bids, awarding of contracts, performing the work contracted and invoicing of constructional services are summarized in the Construction Services and serve as the legal basis for private construction contracts. Of particular interest here are the Agreement on Construction Services (electrical cable and line systems in buildings), (General Regulations for Constructions of all Types) and (Lightning Protection Systems) [1].

The Regulations for Contracting System Installations regulates the payments and describes the services in detail, as well as specifying acceptable ranges of remuneration (Table 2.1).

Table 2.1: Acceptable ranges of remuneration

Remuneration range I	Simple low voltage and telephone installations
Remuneration range II	Compact stations, low-voltage installations and distribution systems telecommunication installation not belonging to remuneration ranges I and III, lightning protection systems, lighting systems
Remuneration range III	High-voltage and medium-voltage systems, low-voltage switchgear, current generating and converting systems, low-voltage line systems and lighting systems requiring extensive planning costs, large telephone systems and networks

The Engineering Services Manual deals with all contractors' services. The electrical system planner determines his costs, following the prescribed cost groups. Engineering services can be described either inthe form of a directory of services (scope book) or in the form of a system description. The individual items include details by number of times applicable, meter or lump sums.

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The system description contains only the equipping and function of the electrical systems. The contracting company is obligated to submit any criticism of the proposed work in writing prior to beginning the work. The contracting company must take into proper account the validity of regulations and the transitional periods defined for new regulations.

After completing the contracted work, the contractor must also supply overview circuit diagrams and installation plans. Prior to commissioning, IEC 60 364 Part 61 requires that the system be tested with respect to operational capability. Detailed descriptions can be found in the Expert's Planning Guide [2].

The project is carried out e.g. according to the following sequential steps:

- Customer consultation
- Preliminary design and submission of bid
- Cost estimate
- Negotiations
- Beginning of project, processing
- Creation of project plan, invitation for bids
- Writing contracts for the system
- Carrying out, monitoring
- Installation of the system
- Commissioning, measurements
- Turnover, documentation, warranty

2.2
Guidelines for Project Planning of Electrical Systems

The following circuit diagrams, drawings and technical documents are required for the installation of electrical systems:

1. Power balance of entire system
   - low voltage (230 V, 400 V, 690 V)
   - medium voltage (6 kV, 10 kV, 20 kV)
   - high voltage, as required (110 kV, 220 kV, 380 kV)
2. Motor lists in accordance with IEC 34
   - rated power in kW
   - rated voltage in V
   - rated motor speed in rpm
   - rated torque in Nm
   - moment of inertia in kg/m^2
   - ambient temperature in °C
   - motor type and class
   - design, size and type of protection
   - manufacturer, accessories
   - terminal designations
   - load data, mode of operation

- breakaway torque, starting current
- efficiency
- operating cycle

3. Overview circuit diagrams An overview diagram is the simplified representation of a circuit. It shows the functional principle and the structure of an electrical system and includes e.g. voltages, frequency, power, terminal designations and transformer data.
4. Network diagrams The network diagram shows all connections and parts of a network, not drawn to scale.
5. Single-line or three-line diagrams
   These diagrams include e.g.
   - high-voltage switchgear
   - medium-voltage switchgear
   - low-voltage switchgear
   - light distributions
   - power distributions
   - weak current distributions
   - DC current distributions
   - Standby power supply
6. Location diagram The location diagram includes the installation locations of all operational equipment.
7. Routing diagrams
   Routing diagrams show the type of cable installation within a building or system part, e.g. on cable racks.
8. Construction details All electrical objects, such as transformers, switchrooms, cable ducts, cutouts and cable and line installation, are shown in their correct locations.
9. Functional descriptions
   The function of the system, all operating conditions, the number and type of controls in the form of a logic diagram, functional diagram and structogram or equipotential bonding diagram are described in detail. Circuit diagrams can be created on the basis of these.
10. Circuit diagrams A circuit diagram is the detailed representation of a system or circuit with its details. All overcurrent protection equipment and units, terminals and terminal strips, cable installation types, cross-sections, power ratings, voltages and frequencies must be entered. The list of components includes all units shown in the circuit diagram.
11. Terminal and cross-connection diagrams (execution company)
    Terminal and cross-connection diagrams are connection diagrams for terminal strips in cross-connection fields. They represent the electrical connections of the system. Terminal numbers, destination names and cable types must be specified.
12. Cable list
    The cable list shows the cable number, type, cross-section, voltage, number of cores, interconnections of grounding electrodes.

13. Weak current systems
    Weak current systems, such as intercom, telephone and fire alarm systems, must be shown on separate installation diagrams.
14. Material lists
    Material lists include all documentation for the quality of the electrical material and for the specification of installations as described in the project.
15. Installation schedule
    The entire installation schedule, including periods for the specified tasks and time in hours, is summarized.
16. Documentation
    Following installation of the systems, all drawings, documents and measurement certificates must be checked for correctness and if necessary corrected.

As an example of modern project planning programs, you will find on the CD which accompanies this book. This software enables rational planning, calculations, administration and archiving in the distribution cabinet.

3
Electrical Systems

3.1
Medium-Voltage Systems

According to IEC 38 medium voltage systems are driven with voltages between 1 and 36 kV and fed from high-voltage networks (Figure 3.1). The rated voltage is 10 or 20 kV. Transmission is normally with the use of buries cables, which connect the individual stations to each other in a ring structure with the help of isolating points. The lines between the stations can be isolated in the event of a disturbance (Figure 3.2).

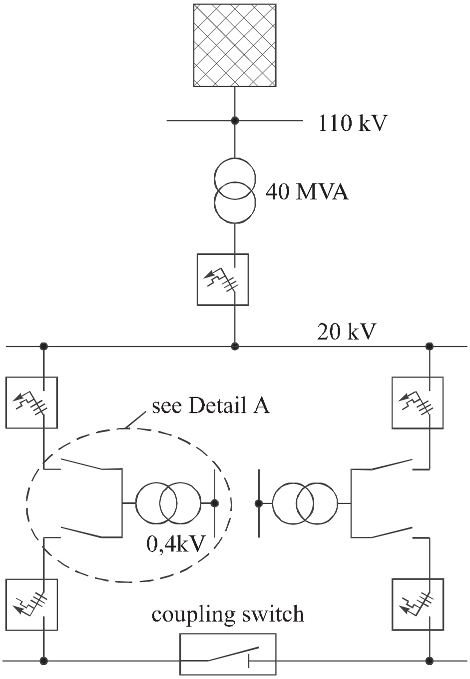

Figure 3.1 Overview of a medium voltage system

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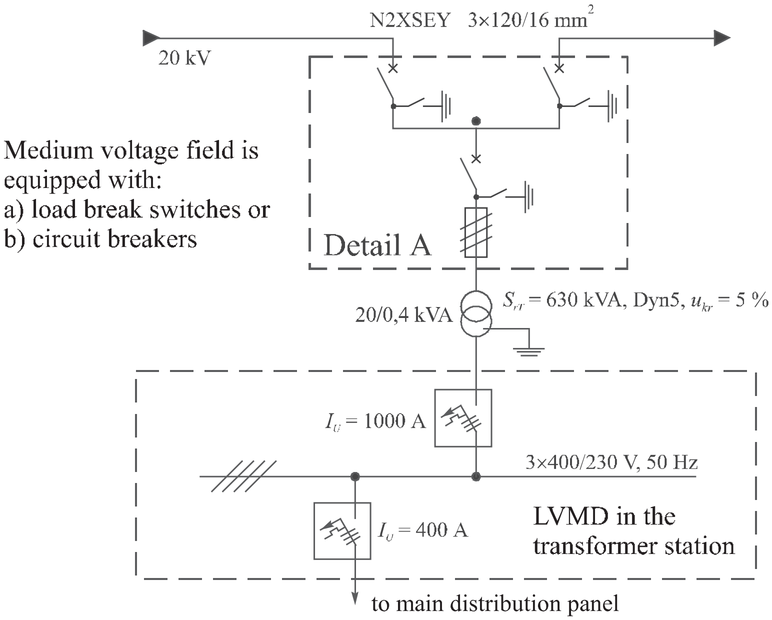


Figure 3.2 Feed-in and load field

The network stations often incorporate two network transformers in a room (for greater availability) and the main low-voltage distribution (LVMD), which supplies the loads in the form of a radial network. The rated transformer powers cover the range from 100 to 2500 kVA. The stations can be housed in precast concrete cells, containers or special rooms (Figure 3.3).

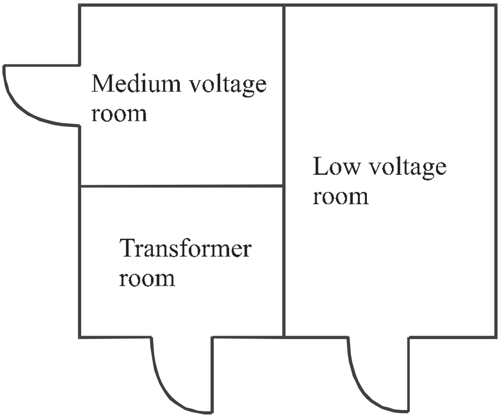


Figure 3.3 Arrangement of the system parts

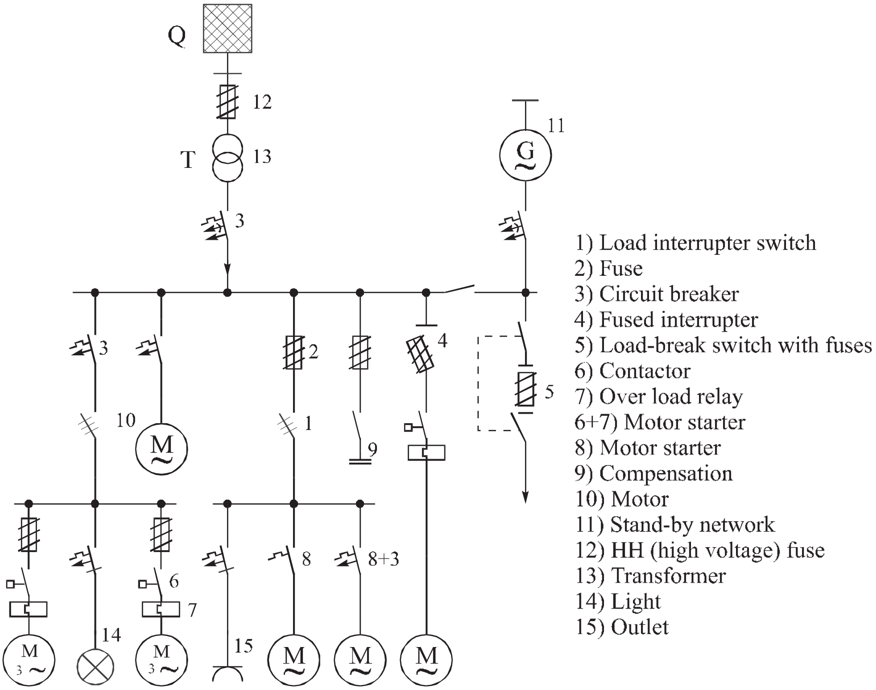
3.2
Low-Voltage Systems

Electrical switchgear comprises a multitude of various operational equipment and components. The generation, transmission and distribution of electrical energy takes place with these elements as shown in Figure 3.4. When all these components are adequately dimensioned for their intended purposes under all operating conditions, economical and stable operation can be expected.

For planning the supply network, it is necessary to thoroughly consider the network design in order that the regulations and requirements are satisfied.

The following requirements can be summarized here:

- The network should be as simple as possible and its design should be easy to oversee
- There must be optimum protection for the equipment installed
- Good security of supply and low network losses must be guaranteed
- Operation and maintenance of the network must be convenient
- The network must have good supply quality and minimum harmonics
- The network should be designed as well as possible as a radial system
- Project-related regulations must be observed.



1) Load interrupter switch
2) Fuse
3) Circuit breaker
4) Fused interrupter
5) Load-break switch with fuses
6) Contactor
7) Over load relay
6+7) Motor starter
8) Motor starter
9) Compensation
10) Motor
11) Stand-by network
12) HH (high voltage) fuse
13) Transformer
14) Light
15) Outlet

Figure 3.4 Principle of switchgear

For the planning of networks and electrical systems, the total power of the system, the size and number of transformers, the dimensioning of cables and lines, the size and distribution o operating and short circuit currents, operational failures and changes in loads must all be clarified as soon as possible. The thermal and dynamic short circuit currents and the making and breaking capacities of the protective equipment, the contributions of low-voltage motors to the initial symmetrical short circuit current, to the peak short circuit current and to the breaking current, the voltage drop and the system perturbations determine the stability of the system. Electrical equipment must be designed so that its operation is not impaired by external electromagnetic influences and so that the equipment itself dose not become a source of disturbance for other equipment [3]. For this reason, during the planning of systems it is necessary to clarify possible sources of disturbance as early as possible and initiate appropriate countermeasures. The following characteristic specifications are part of planning a low-voltage system:

- Type of supply
- Power capacity
- Coincidence factor
- System forms
- External influences on operational equipment
- Compatibility and serviceability
- Maximum transmission length
- Number of power supply units connected
- Cross-sections for the loads
- Fusing of circuits

The planning and installation of an electrical system requires the meticulous calculation of the power demands for which the system is to be designed. This is determined by the equation

$$P_{max} = \sum (P_i \, g_i) \tag{3.1}$$

The coincidence factor or demand factor g_i indicates how many consumers are in operation at the same time (Tables 4 and 5). It is an important factor for determining the feed-ins. When more motor drives are connected in the system, it is also necessary to consider the utilization factor a_i and the efficiency η_i in this calculation. The maximum power demand is then [31]:

$$P_{max} = \sum \frac{P_{rM} \, g_i \, a_i}{\eta_i} \tag{3.2}$$

The meanings of the symbols are:

P_{max} Power demand
P_i Installed power

g_i	Coincidence factor
a_i	Utilization factor of motor
η_i	Efficiency of motor
P_{rM}	Rated power of motor

Table 3.1: Coincidence factors for the main feed-in

Building type	**Factor**
Residential	0,4
Apartment blocks	
with electrical heating	0,8–1
without electrical heating	0,6
High-rise office building	
Ventilation, heating	1
Data processing	1
Lighting	1
Sprinkler system	1
Sanitation facilities	0,8
Elevators	0,7
Cooling system	1
Schools	0,6–0,7
Assembly rooms, Theater, restaurants, etc.	0,6–0,8
Stores	0,6–0,7
Traffic systems	1
Administrative offices, banks	0,7–0,9
Kindergartens	0,6–0,9
Carpenters' shops	0,2–0,6
Butchers	0,5–0,8
Bakeries	0,4–0,8
Construction sites	0,2–0,4
Cranes	0,7 per crane

Table 3.2: Coincidence factors for important consumers

Consumer groups	**Office buildings**	**Hospitals**	**Department stores**
Lighting	0,85–0,95	0,7–0,9	0,85–0,95
Electrical outlets	0,1–0,15	0,1–0,2	0,2
Kitchens	0,5–0,85	0,6–0,8	0,6–0,8
Air conditioners	1	1	1
Elevators, escalators	0,7–1	0,5–1	0,7–1

The apparent power of the network input can be calculated from the calculated P_{max} and the average power factor cos φ. Once the total power, with a reserve factor, has been defined the size and type of the transformer can be established. Supply takes place in either a ring network or a radial network (Figure 3.5). Here it is necessary to give some thought to the characteristics of the operational electrical equipment which can affect other operational equipment, such as harmonics, reactive power compensation, overvoltages, electromagnetic fields, voltage quality and power system protection.

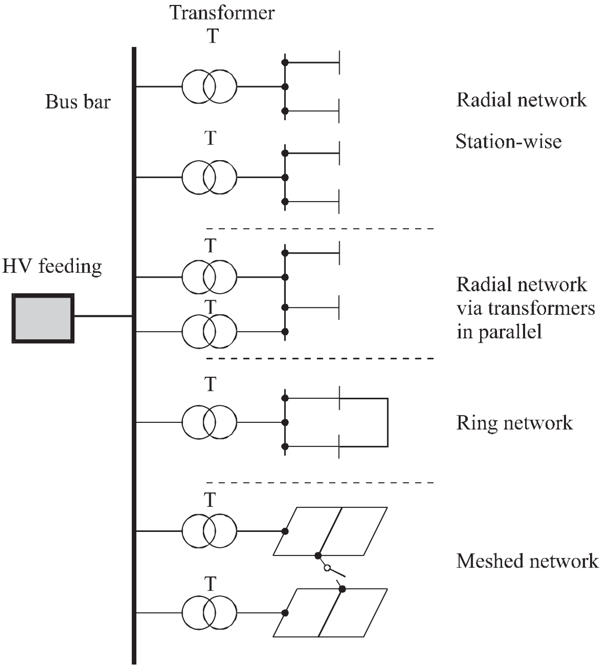


Figure 3.5 Low-voltage concept

The operational electrical equipment, such as cables and lines, fuses, circuit breakers and transformers must be optimally chosen and dimensioned both economically and technically. If no information is available, Table 2.3 can be used for this purpose. The minimum fuse protection for a residential installation is 63 A. For larger buildings, with or without electrical water heating for bathing/showering, the effective powers for the dimensioning of the main lines can be taken from the diagram in Figure 3.6.

Table 3.3: Planning values for networks

Category	Power demand in W/m^2	Reference area
Industry	20–150	Site area
Supermarkets	15–80	Shopping area
Department stores	30–100	Shopping area
Offices	30–60	Total business area
Housing	Figure 3.6	

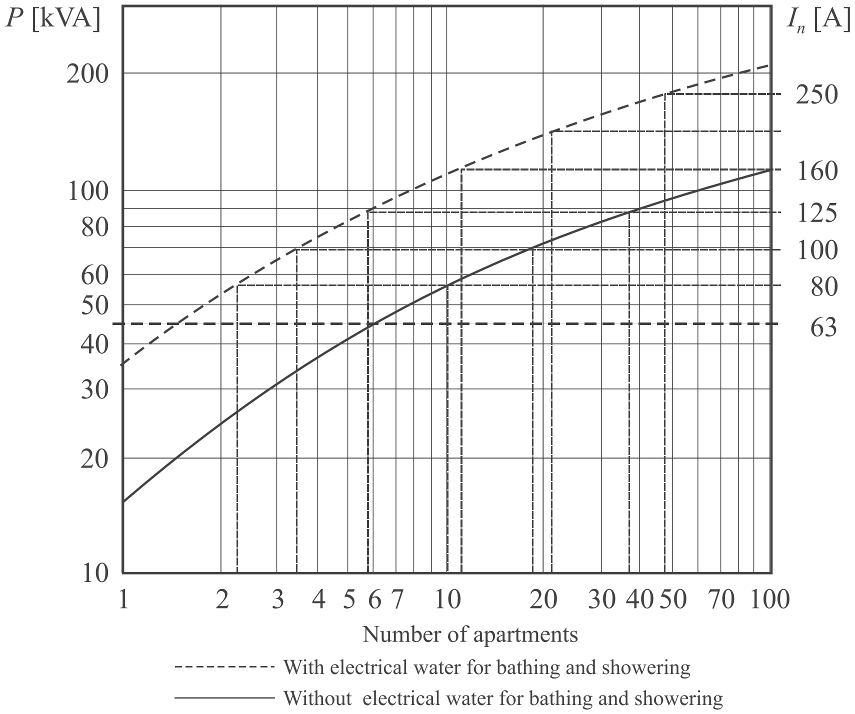


Figure 3.6 Dimensioning of main lines for apartments without electrical heating

Each project planning task begins with the collection of all data required for the calculations and design. The coordination between all those concerned (owner, architect and electrical specialists) plays an important part. The applicable standards and regulations, such as IEC and EN, as well as any country-specific regulations, must always be taken into account. A few of the most important of these are:

- IEC 60 364 Installation of power current systems up to 1000 V
- IEC 60 909 Calculation of short circuit currents in three-phase networks
- IEC 523 Current carrying capacity of lines and cables
- Conversion factors for the current carrying capacity of lines and cables
- Accident prevention regulations of the trade union for electrotechnology
- Planning of electrical systems in residential buildings
- regulations of fire alarm installations
- IEC 1024 Lightning protection systems
- EN 60204-1 Equipping of industrial machines
- Electrotechnical operating, service panel
- Lighting engineering
- Regulations for construction of the German federal states
- Accident prevention regulations

- Circuit documentation
- Power economics law
- Supply service
- Concrete-footing grounding electrodes

In practice we can speak of the following cases:

Case I:

1. The short circuit power is known or can be obtained from the power supplier.
2. The power and the short circuit voltage of the transformer are given.
3. The consumers and the connection locations are known.
4. The coincidence factor is given or can be taken from the tables.
5. It is therefore possible to calculate the cross-section of the main line,the short circuit currents and the voltage drops.

Case II:

1. The source impedance of the source network and the length up to the feed-in of the main distribution are known.
2. The consumer data are known and are drawn in on the planimetric map.
3. The coincidence factor is given.
4. The protective measures (TN or TT system) are known.
5. The installed total effective and reactive powers must be calculated.
6. The operating current is calculated from the total effective power.
7. The cross-section of the feeder line is calculated, considering the type of cable installation and the voltage drop.
8. The main fuse or circuit breaker is determined from the cabling selected.
9. For the calculation of short circuit currents it is necessary to determine the impedances of the individual lines and cables.
10. The short circuit currents for three-pole and single-pole short circuits are calculated.
11. The cross-sections of the lines and cables are determined in accordance with existing regulations (IEC 60 364 Parts 41, 43, 52 and 54).
12. The overcurrent protection equipment (OPE) must be chosen for these cross-sections.
13. The break times of the individual fuses are read from either the characteristic curves or from IEC 60 364 Parts 61.
14. The selectivity of the overcurrent protection equipment must be determined.
15. All data compiled can then be transferred to the overview, circuit diagrams and the planimetric map.

4
Transformers

IEC 60076-1-2-3-4-5-8, IEC 600726

4.1
Physical Basis

The industrial system with operational equipment depicted in Fig. 2.4; will now be explained. First we will discuss the transformer.

A transformer is an alternating current device, in which electromagnetic induction transfers an alternating voltage and current between two or more windings having the same frequency and in general different values of voltage and current. It is therefore a device for the transmission and transport of electrical energy. We distinguish here between main transformers (machine transformers), for transforming the generator voltage to the high voltage required for the transmission lines, and transformer substations (distribution transformers) between medium-voltage networks and consumers (local networks). Low-power transformers find use in communications engineering, for transforming voltages in the power supplies of the electrical industry and as isolating transformers when it is necessary to work with low voltages.

The following relationships are important for the functioning of the transformer:

1. Biot-Savart law

   The Biot-Savart law describes the relationship between the magnetic field and the electrical current which generates this field. The permeability quantifies this relationship.

   Magnetic induction (flux density):

   $$B = \mu_0 \, H \tag{4.1}$$

   magnetic field strength:

   $$H = \frac{\Theta}{l} \tag{4.2}$$

   electrical flux:

   $$\Theta = I \, N \tag{4.3}$$

Analysis and Design of Low-Voltage Power Systems. Ismail Kasikci

ISBN: 3-527-30483-5

In a closed field, the magnetomotive force represents the sum of all currents linked with the induction lines (Figure 4.1).

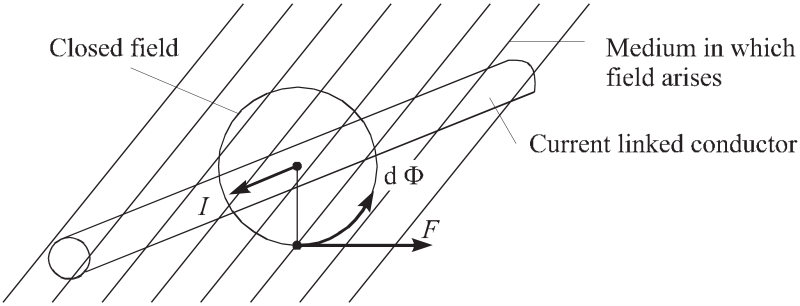


Figure 4.1 Biot-Savart law

2. Law of Conservation of Energy
   The power input is equal to the power output plus the sum of all losses which result from effective power losses and reactive power losses (Figure 4.2).

$$P_{input} = P_{output} + \sum P_{loss} \tag{4.4}$$

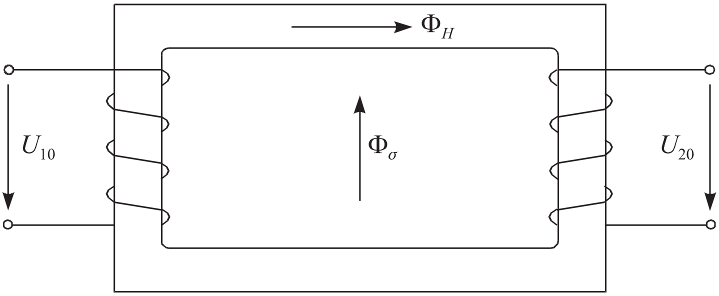


Figure 4.2 Law of conservation of energy

3. Faraday's law
   Sine-wave voltages can be generated by the movement of windings in magnetic fields or vice versa. When a changing magnetic field cuts through a conducting loop, a voltage is induced in this conducting loop (Figure 4.3). The induced voltage is proportional to the rate of change of the flux $\frac{\mathrm{d}\Phi}{\mathrm{d}t}$ and the number of windings N proportional:

$$u_0 = -N\frac{\mathrm{d}\Phi}{\mathrm{d}t} \tag{4.5}$$

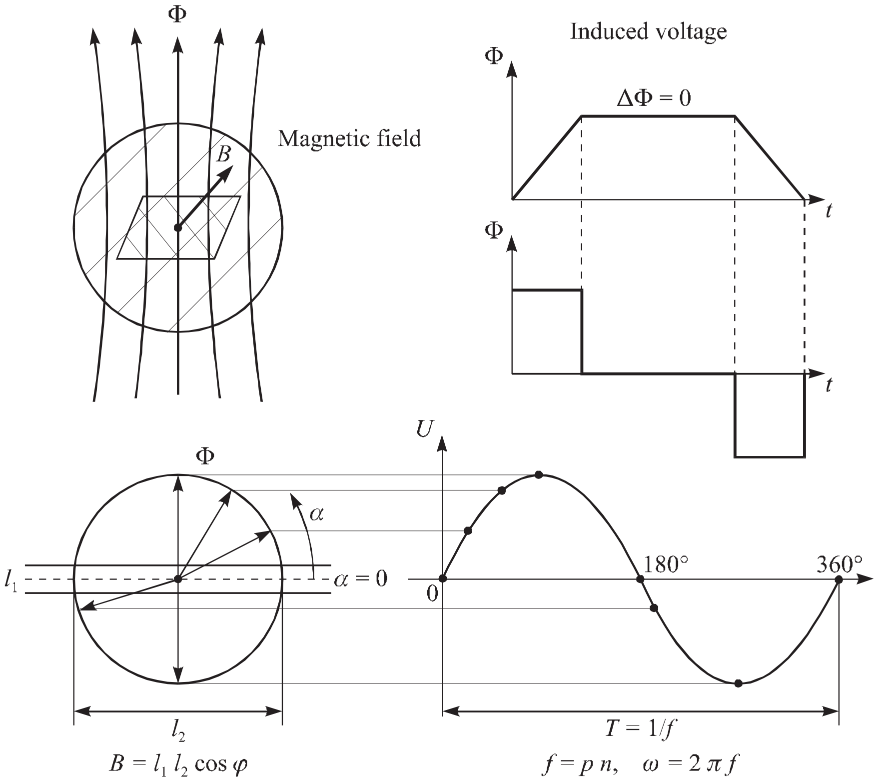


Figure 4.3 Faraday's law

4. Principle of the transformer
   When a current varying in time passes through a coil, a magnetic field is produced. A second coil located nearby (on a common iron core) is also subjected to this induction (Principle of the transformer, Figure 4.4).
   The following relationships apply here:

$$u = \frac{N_1\{\mathrm{d}\Phi}{\mathrm{d}t} = N_1 \frac{\mathrm{d}}{\mathrm{d}t}\mathrm{Re}\left[\Phi \mathrm{e}^{\mathrm{j}\omega t}\right] \tag{4.6}$$

$$u = \mathrm{Re}\left[\mathrm{j}\omega w_1\ \Phi \mathrm{e}^{\mathrm{j}\omega t}\right] = \mathrm{Re}\left[\underline{U}\sqrt{2}\mathrm{e}^{\mathrm{j}\omega t}\right] \tag{4.7}$$

$$\underline{U} = \mathrm{j}\frac{\omega}{\sqrt{2}} N_1 \Phi \tag{4.8}$$

$$U = |\underline{U}| = \frac{\omega}{\sqrt{2}} N_1 \Phi \tag{4.9}$$

$$U = \frac{2\pi f}{\sqrt{2}} N_1 \Phi = 4.44 f\, N_1 \Phi \qquad [\mathrm{V,\ Hz,\ Vs}] \tag{4.10}$$

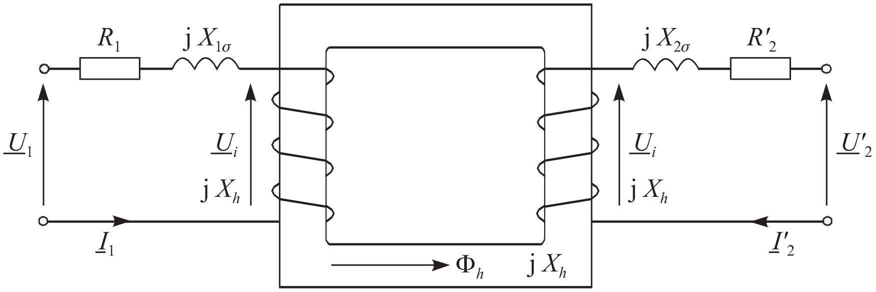


Figure 4.4 Principle of the transformer

5. Magnetic leakage
   A part of the flux which does not contribute to the envisaged purpose, but which is linked to a winding or a part of this, is found outside of the iron core (in the air, Figure 4.5). This causes ohmic voltage drops in the primary winding and thermal losses in the iron core. The entire magnetomotive difference gives rise to a magnetic force, this in turn producing a leakage flux in the air gap between the windings. Potential differences arise within a conductor, leading to eddy currents or circulating currents.

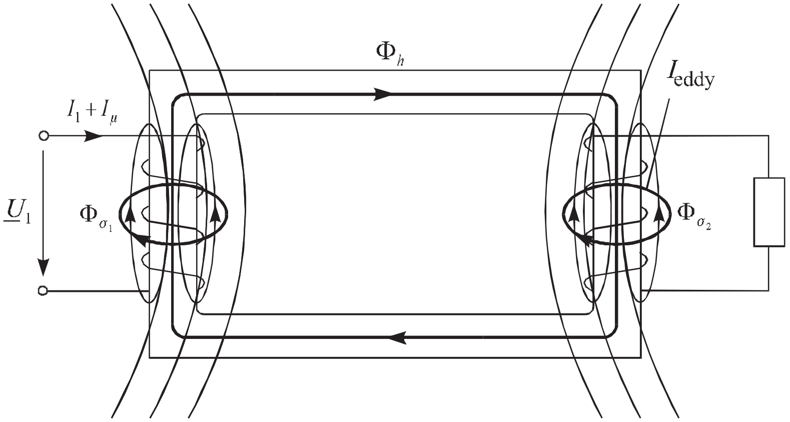


Figure 4.5 Magnetic leakage

Figures 4.6 and 4.7 illustrate the main components of distribution transformers (oil and cast resin versions) from 50 to 2500 kVA.

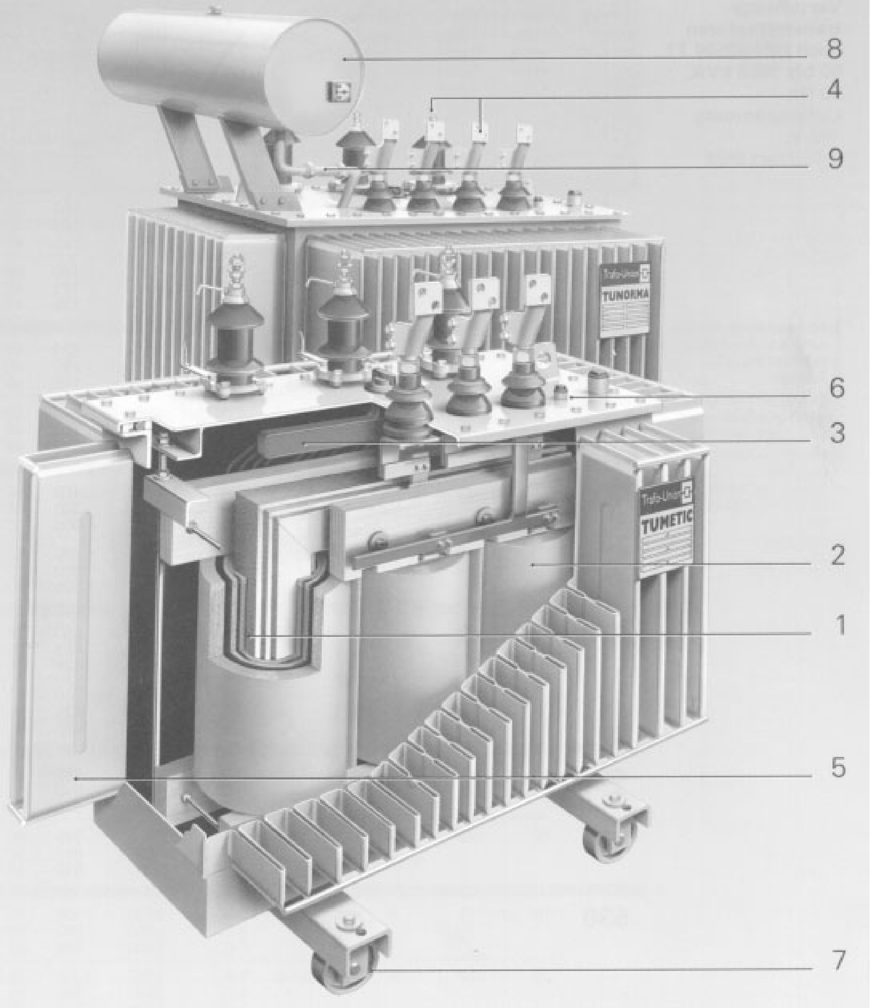


Figure 4.6 Construction and features of an oil transformer [43]

Iron core (1), windings (2), tap changer (3), insulating bushings (4), tank (5), tank lid (6), truck (7), expansion vessel (8), Buchholz relay (9)

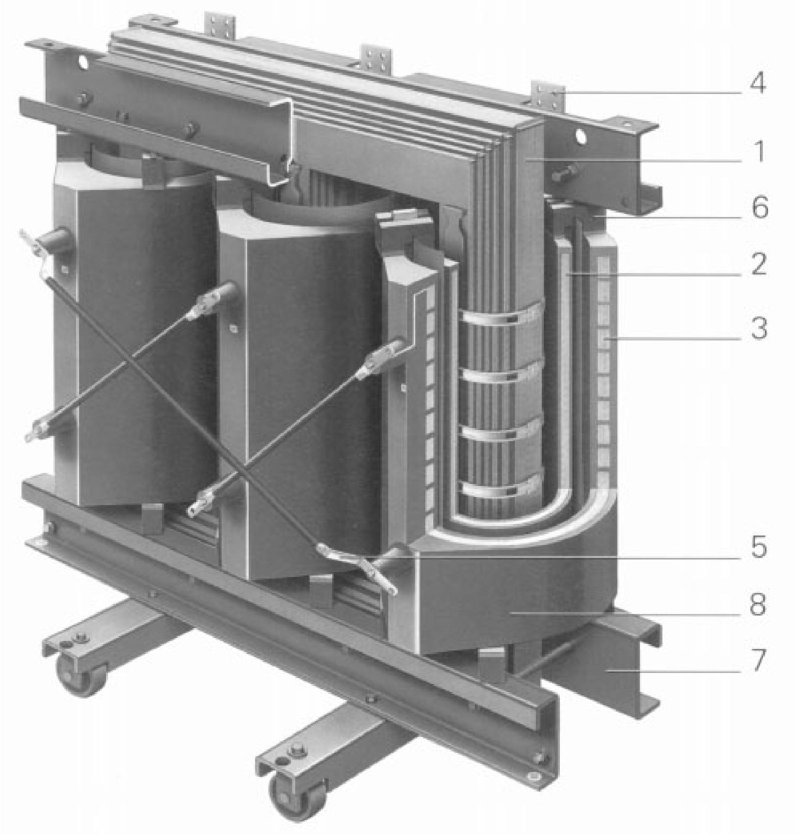


Figure 4.7 Construction and features of cast resin transformer [44]

Three-limb core (1), lower voltage winding (2), higher voltage winding (3), lower voltage connections (4), higher voltage connections (5), elastic spacers (6), end frame and truck (7), quartz powder filled epoxy resin insulation (8)

4.2
Cores

The iron core serves for the magnetic coupling of the two separate electrical circuits. It is painted over by cold-rolled, lacquer-insulated individual laminations with a maximum thickness of 0.35 mm (soft material) in order to minimize the non-magnetized losses. The use of ferrite (core plating) is necessary in order to minimize eddy currents. The core must be as good as possible magnetically and at the same time the electrical conductivity must be as poor as possible electrically. Pressing the core laminations together prevents losses and noise from hum. The iron core vibrates (magnetostriction), which manifests itself in the form of hum.

4.3
Windings

The windings are comprised of Cu or Al conductors with round or rectangular cross-section, such as laminations or foils. The windings are located on the coil form and are usually lacquer-insulated copper wire of circular cross-section.

The windings are designated as follows:

1. according to the direction of power flow
   - primary winding: takes up energy, index 1
   - secondary winding: supplies energy, index 2
2. according to the rated voltage
   - higher voltage winding (PV): winding at the higher voltage
   - lower voltage winding (SV): winding at the lower voltage

4.4
Types

1. Shell-type transformer
   - iron core surrounds the winding like a shell
   - has minimal leakage filed and minimal short circuit current
   - used as network, control and rectifier transformers
   - coils separated spatially
   - has relatively strong leakage fields
   - has relatively large short circuit voltage
2. Core transformer
   - coil surrounds the limb of the iron core
   - winding is single-layer and has large size
3. Cut strip-wound core
   - shell-type and core designs
   - has minimal losses
   - 30–40% more expensive
4. High reactance transformer
   - for special gas discharge lamps
   - has large magnetic leakage fields

4.5
A.C. Transformers

4.5.1
Design

Single-phase or A.C. transformers consist of at least two metallically separated windings on the same iron core (Figure 4.8). The core is connected through an upper and a lower yoke, so that a closed magnetic circuit arises. The iron core is made of soft iron laminations which are isolated from each other (in order to minimize losses due to remagnetizing and eddy currents).

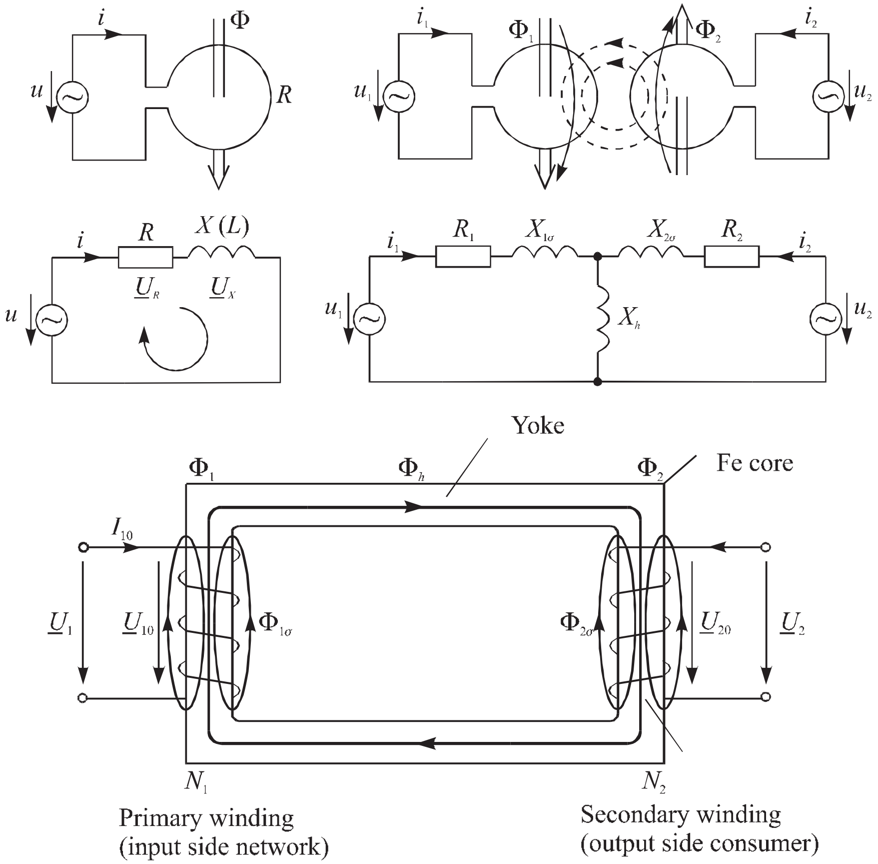


Figure 4.8 Principle of the A.C. transformer

4.5.2
Principle of Operation

The transformer effect is based on Faraday's law. An alternating voltage U_1 produces an alternating current I_1 which flows in the primary winding. I_1 then produces an alternating field. This causes self-inductance in the primary winding. This self-inductance produces an alternating voltage in the secondary coil:

$$U_2 = N\frac{\mathrm{d}\Phi}{\mathrm{d}t} \tag{4.11}$$

For the primary-side and secondary -side induced voltages, we then have:

$$U_1 = 4.44 f\, N_1\, \Phi_m \tag{4.12}$$

$$U_2 = 4.44 f\, N_2\, \Phi_m \tag{4.13}$$

4.5.3
No-Load Voltage

The no-load voltage (U_{20}) is the voltage on the secondary side when no consumer is connected. Here, the basic transformer equation applies:

$$U_{20} = \Phi\, w\, N \tag{4.14}$$

$$w = 2\,\pi\, n \tag{4.15}$$

4.5.4
Voltage and Current Transformation

From Faraday's law it follows that:

Primary coil:

$$U_1 = N_1 \frac{\mathrm{d}\Phi}{\mathrm{d}t} \tag{4.16}$$

$$\frac{\mathrm{d}\Phi}{\mathrm{d}t} = \frac{U_1}{N_1} \tag{4.17}$$

Secondary coil:

$$U_2 = N_2 \frac{\mathrm{d}\Phi}{\mathrm{d}t} \tag{4.18}$$

$$\frac{\mathrm{d}\Phi}{\mathrm{d}t} = \frac{U_2}{N_2} \tag{4.19}$$

For a transformer with no load (no-load state) the voltages behave according to the number of windings:

$$\frac{U_1}{N_1} = \frac{U_2}{N_2} \tag{4.20}$$

The undiminished ratio of the voltages is described by:

$$\ddot{\mathrm{u}} = \frac{U_1}{U_2} = \frac{N_1}{N_2} \tag{4.21}$$

Ignoring losses, it then follows that:

$$\frac{U_1}{I_2} = \frac{U_2}{I_1} \tag{4.22}$$

The currents are inversely proportional to the voltages or to the number of windings:

$$\frac{U_1}{U_2} = \frac{I_2}{I_1} \tag{4.23}$$

Transformers which serve for resistance matching are called one-to-one transformers:

$$\ddot{\mathrm{u}} = \sqrt{\frac{Z_1}{Z_2}} \tag{4.24}$$

4.5.5
Transformer Loading

1. No-load state: The magnetization power loss (iron losses) are measured in the no-load state (Figure 4.9).The no-load current I_0 is made up of the current I_μ and the active current component I_R (heat losses).
2. Short circuit: The short circuit voltage u_k is the primary voltage with which a transformer with short circuited secondary winding already draws its primary current (Figure 4.10). This is used to measure the short circuit losses.
   The short circuit voltage is important for the determination of
   - the impedance
   - the winding power loss
   - the phase shift
   - the short circuit current
   - the arrangement of transformers in parallel

   Mostly u_k is given as the relative short circuit voltage in percent of the primary voltage. It is a measure of the loading when a change of voltage occurs.
3. Short circuit current: When a short circuit arises on the secondary side of a transformer during operation, the peak short circuit current i_p will first flow. After a certain time, this becomes the steady state short circuit current I_k. The magnitude of i_p depends on the momentary value of the voltage and on the magnetic state of the iron core. The worst case, zero crossing and a saturated iron core, results in the highest peak short circuit current at the moment in which the short circuit arises. It consists of an A.C. component as the steady state short circuit current and a D.C. component which arises due to the collapse of the field and becomes zero after a time $t \approx 5$ seconds:

$$i_p = 2.54\, I_k \tag{4.25}$$

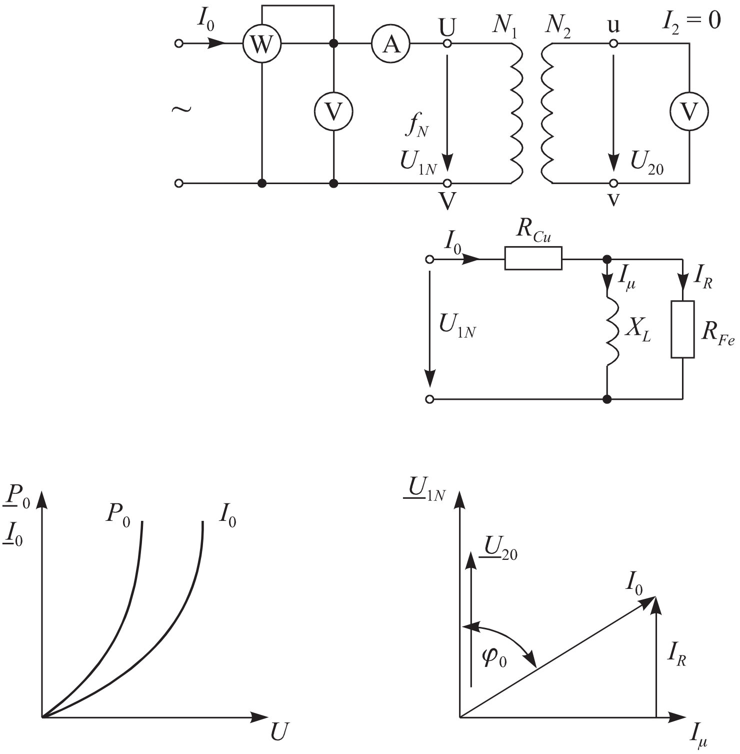


Figure 4.9 No-load state of a transformer

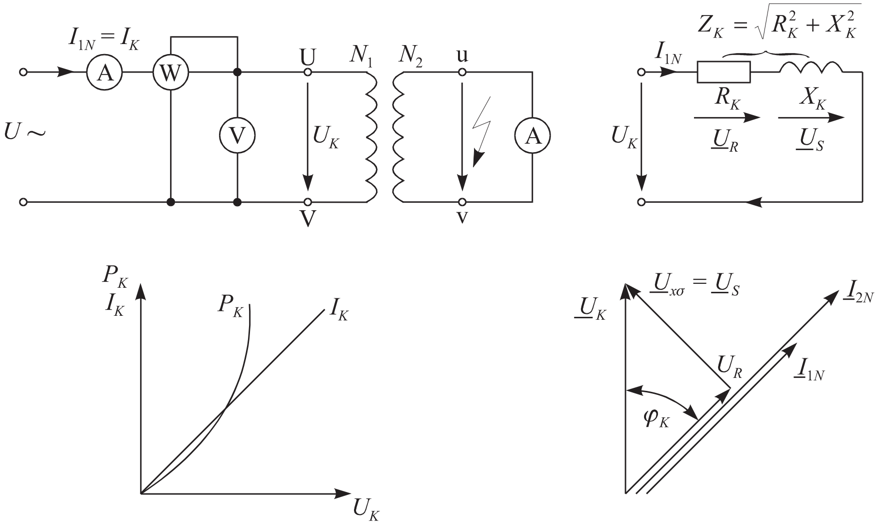


Figure 4.10 Short circuit of a transformer

The size of the steady state short circuit current I_k depends on the short circuit voltage u_k and the internal impedance Z.

The output voltage depends on:

- the magnitude of the load
- the size of the relative voltage u_k
- the phase φ of the load current

The load voltage at the output is measured for the rated load. This terminal voltage depends on the load type and the load current (Figure 4.11).

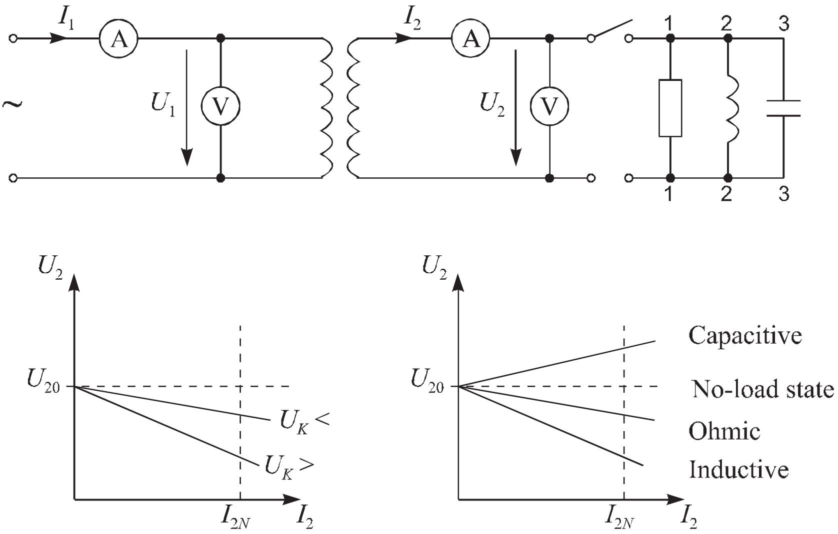


Figure 4.11 Loading of the transformer

4.6
Three-Phase Transformers

4.6.1
Design

The three-phase transformer consists of three single-phase transformers built together, i.e. the voltages are offset by 120° from each other (Figure 4.12). As a result, the sum of the magnetic fluxes in the middle limbs is zero at any time. For the three-phase transformer u_k is very small, so that the SV/PV windings are over one another on every limb.

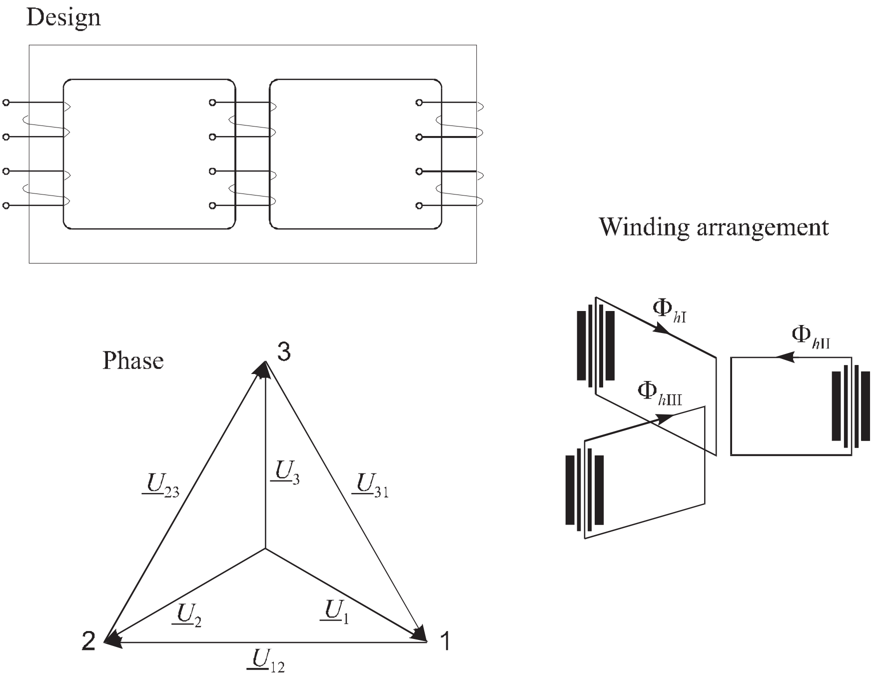


Figure 4.12 Design and winding arrangement of the three-phase transformer

4.6.2
Winding Connections

Here, connection (Figure 4.13) is understood to mean the connection of the winding phases to a single winding. The upper case letters refer to the higher voltage side (PV) and the lower case letters refer to the lower voltage side (SV).
With three-phase transformers, we must distinguish between:

1. Winding phases in delta connection (D,d)
2. Winding phases in star connection (Y,y)
3. Winding phases in zigzag connection (Z,z)
4. Winding phases in open connection (III,iii)
5. Winding phases open

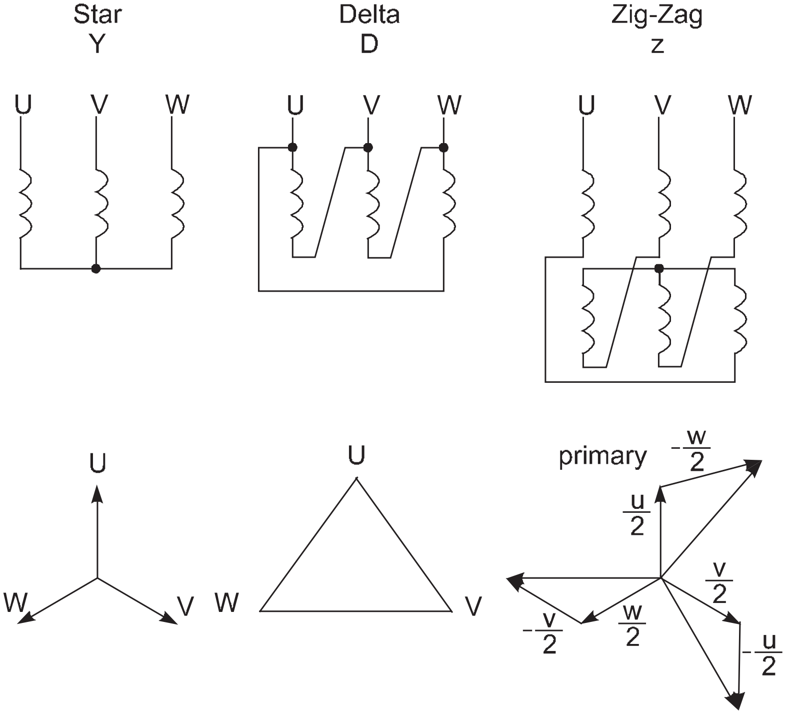


Figure 4.13 Connections

4.6.3
Connection Symbols

The connection symbols (Figure 4.14) indicate how the two windings of a transformer are connected and by what factor of 30° the pointer of the lower voltage side trails that of the higher voltage side with terminal designation coordinate in the counterclockwise direction.

The following symbols are used:

Y, D, Z	according to function and manufacture of the transformer
Y	for star point and high voltage
D	for isolation of the zero sequence system
Z	for low resistance zero sequence system

The preferred connection groups are Yy0, Dy5, Yd5, Yz5 and Dyn5.

For low-voltage networks, the lower voltage side is not implemented as a delta because the neutral conductor could otherwise not be connected.

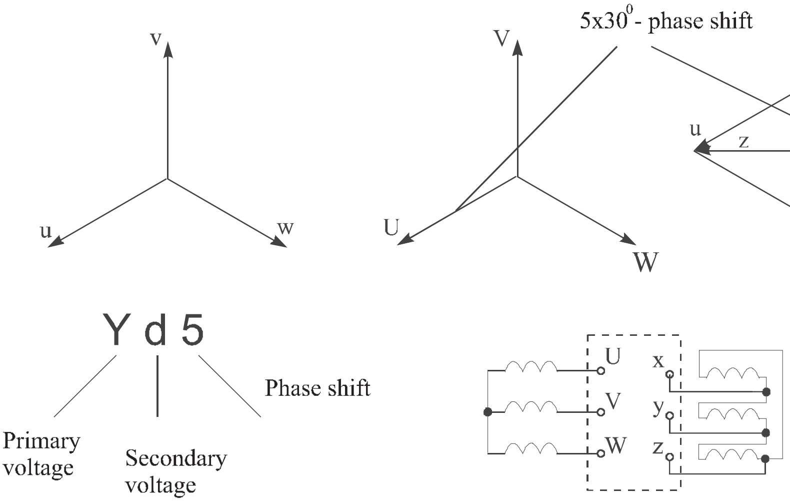


Figure 4.14 Connection symbols

4.6.4
Parallel Connection of Transformers

The parallel connection of transformers serves to increase the power of a system (Figure 4.). In order to prevent exceeding the rated current or overloading of the individual transformers, the following conditions must be adhered to:

1. The same rated frequency and rated voltage (not ü!),
2. Approximately the same short circuit voltages (maximum ± 10% deviation),
3. The same connection symbol
4. Maximum rated power ratio 1 : 3,
5. Connection in correct phase sequence

The following relationships can be used for transformers connected in parallel:

1. for the same short circuit voltages
   the load output of the transformer:

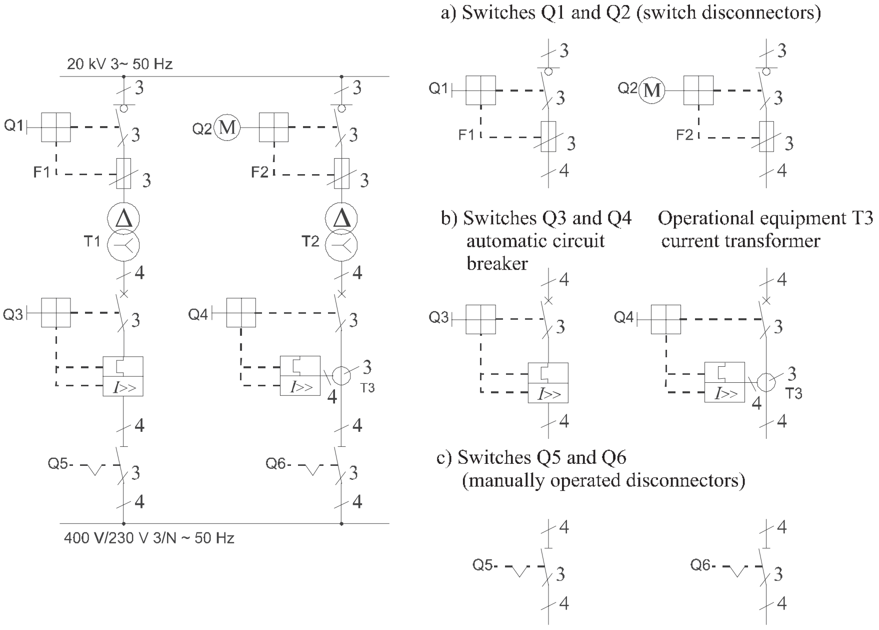
$$S_{L1} = \sum S_{GL} \frac{S_{rT1}}{\sum S_{rT}} \tag{4.27}$$

2. for unequal short circuit voltages
   the load output of the transformer:

$$S_{L1} = S_{rT1} \frac{u_{krm}}{u_{kr1}} \frac{\sum S_{GL}}{\sum S_{rT}} \tag{4.28}$$

The average short circuit voltage u_{krm} is given by:

$$u_{krm} = \sum S_{rT} \frac{S_{rT1}}{u_{kr1}} + \frac{S_{rT2}}{u_{kr2}+\cdots} \tag{4.29}$$


a) Switches Q1 and Q2 (switch disconnectors)

b) Switches Q3 and Q4 automatic circuit breaker

Operational equipment T3 current transformer

c) Switches Q5 and Q6 (manually operated disconnectors)

Figure 4.15 Parallel connection of transformers

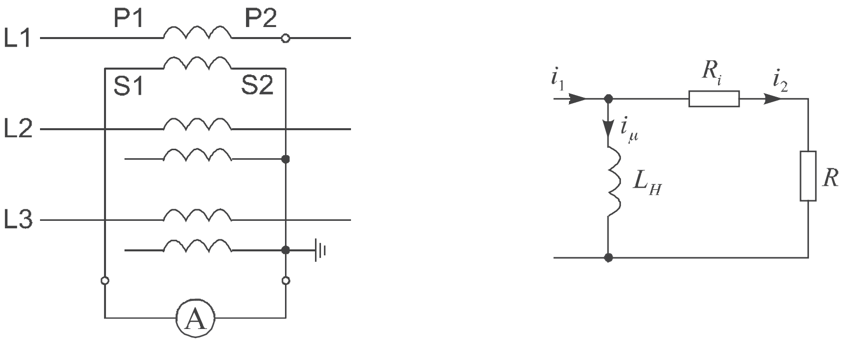
The meanings of the symbols are:

S_{rT1}	Rated power of the first transformer in kW
u_{kr1}	Short circuit voltage of the first transformer in %
S_{L1}	Load output of the first transformer in kW
S_{rT2}	Rated power of the second transformer in kW
u_{kr2}	Short circuit voltage of the second transformer in %
S_{L2}	Load output of the second transformer in kW
S_{rT}	Sum of the rated powers in kW
u_{krm}	Average short circuit voltage in %
S_{GL}	Total load in kW

4.7
Special-Purpose Transformers

4.7.1
Current Transformers

Current transformers are used for measurement and protection purposes (Figure 4.16). They separate the measurement (M) and protection (P) circuit from the primary voltage and protect the equipment against overloading. Measuring transformer: class 0.1 M; 1 M, protection transformer: class 5 P; 10 P



a) Block diagram

b) Equivalent circuit diagram

Figure 4.16 Current transformer

The current transformer

- is connected in series with the network
- generates no power
- is along the line to the primary winding
- is short circuited through the connected equipment, counters and relays on the secondary side
- functions in a short circuit

4.7.2
Voltage Transformers

Voltage transformer (Figure 4.17) transform high voltages to measurable voltages. The rated voltage of the voltage transformer is standardized to 100 V.

- The load is designated as the load impedance
- Functions nearly in no-load state, since the measuring instrument does not represent a large load – otherwise the transformer could be destroyed
- The secondary side must not be short circuited
- The secondary and the primary sides must be fuse-protected
- Grounding through 1 kV
- Standard voltage according to choice: $U_2 = 100$ V or 100/3 V

Measuring transformer: class 0.1 M; 1 M, protection transformer: class 3 P; 6 P
Use:

- Inductive transformer for low-voltage side
- Capacitive transformer for high-voltage side

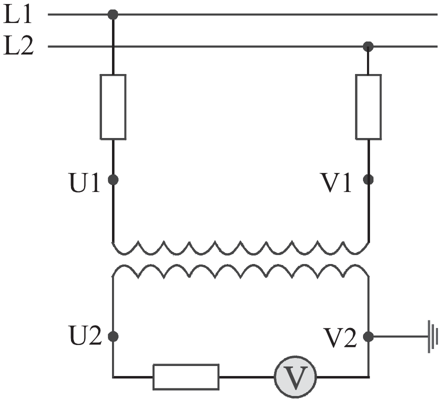


Figure 4.17 Voltage transformer

4.7.3
Autotransformers

This type of transformer represents an inductive voltage distributor and has no metallic isolation of the higher voltage and lower voltage sides (Figure 4.18). The throughput power is transferred partly conductively and partly inductively.

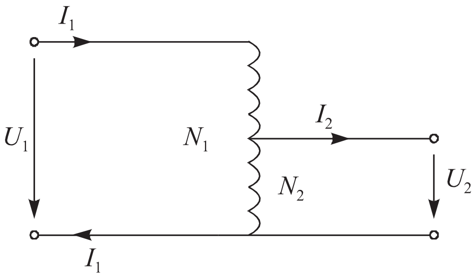


Figure 4.18 Autotransformer

Use:

- Compensation for voltage fluctuations in networks
- Special transformers for feeding traveling motors
- Coupling high-voltage networks
- Dry-type transformers up to 300 kVA
- Oil-filled transformers from 300 kVA
- Self-cooling (S)
- Forced cooling
- Forced oil circulation

The size of autotransformers can be calculated from the known throughput power according to the relationship:

$$S = P_d \left(1 - \frac{U_{SV}}{U_{PV}}\right) \tag{4.31}$$

4.8
Efficiency of Transformers

The magnetic or iron core losses consist of the hysteresis and eddy current losses in the iron core and in the dielectric material. These losses are independent of the loading. The short circuit losses are made up of the ohmic losses in the windings. The winding losses increase in proportion to the square of the load. The efficiency of a transformer can be calculated for any arbitrary load n and is given by:

$$\eta = 100\,\% - \frac{P_0 + n^2\, P_k}{n\, S_{rT} \cos\varphi + P_0}\, 100\,\% \tag{4.32}$$

A transformer has its maximum efficiency at a load for which $P_0 = n^2\, P_k$. This condition is satisfied for a load factor of

$$n = \sqrt{\frac{P_0}{P_k}} \tag{4.33}$$

The total losses of a transformer for any arbitrary loading are given by:

$$P_v = P_0 + n^2\, P_k \tag{4.34}$$

4.9
Protection of Transformers

- Protection against internal faults
  1. The Buchholz relay responds to internal damage as a result of outgassing or oil flow. It generates a warning message for smaller faults and initiates the tripping of a switch for larger faults.
  2. The differential protection relay compares the input and output currents of the transformer. In the event of a fault (short circuit to ground, short circuit or interturn fault) it triggers the protective relay. It must be stable with respect to the making current of the transformer in the no-load state.
- Protection against overloading
  1. The thermistor protection signals an overload and is used to protect against non-permissible heating of the transformer.
  2. The overvoltage protection is accessible through the surge arrester.

4.10
Selection of Transformers

The characteristic data of transformers are determined by the requirements of the network. The effective power determined must be multiplied by the power factor cos φ to give the rated power S_{rT}. In distribution networks the value $u_k = 6\%$ is preferred. Transformer losses are made up of no-load losses and short circuit losses. The no-load losses are caused by the continuous reversal of magnetization of the iron core and are practically constant and independent of loading. The short circuit losses are made up of the ohmic losses in the windings and losses due to leakage fields. They are proportional to the square of the loading. Oil-filled transformers and cast resin dry-type transformers are preferred; the use of askarel transformers is forbidden. In this section, the most important criteria for the selection of distribution transformers in the power range from 50 to 2500 kVA for supplying power to low-voltage networks will be discussed.

1. Requirement of operational safety
   - Routine tests (losses, u_k, voltage test)
   - Type testing (heating, surge voltage)
   - Special tests (short circuit strength, noise)
2. Electrical conditions
   - Short circuit voltage
   - Connection symbol
   - Transformation ratio
3. Installation conditions
   - Interior and outside installation
   - Special local conditions
   - Environmental protection conditions
   - Designs: oil-filled or cast resin dry-type transformer
4. Operating conditions
   - Loading capacity (oil-filled transformers) or (cast resin dry-type transformers)
   - Load fluctuations
   - Number of hours in operation
   - Efficiency (oil-filled transformers) or (cast resin dry-type transformers)
   - Voltage regulation
   - Parallel operation
5. Characteristic data for transformers with examples
   - Rated power $S_{rT} = 1000$ kVA
   - Rated voltage $U_{rOS} = 20$ kV
   - Lower side voltage $U_{rUS} = 0.4$ kV
   - Rated lightning impulse withstand voltage $U_{rB} = 125$ kV
   - Loss combination
   - No-load losses $P_0 = 1700$ W
   - Short circuit losses $P_k = 13000$ W

- Acoustical power $L_{WA} = 73$ dB
- Short circuit voltage $u_{kr} = 6\%$
- Transformation ratio PV/SV = 20 kV/0.4 kV
- Connection symbol Dyn5
- Termination systems, e.g. lower voltage and upper voltage side flange systems
- Interior or outside installation

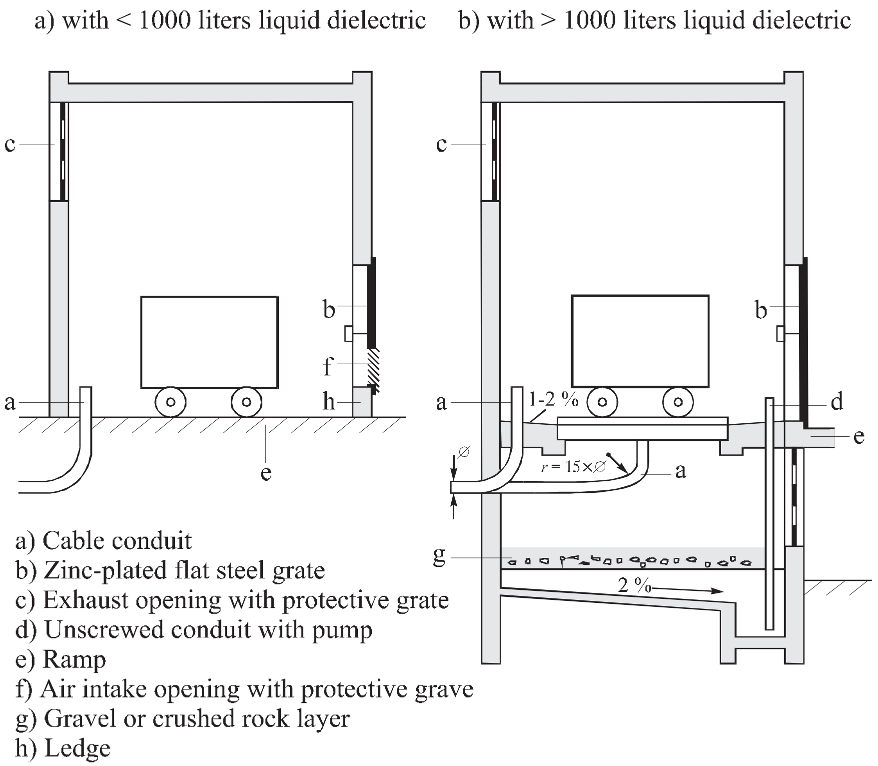


Figure 4.19 Interior installation of liquid-filled transformers [45]

The installation of transformers should be free of underground water and flooding. The cooling must be protected against sunlight. Fire protection measures and environmental compatibility must also be ensured. Figure 4.19 illustrates a transformer with oil filling < 1000 liters. Here, an impermeable floor is sufficient. For oil filling > 1000 liters, oil collecting troughs or oil sumps are mandatory.

The heat losses of transformers must be dissipated. This requires air intake and exhaust openings. The air intake must flow in underneath the transformer close to the floor and the exhaust must be led upwards. The size of the exhaust opening is shown without grate in Figure 4.20 for a room heating of 15 K.

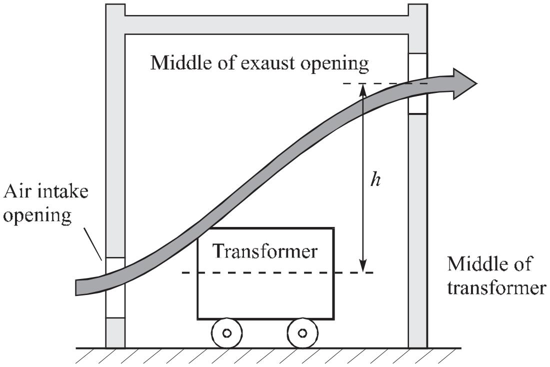


Figure 4.20 Ventilation for the interior installation of a cast resin transformer [45]

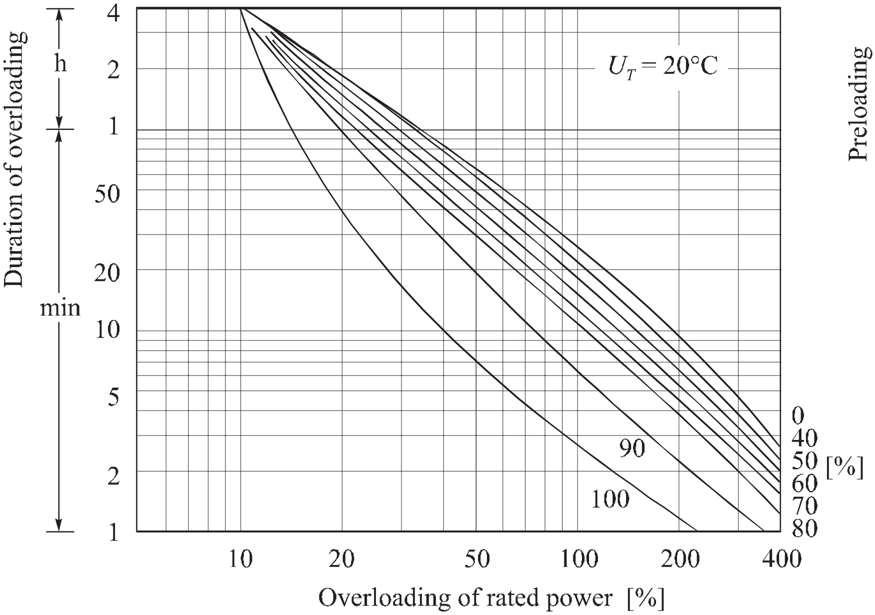


Figure 4.21 Permissible overloading of GEAFOL cast resin transformers [45]

$$P_v = P_0 + k\,P_{k75} \qquad [\text{kW}] \tag{4.35}$$

The meanings of the symbols are:

A Air exaust opening and intake opening
P_v Transformer power loss
$k =$ 1.06 for oil-filled transformers
$k =$ 1.2 for cast resin transformers

P_0	no-load losses
P_{k75}	Short circuit losses at 75 °C in kW
h	Difference in height in meters

Figure 4.21 gives the permissible overload capacity of cast resin transformers in the power range from 400 to 2500 kVA. The determination of the loading capacity of oil-filled transformers can be made on the basis of IEC 60076-1.

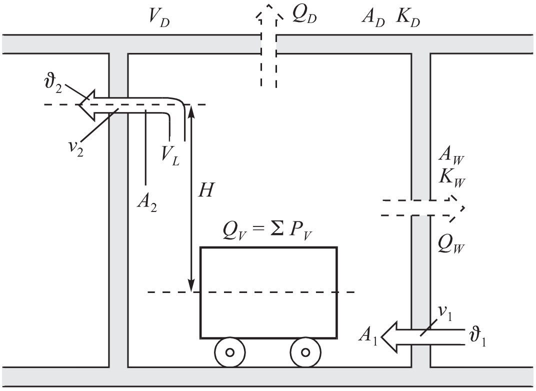


Figure 4.22 Ventilation of the transformer room [45]

The heating losses which arise while operating a transformer (Figure 4.22) must be dissipated. If it is not possible owing to the conditions for installation to utilize natural ventilation, it is necessary to install a fan. The overall temperature of the transformer must not exceed 40 °C. The overall losses in a transformer room are given by:

$$Q_{loss} = \sum P_{loss} \tag{4.37}$$

$$P_{loss} = P_0 + 1.2\, P_{k75} \left(\frac{S_{AF}}{S_{AN}} \right)^2 \tag{4.38}$$

The total losses are dissipated through:

$$Q_v = Q_{loss1} + Q_{loss2} + Q_{loss3} \tag{4.39}$$

The individually dissipated amounts of heat can be calculated from the following:
Natural air current:

$$Q_{loss1} = 0.098\, A_{1.2} \sqrt{H\, \Delta\vartheta_L^3} \tag{4.40}$$

Losses dissipated by forced air currents: (Figure 4.21):

$$Q_{loss3} = V_L\, C_{PL}\, \varrho_L\, \Delta\vartheta_L \tag{4.41}$$

Losses dissipated through walls and the ceiling (Figure 4.22):

$$Q_{loss2} = 0.7\, A_W\, K_W\, \Delta\vartheta_W + A_D\, K_D\, \Delta\vartheta_D \tag{4.42}$$

The meanings of the symbols are:

P_v	Transformer power loss in kW
Q_v	Dissipated losses in kW
$Q_{W,D}$	Dissipated losses through walls and ceiling in kW
$A_{W,D}$	Area of walls and ceiling in m^2
$K_{W,D}$	Heat transfer coefficient in kW/m^2 K
S_{AF}	Power for the cooling type AF in kVA
S_{AN}	Power for the cooling type AN in kVA
V_L	Air flow rate in m^3/s, m^3/h
Q_{v1}	Part dissipated in natural air current in kW
Q_{v2}	Part dissipated through walls and ceiling in kW
Q_{v3}	Part dissipated in forced air current in kW

The transformer noise is a combination of magnetic noise and the noise of additional ventilation. Figure 4.23 shows the noise level of different transformers according to IEC Publication 551. The magnetic noise is the result of oscillations of the iron core (induction-dependent) and depends on the material properties of the core laminations.

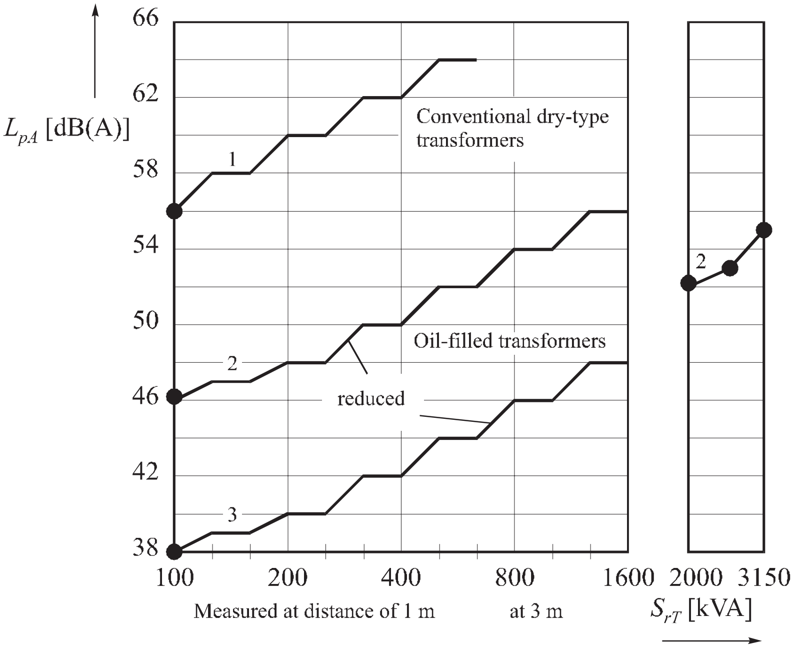


Figure 4.23 Sound pressure level of transformers [45]

The acoustical power (Figure 4.24) is a measure of the noise level produced by an acoustical source.

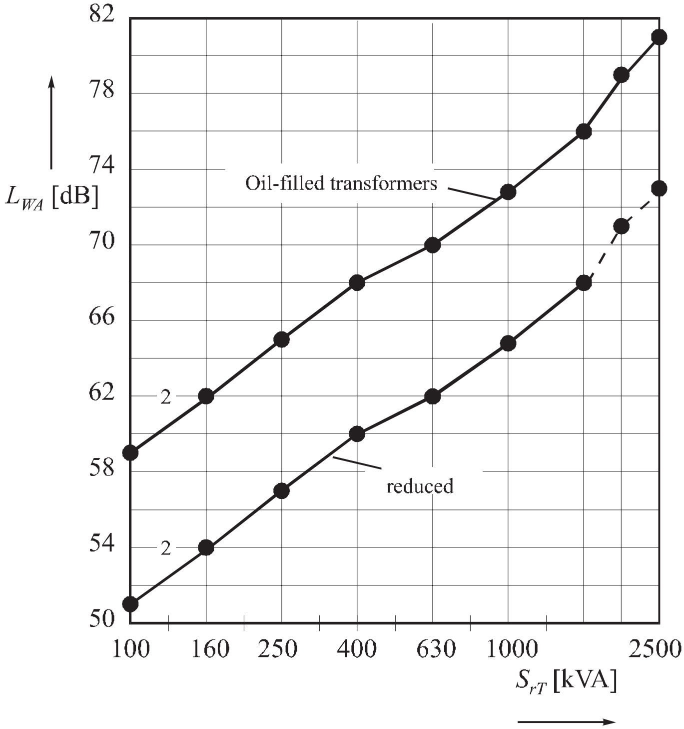


Figure 4.24 Acoustical power level of transformers [45]

4.11
Rules of Thumb for Calculating Short Circuit Currents on the Low-Voltage Side

In low-voltage radial networks it is possible to make use of approximation methods for the calculation of short circuit currents in transformers. In general, in terms of the rated transformer current, we can thus use:

$$I_{rT} \approx k\, S_{rT} \tag{4.44}$$

Here, the factor $k\left(\frac{1}{10^3\,\mathrm{V}}\right)$ is:

at 400 V 1.45
at 525 V 1.1
at 690 V 0.85

The initial symmetrical short circuit current of a transformer is given by:

$$I''_k \approx \frac{I_{rT}}{u_{kr}} \cdot 100\% \tag{4.46}$$

Table 47 lists the rated data for oil-filled and Geafol transformers ([6],[7]).

Table 4.1: Rated data for transformers

S_{rT} kVA	U_{rTOS} kV	u_{kr} %	SG –	I_{rT} A	I''_k kA	P_{k75} W	P_0 W
Oil-filled distribution transformers in accordance with DIN 42500 Part 1, 50 Hz, 400 V							
50	20	4	Yzn5	73	1.8	1350	190
100	20	4	Yzn5	145	3.6	2150	320
160	20	4	Dyn5	231	5.7	3100	460
250	20	4	Dyn5	361	8.9	4200	650
400	20	4	Dyn5	578	14.2	6000	930
630	20	4	Dyn5	910	22.1	8400	1300
630	20	6	Dyn5	910	14.8	8700	1200
1000	20	6	Dyn5	1444	23.2	13000	1700
1600	20	6	Dyn5	2310	36.4	20000	2600
2500	20	6	Dyn5	3609	55.3	29000	3500
GEAFOL cast resin transformers in accordance with DIN 42523, 50 Hz, 400 V							
100	10	4	Dyn5	144	3.6	1600	440
100	20	6	Dyn5	144	2.4	1800	330
160	10	4	Dyn5	230	5.75	2300	610
160	20	6	Dyn5	230	3.8	2500	480
250	10	4	Dyn5	360	9	3000	820
250	20	6	Dyn5	360	6	3100	650
400	10	4	Dyn5	589	14.7	4300	1150
400	20	6	Dyn5	589	9.8	4100	1200
630	10	4	Dyn5	910	22.7	6400	1500
630	20	6	Dyn5	910	15	6400	1250
1000	20	6	Dyn5	1444	24	8900	2200
1600	20	6	Dyn5	2312	38.5	11000	2400
2500	20	6	Dyn5	3600	60	17600	3600

4.12
Examples for Transformers

4.12.1
Example 1: Calculation of the Initial Symmetrical Short Circuit Current for a Transformer

Given the following data for a transformer:

$$S_{rT} = 630\text{kVA},\ u_{kr} = 6\,\%,\ U_{rT} = 400\ \text{V},\ k = 1.45$$

The rated current of the transformer is then:

$$I_{rT} \approx k\,S_{rT} = 1.45 \cdot \text{kVA} = 913.5\ \text{A}$$

The initial symmetrical short circuit current for the transformer is then:

$$I_k'' \approx \frac{I_{rT}}{u_{kr}} \cdot 100\% = \frac{913.5\ \text{A}}{6\%} \cdot 100\% = 15.225\,\text{kA}$$

4.12.2
Example 2: Calculation of Equalizing Currents

Given two transformers with the following data are connected in parallel:

$$S_{rT1} = 630\,\text{kVA},\ u_{kr1} = 4\,\%,\ U_{rT1} = 400\,\text{V}$$
$$S_{rT2} = 1000\,\text{kVA},\ u_{kr2} = 6\,\%,\ U_{rT2} = 380\,\text{V}$$

calculate the equalizing current.

$$\Delta u = \frac{U_{rT1} - U_{rT2}}{U_{rT1}} \cdot 100\,\% = \frac{400\,\text{V} - 380\,\text{V}}{400\,\text{V}} \cdot 100\,\% = 5\,\% \tag{4.48}$$

$$I_a = \frac{\Delta u}{u_{kr1} + u_{kr2}\,\frac{S_{rT1}}{S_{rT2}}} \cdot 100\,\% = \frac{5\,\%}{4\,\% + 6\,\% \cdot \frac{630\,\text{kVA}}{1000\,\text{kVA}}} \cdot 100\,\% = 64.26\,\% \tag{4.49}$$

The smaller transformer has the higher voltage on the low-voltage side and therefore the higher current. For an equalizing current of 64.26%, only a load current of 35.74% is permissible. From the total power of the two transformers, only 582.562 kVA can be utilized. As a result of the decrease in the short circuit voltage, the total power of the transformers increases. This means that the transformer with the lower short circuit voltage has a greater load than the transformer with the higher short circuit voltage.

4.12.3
Example 3: Economic Efficiency of Transformers

The economic efficiency of three transformers connected in parallel can be checked making use of the partial load factor a, describing the economy of operation of the transformer connection.

Rated data of the transformers

$ü_r$	20/0.4 kV
S_{rT}	630 kVA
P_0	800 W
P_{krT}	6750 W
u_{kr}	6 %
Connection symbol	Dyn5

For $n = 2$:

$$a = \sqrt{\frac{n\,(n-1)\,P_0}{P_{krT}}} = \sqrt{\frac{2 \cdot (2-1) \cdot 800\,\mathrm{W}}{6750\,\mathrm{W}}} = 0.486 \qquad (4.51)$$

Power for the transformer group:

$$S_G = a\,S_{rT} = 0.486 \cdot 630\,\mathrm{kVA} = 306.18\,\mathrm{kVA} \qquad (4.52)$$

For $n = 3$:

$$a = \sqrt{\frac{n\,(n-1)\,P_0}{P_{krT}}} = \sqrt{\frac{3 \cdot (3-1) \cdot 800\,\mathrm{W}}{6750\,\mathrm{W}}} = 0.843 \qquad (4.53)$$

Power for the transformer group:

$$S_G = a\,S_{rT} = 0.843 \cdot 630\,\mathrm{kVA} = 531.09\,\mathrm{kVA} \qquad (4.54)$$

The economic efficiency of two transformers is 306.18 kVA and of three transformers 531.09 kVA.

4.12.4
Example 4: Calculation of Efficiency Over a Year

The following data were recorded for a transformer:

$S_{rT} = 630\,\mathrm{kVA}$, $u_{kr} = 4\,\%$, $P_0 = 860\,\mathrm{W}$, $P_{krT} = 6500\,\mathrm{W}$, $t_B = 8760$ hours switched on during the year, but only with $\cos\varphi = 0.85$ and $t_E = 1800$ hours on-load time.

Find the efficiency over the entire year.

$$W_{ab} = S_{rT}\,\cos\varphi\,t_B = 630\,\mathrm{kVA} \cdot 0.85 \cdot 8760\,\mathrm{h} = 4690980\,\mathrm{kWh} \qquad (4.55)$$

$$W_{Fe} = P_{VFe}\,t_B = 860\,\mathrm{W} \cdot 8760\,\mathrm{h} = 7533.6\,\mathrm{kWh} \qquad (4.56)$$

$$W_{Cu} = P_{VCu}\,t_e = 6500\,\mathrm{W} \cdot 1800\,\mathrm{h} = 11700\,\mathrm{kWh} \qquad (4.57)$$

$$\eta = \frac{W_{ab}}{W_{ab}+W_{Fe}+W_{Cu}} = \frac{4690980\,\mathrm{kWh}}{4690980\,\mathrm{kWh}+7533.6\,\mathrm{kWh}+11700\,\mathrm{kWh}} = 0.995 \qquad (4.58)$$

4.12.5
Example 5: Calculation of Efficiency

The following data were recorded for a transformer:

$S_{rT} = 630\,\text{kVA}$, $u_{kr} = 6\,\%$, $P_0 = 0.8\,\text{kW}$, $P_{krT} = 6.75\,\text{kW}$, $\cos\varphi = 0.8$ and the load factor $a = 0.5$.

Calculate the efficiency.

$$\eta = 100\,\% - \frac{P_0 + a^2\, P_{krT}}{a\, S_{rT}\, \cos\varphi + P_0} \tag{4.59}$$

$$\eta = 100\,\% - \frac{0.8\,\text{kW} + 0.5^2 \cdot 6.75\,\text{kW}}{0.5 \cdot 630\,\text{kVA} \cdot 0.8 + 0.8 = 99.99\,\%} \tag{4.60}$$

5
Asynchronous Motors (ASM)

Asynchronous motors require little maintenance, are simple and sturdy in their construction and are the most widely used motors. In this chapter, only this type of motor will be dealt with. For other types of motors the books [5, 6] can be recommended. Asynchronous motors have a fixed field winding and are connected to a three-phase power line. The armature (rotor) is arranged according to this. The rotating field revolves spatially with the rated frequency. The rotor moves asynchronously, that is not simultaneously with the speed of rotation of the stator field. Instead, the speed of rotation of the rotor trails the speed of rotation of the rotating stator field due to the slip.

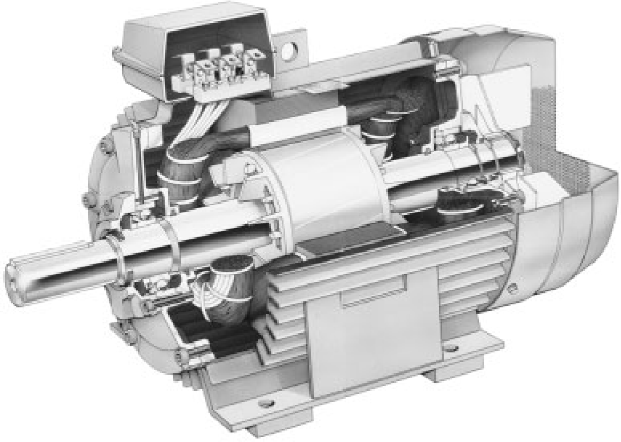


Figure 5.1 Overview of an ASM (stator and rotor) [62]

5.1
Designs and Types

We must distinguish between squirrel cage (short circuit) and slipring rotors. For squirrel cage rotors (Figure 5.1) the bars of the cage are in slots in the laminated

Analysis and Design of Low-Voltage Power Systems. Ismail Kasikci

ISBN: 3-527-30483-5

core and are connected to each other on the front side through short circuit rings. The winding of the rotor is internally short circuited and not connected to an external network. The transmission of power takes place only through the air-gap field (induction). We can therefore compare an asynchronous machine with a transformer, in which the primary winding (stator winding) is fixed and the secondary winding (rotor winding) rotates. Since by contrast with a transformer there is an air gap between the stator and the rotor windings, a greater current is required to build up the field in an asynchronous motor. This magnetization current is a purely reactive current and must be supplied from the network in both motor and generator operation. The bars are made of copper or aluminum. The stator consists of a housing, laminated core and winding. The beginnings and ends of the coils are led to the connecting terminal plate. Due to eddy current losses, the laminated cores are isolated and laminated on one side. For slipring rotors, the rotor leads are connected as a normal winding and to each other through two sliprings with resistances. During startup a starting resistor is used which is connected through the sliprings to the rotor circuit. During startup, the individual resistors are switched off stepwise with increasing motor speed. The rotor winding is then short circuited, and the motor functions as a squirrel cage rotor. Due to their more complicated construction and to the starting resistors, slipring motors are more expensive and require more maintenance than squirrel cage motors. If direct switch-on is not permissible and the breakaway torque of the squirrel cage motor is too low for the star-delta startup, the use of a slipring motor must be considered.

In industry and trade asynchronous motors are used to drive conveyor systems, textile machines, pumps and fans. In households they are used e.g. as single-phase motors in fan-forced heaters and washing machines.

5.1.1
Principle of Operation (No-Load)

Connecting the stator winding to the three-phase network results in a rotating magnetic field (rotating field) which induces a voltage in the rotor (armature) given by

$$U_{02} = B\,l\,v. \tag{5.1}$$

This induction (with the armature circuit closed) causes a current to flow, which in turn results in a magnetic field in the rotor:

$$I_2 = \frac{U_2}{Z_2}. \tag{5.2}$$

This current produces a force of deflection F_2 in the direction of the rotating field.

The magnetic poles of the rotor are repelled by the same poles of the stator rotating field and attracted by the opposite poles. The rotor is thus pulled along by the stator.

When $n_2 = n_1$, there is no change in the flux and therefore no torque.

A slip is therefore required for induction:

$$F_2 = B\,l\,I_2. \tag{5.3}$$

This force F_2 produces a torque, given by

$$M = F_2\,r. \tag{5.4}$$

Motor behavior

Applying a load to the motor, i.e. braking the shaft, increases the relative speed between the stator rotating field and the rotor. The voltage induced in the rotor then becomes greater, so that the current increases and with it the torque (Figure 5.2).

Generator behavior

Driving the rotor externally reaches a speed of rotation at which all losses are mechanically compensated. The value cos φ is then zero. Purely reactive current then flows in the stator winding. When cos $\varphi > 90\,°$, the machine then functions as a generator (Figure 5.2).

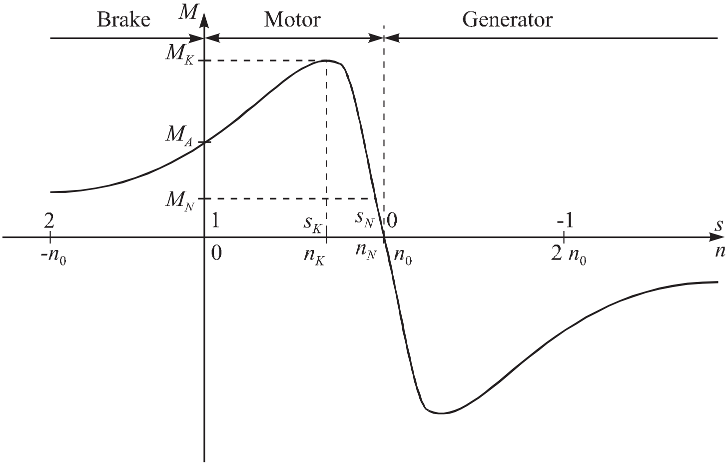


Figure 5.2 Motor and generator operation

5.1.2
Typical Speed-Torque Characteristics

The torque of a motor describes the turning capacity of the rotor. During startup the torque of the motor first drops, but then increases to a maximum value known as the breakdown torque. This is reached at 85–95 % of the full speed of rotation (Figure 5.3).

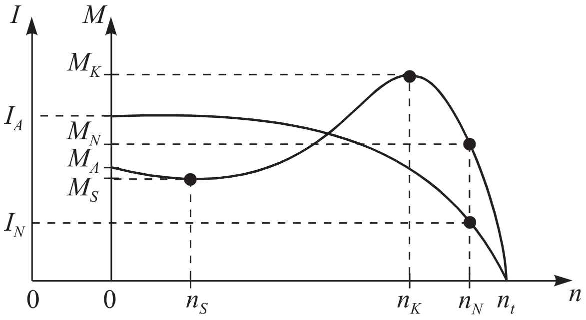


Figure 5.3 Speed-torque characteristics

The meanings of the symbols are:

M_A	The startup torque (accelerating torque, breakaway torque) is the torque supplied by the motor at rest.
M_S	The pull-up torque is the smallest torque supplied during startup. In accordance with IEC Publication 34-1, the pull-up torque for motors with a rated power < 100 kW must not be less than 50% of the rated torque and not less than 50% of the breakaway torque. For a rated power > 100 kW, these figures are 30% and 50%, respectively. For single-phase motors and three-phase motors with several speeds, the figure is 30% of the torque.
M_K	The breakdown torque is the largest torque which the motor can supply. If this value is exceeded, the motor will stall. It is therefore a measure for the overload capacity of the motor. It must be at least 1.6 M_N and must run 15 seconds long without the motor stalling or the speed of rotation suddenly changing.
M_N	The rated torque is the torque supplied by the motor at the rated load and rated speed of rotation.

5.2
Properties Characterizing Asynchronous Motors

5.2.1
Rotor Frequency

Rotor frequency can be given as

$$f_2 = sf_1 \tag{5.5}$$

Here:

f_1	Stator frequency
f_2	Rotor frequency
s	Slip

5.2.2
Torque

The torque of a motor expresses the turning capacity of the rotor. If the power and speed of rotation are known, the torque can be easily calculated. Along the perimeter of a belt pulley a certain belt force is present. The product of the force F and the radius of the of the belt pulley r is the torque of the motor M. The power is the work which the motor performs per unit of time, and the work is the product of the force times the distance. The force F thus rotates through n revolutions during one minute and covers a distance $(n\,2\,p\,r)$. The rated torque is given by the following relationship:

$$M_N = \frac{9550 P_n}{n} \tag{5.6}$$

$$M \geq B\, I_2 \cos\varphi_2 \tag{5.7}$$

$$\cos\varphi = \frac{I_2}{U_2} \tag{5.8}$$

The meanings of the symbols are:

M_N	Rated torque in Nm
P_n	Rated power in W
n	Rated speed in min^{-1}

5.2.3
Slip

The slip is proportional to the load and inversely proportional to the square of the voltage. Figure 5.4 shows the load characteristics. These curves give information about the torque, current draw and startup of a motor. The speed of rotation changes very little during loading and shows the same behavior as for a DC shunt-wound motor.

$$s = \frac{n_1 - n_2}{n_1} \cdot 100\% \tag{5.9}$$

$$n_2 = n_1\,(1 - s) \tag{5.10}$$

$$n_s = n_1 - n_2 \tag{5.11}$$

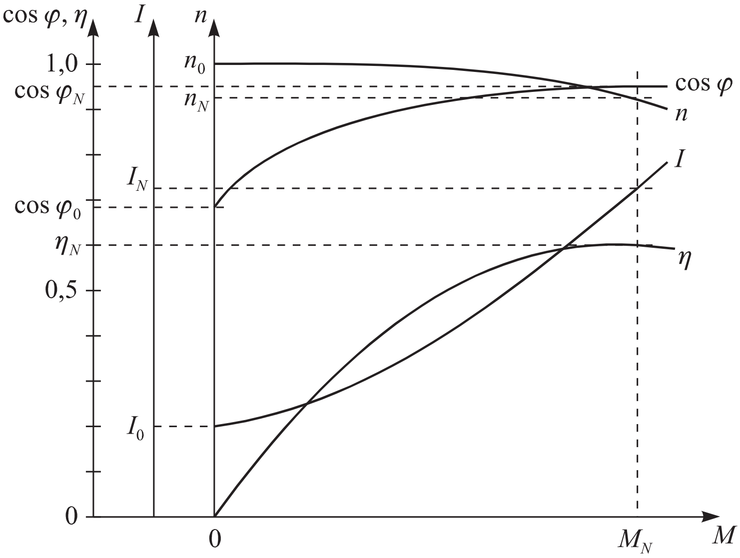


Figure 5.4 Load characteristics

5.2.4
Gear System

With a gear system between the motor and the load, the moment of inertia must be recalculated to the motor speed in order to determine the moment of inertia acting on the motor shaft. Here:

$$J_L(M) = J_L\left(\frac{n_L}{n_M}\right)^2 \qquad \text{5.12)}$$

The load torque characteristic must be recalculated in proportion with the transmission ratio of the gear system and its efficiency. For the load torque:

$$M_L(M) = M_L \cdot \frac{n_L}{n_M} \cdot \frac{1}{\eta} \qquad (5.13)$$

When the flywheel moment is known, the mass moment of inertia is calculated from the following relationship:

$$J_L = \frac{GD^2}{4} \qquad (5.14)$$

The meanings of the symbols are:

M_L	Load torque in Nm
n_M	Motor speed in min^{-1}
n_L	Load speed in min^{-1}
η	Efficiency of gear system

J_L	Mass moment of inertia of load in kg m^2
$M_L(M)$	Load torque relative to motor shaft in Nm
GD^2	Flywheel moment in kg m^2

5.3
Startup of Asynchronous Motors

The manually operated motor starter and contactors are combined with the overcurrent protection equipment. There are several designs for the combination of contactor and overload protection. As motor protection, motor starters are used for the direct switch-on of squirrel cage motors. Reversing switches are used for both directions. Pole changing switches are provided when there is more than one speed of rotation. The star-delta motor starter is the most common motor starter for limiting the breakaway starting current. The overload protection is in series with the stator winding and must therefore be set to the phase current having the value of the rated motor current divided by $\sqrt{3}$. Short circuit protection for motors is provided by fuses. Alternatively, motor starting circuit breakers with thermal and magnetic trip elements provide overload and short circuit protection.

In accordance with the technical conditions for connection, AC motors up to 1.4 kW and three-phase motors up to $I_a < 60$ A or $8\,I_n < 60$ A can be connected directly.

5.3.1
Direct Switch-On

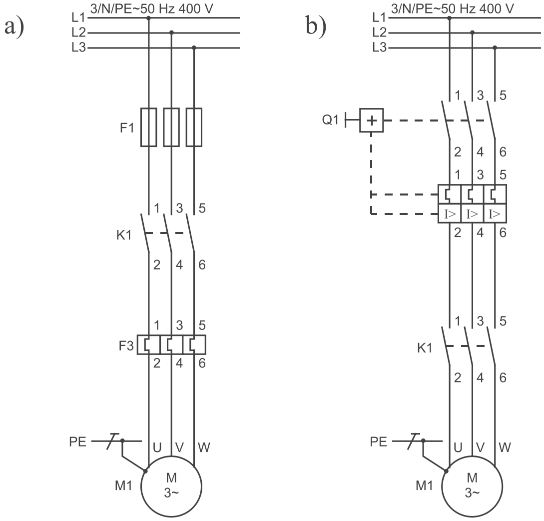


Figure 5.5 Direct switch-on
a) Fuses with motor protective relay, b) Fuseless without motor protective relay

Direct switch-on (Figure 5.5) requires only a single switch and three terminals. In accordance with the technical conditions for connection of the A.C. motors up to 1.4 and three-phase motors up to 4 or with a starting current of 60 can be connected directly. In general, for the starting torque and the starting current:

$$M_A = (1.5 \cdots 2.8)\, M_N \tag{5.15}$$

$$I_A = (4 \cdots 8)\, I_{rM} \tag{5.16}$$

The reversing of the direction of rotation of a three-phase asynchronous motor is shown in Figure 5.6. Operationally ready circuit diagrams and data for reversing starters which are mechanically locked and completely wired, can be taken from the respective manufacturer's information.

For switching three-phase single-winding asynchronous motors, the use of the Dahlander pole-changing switch represents an improvement (Figure 5.7). Pole changing is achieved by switching over and reversing the direction of current in the coil groups. The most important of these circuits are the:

- Delta/star-star for drives with constant torque
  power ratio: $P_1/P_2 = 1:1.4$
- Star-star/delta for drives with constant power
  power ratio: $P_1/P_2 = 1:1$
- Star/star-star for drives with square law torque
  power ratio: $P_1/P_2 = 1:4$ bis 1:8

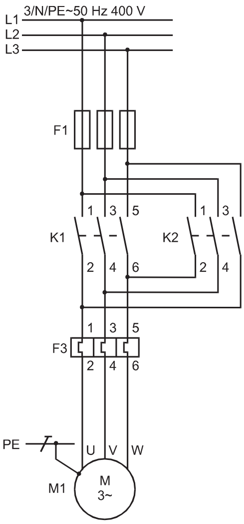


Figure 5.6 Reversing starter

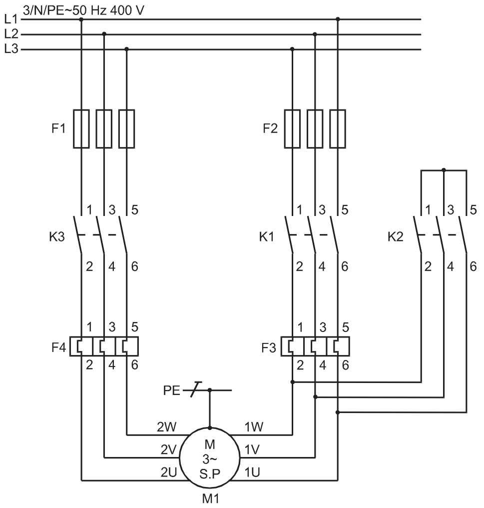


Figure 5.7 Pole changing with a winding, two speeds, one direction of rotation

5.3.2
Star Delta Startup

Figure 5.8 illustrates typical current and torque characteristics and Figure 5.9 depicts the star delta startup.

The stator winding is first connected in star connection to the network. In this way, the breakaway torque and the breakaway starting current only reach one third the value for direct switch-on. Following startup, the motor is switched over to a delta connection. This requires a star delta switch and at least six terminals. In general, for the starting torque and the starting current:

$$M_A = (0.5 \cdots 0.9)\, M_N \tag{5.17}$$

$$I_a = (1.8 \cdots 2.5)\, I_{rM} \tag{5.18}$$

The meanings of the symbols are (Figure 5.8):

M_M	Motor torque
$M_{M\triangle}$	Motor torque for direct switch-on
M_{MY}	Motor torque for star delta startup
M_L	Load torque (counter-torque)
M_{L0}	Load breakaway torque
M_N	Rated torque
M_S	Breakaway torque
M_{min}	Pull-up torque
M_{max}	Breakdown torque

M_{acc}	Accelerating torque
I	Current
I_r	Rated current
$I_{\triangle}$	Current for delta connection
I_Y	Current for star connection
n	Speed
n_S	Synchronous speed

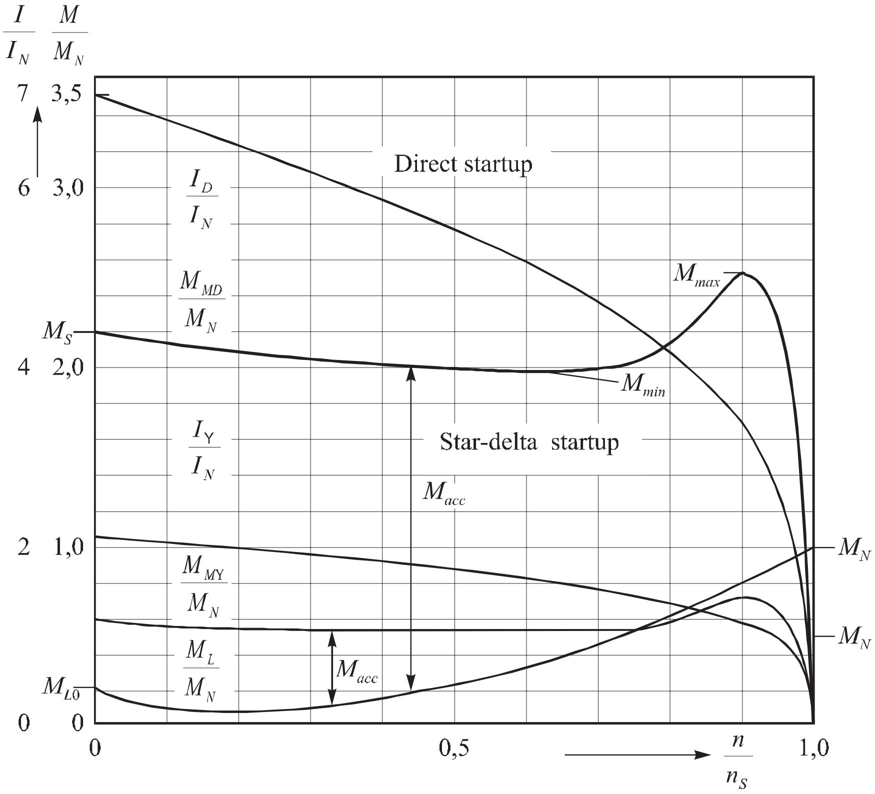


Figure 5.8 Typical current and torque characteristics [11]

In order to prevent short circuits while switching from the star phase to the delta phase during startup with star delta motor starters, a star delta time relay with switchover pause must be used. This ensures that the electric arc has died out when the star contactor opens, before the delta contactor closes.

Current, torque and power conditions for the star delta connection (Figure 5.10)

Starting current:

$$I_{AY} = \frac{1}{3} I_{A\Delta} \tag{5.19}$$

Breakaway torque:

$$M_{AY} = \frac{1}{3} M_{A\Delta} \tag{5.20}$$

Power:

$$P_Y = \frac{1}{3} P_\Delta \tag{5.21}$$

Dimensioning the contactors for startup times up to 10 seconds

The network contactor K1 must be dimensioned for 58 % of the motor power, the star contactor K2 for 33 % of the motor power and the delta contactor K3 for 58 % of the motor power (Figure 5.9).

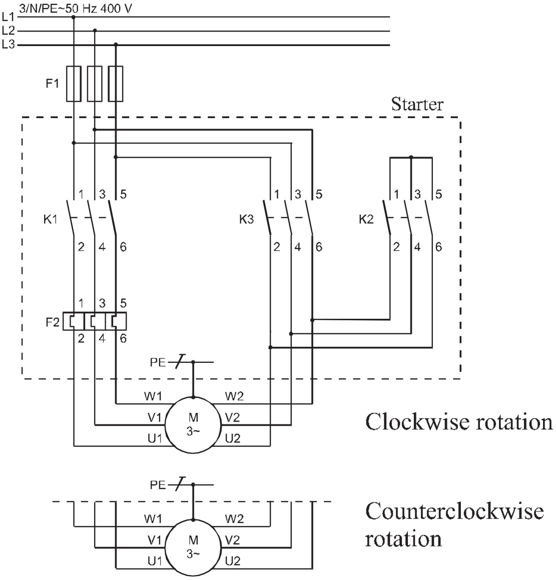
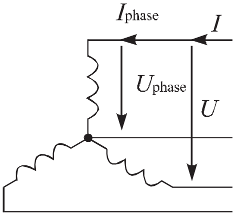
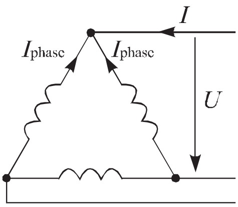


Figure 5.9 Star delta switch with star contactor, delta contactor and network contactor





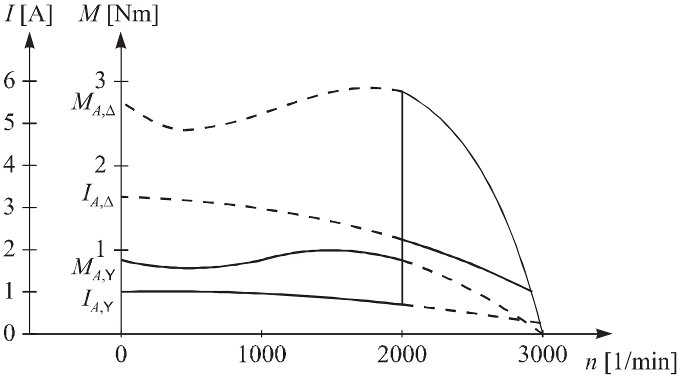


Figure 5.10 Current and torque for star delta startup

The motor protective relay is in series with the terminal leads to the motor terminals and becomes effective in the star connection (Figure 5.11 a). It must be set to 0.58 times the rated current of the motor. The motor protective relay is in the network feeder line (Figure 5.11 b). This circuit does not offer complete protection, since its current is changed to 1.7 times the line-to-line current.

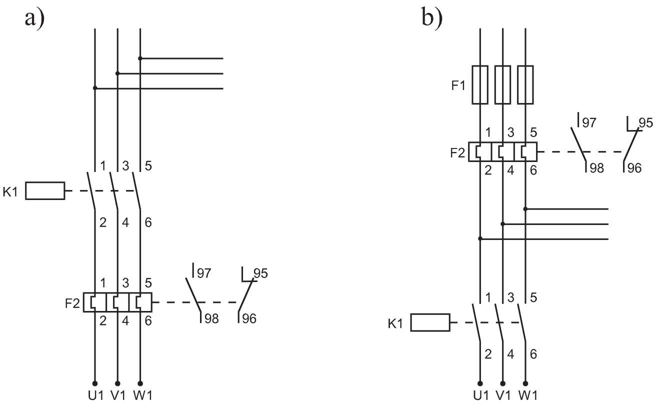


Figure 5.11 Arrangement of the network contactor (a) in the motor line, (b) in the feeder line

The motor protective relay is in the delta star connection. In the star connection, no current flows through the relay. During startup of the motor, no protection is present. This connection is used for high-inertia startup or long-time startup. Figure 5.12 shows the arrangement of the contactors in the delta connection.

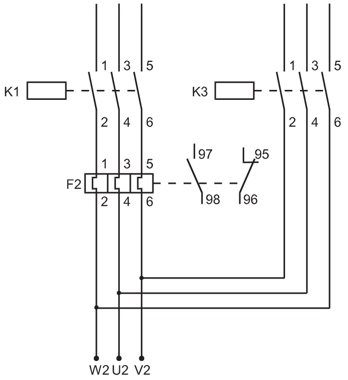


Figure 5.12 Arrangement of the contactors in the delta connection

5.4
Speed Adjustment

Speed control for AS machines is possible by changing the slip, the number of pole pairs and the frequency. Here:

$$n_1 = \frac{60f}{p} \tag{5.22}$$

5.4.1
Speed Control by the Slip

Controlling the slip is possible only with slipring motors. The motor speed depends strongly on the load. An external resistance is connected to the rotor winding. For constant torque, the resistances in the rotor circuit are in the same ratio to the slip speeds. The engaged rotor starter resistance causes a reduction of power and therefore reduces the efficiency.

5.4.2
Speed Control by Frequency

The speed of an AS motor depends on the frequency. In normal three-phase networks the frequency is 50 Hz and in some countries – principally in North America – 60 Hz. Increasing the speed is therefore possible only with the use of a frequency converter.

5.4.3
Speed Control by Pole Changing

There are three possible ways to change the number of poles in squirrel cage motors. The stator can be equipped with either

- two or more separate windings
- a three-phase single winding (enabling pole changing) or
- a combination of both types of winding.

For all three cases, speed control is loss-free. Motors with two speeds and separate windings represent poor utilization of the motor capacity, since for each speed only half of the stator winding is used. Motors with two speeds and a three-phase single winding allow better utilization. The Dahlander pole-changing switch is of particular interest here. The stator winding of the motor is comprised of six coils. Each phase has two winding sections connected in series. The usual Dahlander circuits are discussed below.

- Constant torque: (YY/△)
  The rated torque of the motor is the same for both speeds. The ratio of the rated powers is about 3 : 2. This is obtained by using a winding in double star connection for the higher speed and in delta connection for the lower speed.
- Variable torque: (YY/Y)
  The torque varies with the square of the speed. In practice, one speaks of "falling torque" and "square law torque". The ratio of the speed to the rated powers is about 1 : 5. This is obtained by using a winding in double star connection for the higher speed and in star connection for the lower speed.
- Pole changing contactors
  Pole changing contactors can be used
  - fuseless without motor protective relays with motor starting circuit breakers and separate circuit breakers or
  - with fuses and motor protective relays.

For Y/△ startup (Table 5.1) motors are delta-connected for normal operation. This means that they must always be delta-connected for the operating voltage.

Table 5.1: Comparison of Dahlander circuits

Winding connection for Voltage V	Network voltage V	Direct switch-on	Y/△ – startup
230	230	△	possible
400	400	Y	not possible
400	400	△	possible
690	690	Y	not possible
500	500	△	possible
500	500	Y	not possible
690	690	△	possible

When the motor runs with no load or only with a light load, this reduces the power factor of the feeder network. The motor should then be switched to a star connection.

Connection of pole changing motors

Pole changing motors are normally connected as shown in Figures 5.13 to 5.17. Motors in normal design have six terminal clamps in the terminal box as well as a protective conductor terminal. Motors with two separate windings normally have a △/△ connection, but can also be ordered with a Y/Y, Y/△ or △/Y connection.

Motors with a winding in a Dahlander circuit normally have a △/YY connection if they are intended for drives with constant torque. Fan drives have a Y/YY connection. A circuit diagram is shown for each type of motor.

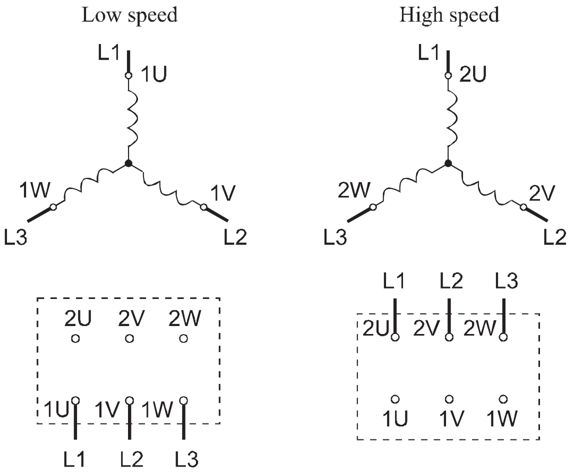


Figure 5.13 Two separate windings Y/Y

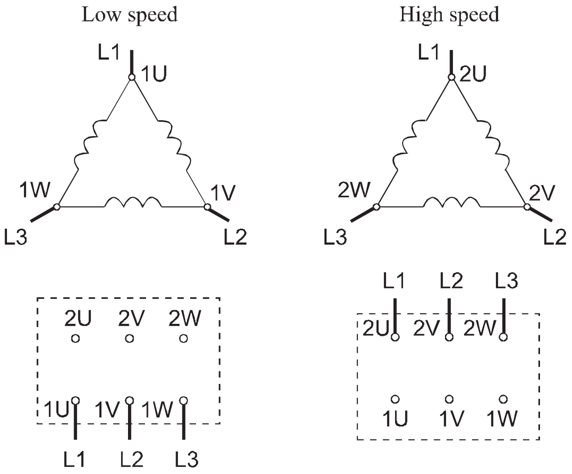


Figure 5.14 Two separate windings △/△

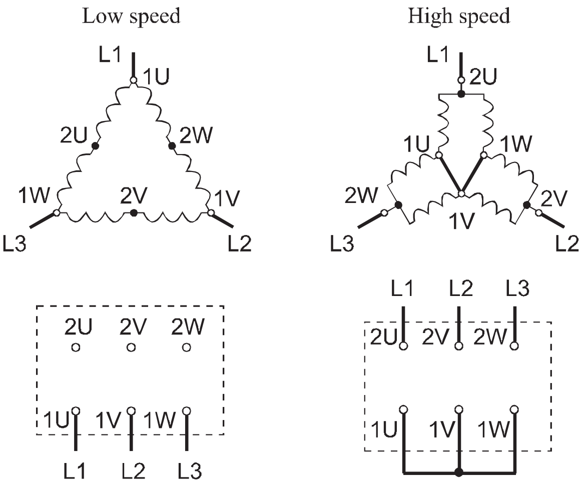


Figure 5.15 Dahlander winding △/YY

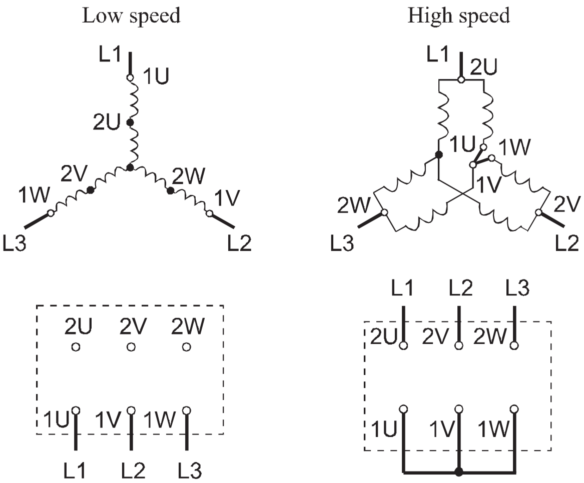


Figure 5.16 Dahlander winding Y/YY

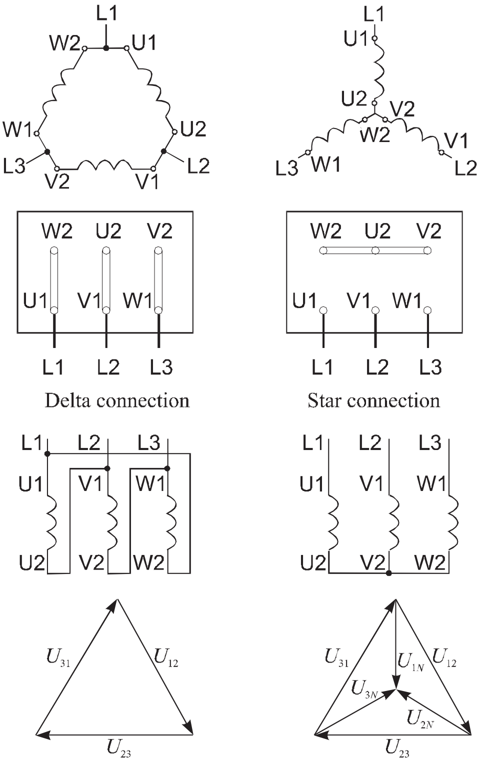
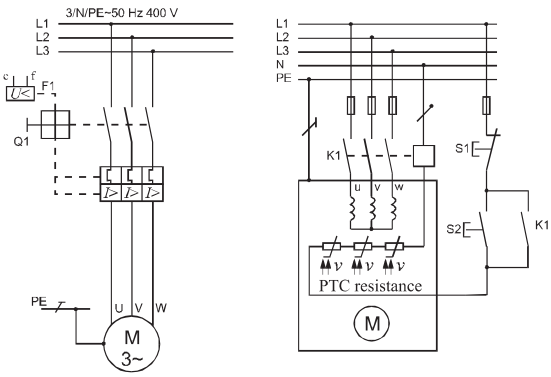


Figure 5.17 Terminal board of a squirrel cage motor

The thermistor protection monitors the temperature of the motor winding (Figure 5.18). The PTC circuit controls an output relay which in turn controls the main contactor. A fault is displayed visually.



a) with circuit breaker b) with fuses

Figure 5.18 Thermistor motor protection [62]

5.4.4
Soft Starters

The asynchronous motor has a high starting torque and a high starting current. In order to avoid these disadvantages different startup procedures are used, as already described. However, fine matching to the particular startup is not possible with all of these. Correct setting of the parameters reduces the load on the motor, resulting in less wear, less downtime and greater operational reliability. With the soft starter to be described briefly in this section, it is possible to set the startup parameters very well [46]. Today, the main circuit of the soft starter is controlled by a semiconductor and not by mechanical switch contacts. Two thyristors in inverse-parallel connection are employed for each phase, so that the current can be switched at any point in time during the positive and negative half-waves. An integrated microprocessor controls the conducting period with the help of the firing angle of the thyristor.

The soft starter permits a gentle startup with a reduced starting current. The starting current depends directly on the required stationary breakaway torque and the mass of the load to be accelerated. In many cases, the soft starter minimizes the energy losses because the motor voltage is continuously monitored and automatically matched to the actual requirement. This is especially true when the motor runs with a light load.

Figure 5.19 represents a comparison between different startup procedures.

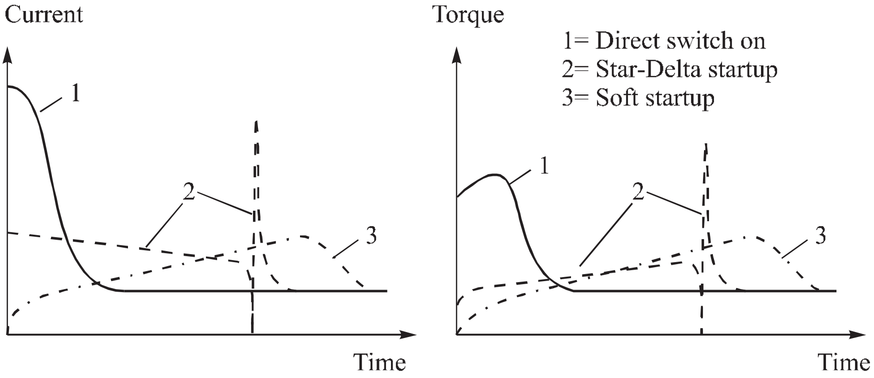


Figure 5.19 Comparison of startup procedures [47]

5.4.5
Motor Operating Modes

S1 Continuous operation

Operation at a constant power level over a period long enough so that thermal equilibrium sets in (Figure 5.20).

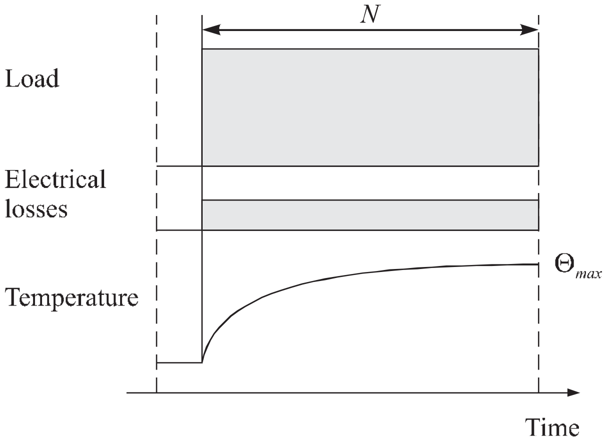


Figure 5.20 Continuous operation [62]

S2 **Short-time operation**

Operation at a constant power level over a period of time which is not sufficient for thermal equilibrium to set in, followed by a pause of duration such that the motor can assume a temperature deviating by no more than 2K from that of the cooling medium (Figure 5.21).

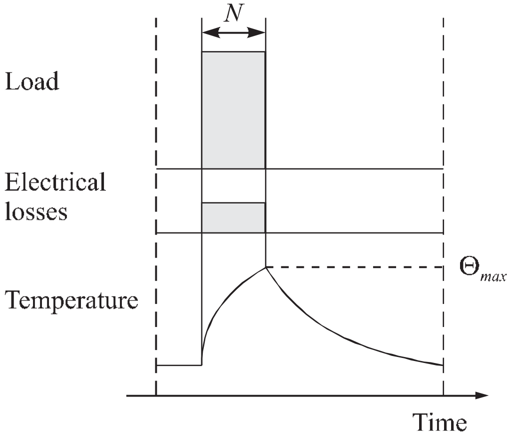


Figure 5.21 Short-time operation [62]

S3 **Intermittent operation**

Operation in a series of similar load cycles, each consisting of a time under constant load and a pause for which the starting current dies not lead to appreciable heating. The load cycle is too short for thermal equilibrium to set in (Figure 5.22).

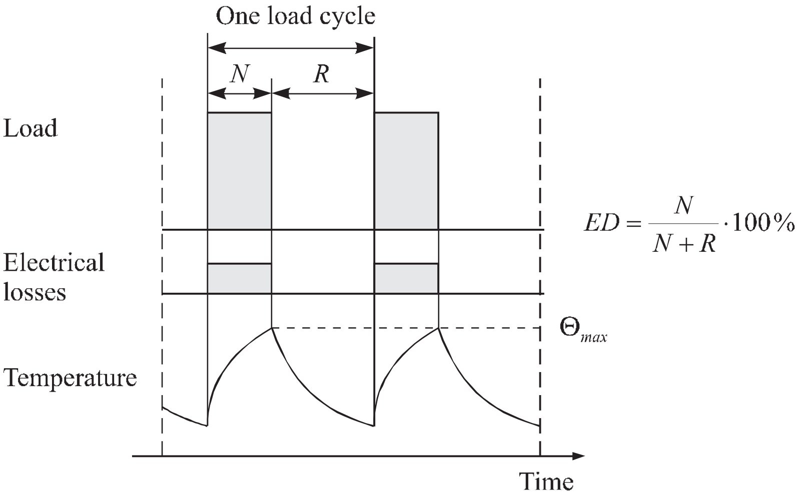


Figure 5.22 Intermittent operation [62]

S4 **Intermittent operation under influence of the startup procedure**

Operation in a series of similar load cycles, each having a startup time the duration of which significantly affects the temperature and consisting of a time under constant load and a pause. The load cycle is too short for thermal equilibrium to set in (Figure 5.23).

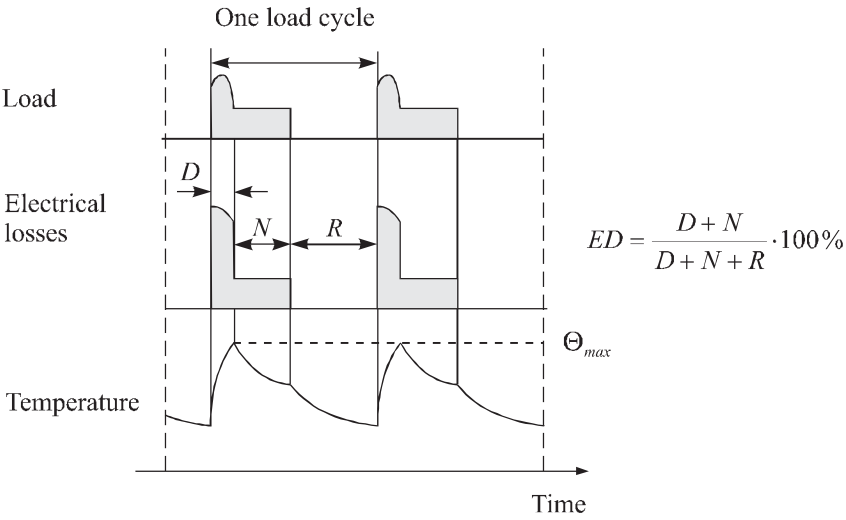
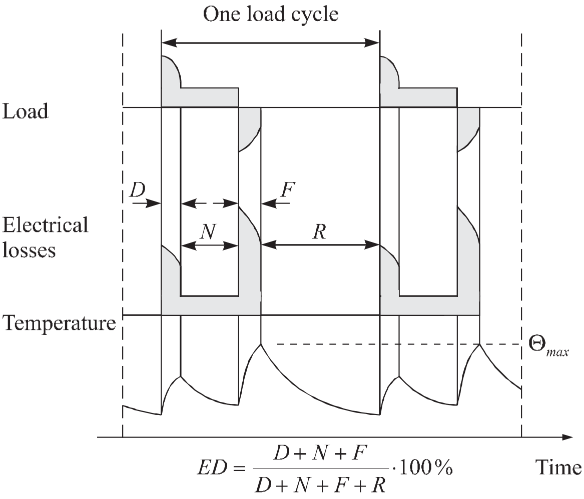


Figure 5.23 Intermittent operation under influence of the startup procedure [62]

S5 Intermittent operation under influence of the startup procedure and braking

Operation in a series of similar load cycles, each consisting of a startup time and a time under constant load, followed by fast electrical braking and a pause. The load cycle is too short for thermal equilibrium to set in (Figure 5.24).

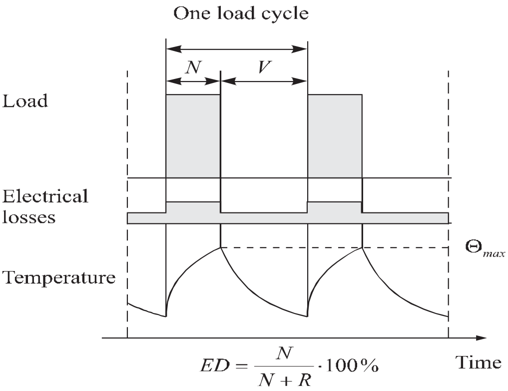


$$ED = \frac{D+N+F}{D+N+F+R} \cdot 100\%$$

Figure 5.24 Intermittent operation under influence of the startup procedure and braking [62]

S6 Uninterrupted periodic operation with intermittent loading

Operation in a series of similar load cycles, each consisting of a time under constant load and a time without load. The load cycle is too short for thermal equilibrium to set in (Figure 5.25).



$$ED = \frac{N}{N+R} \cdot 100\%$$

Figure 5.25 Uninterrupted periodic operation with intermittent loading [62]

S7 Uninterrupted periodic operation with electrical braking

Operation in a series of similar load cycles, each consisting of a startup time, a time under constant load and a time with electrical braking. There is no pause. The load cycle is too short for thermal equilibrium to set in (Figure 5.26).

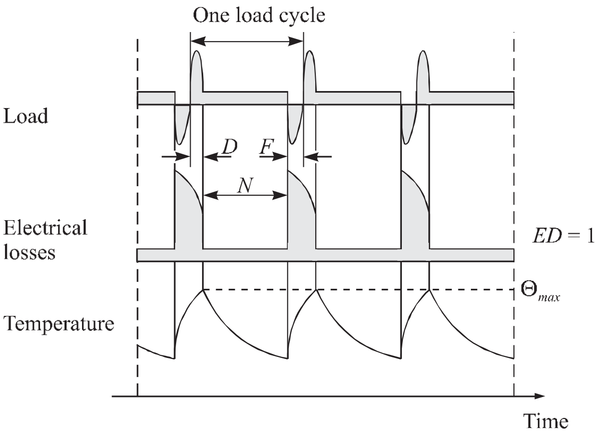


Figure 5.26 Uninterrupted periodic operation with electrical braking [62]

S8 Uninterrupted periodic operation with change of speed

Operation in a series of similar load cycles, each consisting of a time under constant load at a certain speed and then one or more times under a different load, corresponding to different speeds (such as for the operation of a pole-changing asynchronous motor). The load cycle is too short for thermal equilibrium to set in (Figure 5.27).

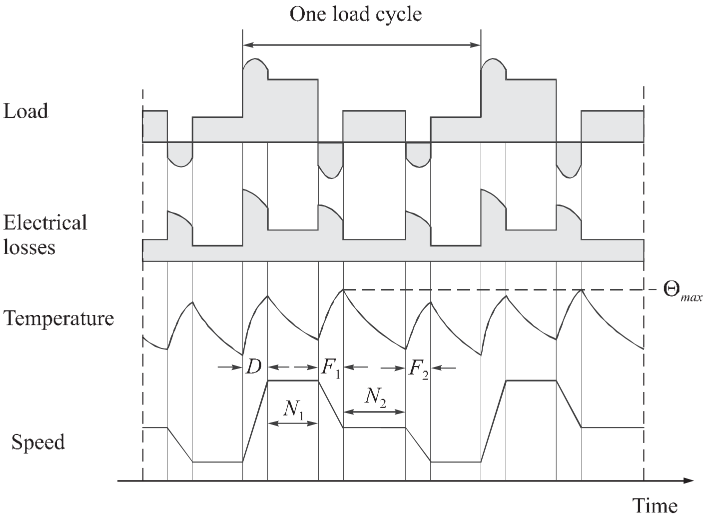


Figure 5.27 Uninterrupted periodic operation with change of speed [62]

S9 **Uninterrupted periodic operation with non-periodic load and speed changes**
Operation in which the load and speed generally change non-periodically within the permissible operating range. In this mode of operation, peak loads frequently occur which can lie well above the rated power. For this mode of operation, an appropriately chosen continuous load must be defined as the reference value for the load cycle (Figure 5.28).

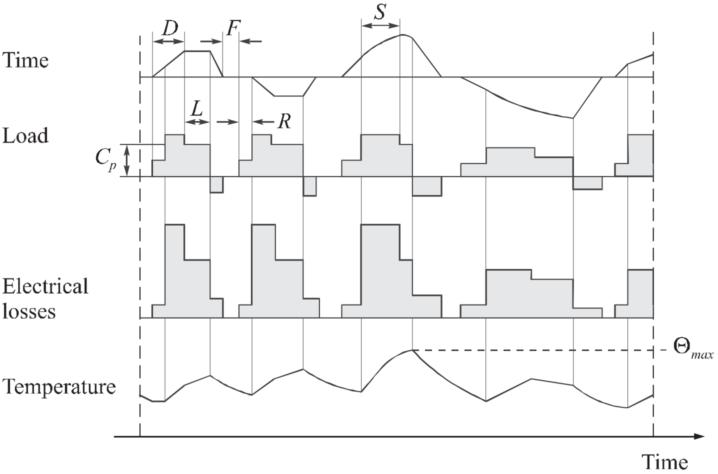


Figure 5.28 Uninterrupted periodic operation with non-periodic load and speed changes [62]

Although there are many standard methods for describing the operating conditions of a motor, the load cycles are often more complicated than as defined. A common method for the determination of the required power dimensioning is the calculation of the effective power from the following equation:

$$P_M^2 = \frac{1}{T}\int_0^T P^2\, \mathrm{d}t \tag{5.23}$$

making use of the load cycle time T, the power P varying over time and the rated power P_M.

The method assumes that the momentary load causes approximately the same thermal stress as the continuous load P_M. Furthermore, it is assumed that the losses vary with the square of the load and that the temperature rise is directly proportional to the total losses. This applies for motors in uninterrupted operation with intermittent loading. If the motor is at rest between the load cycle times, cooling is not as efficient. The above relationship must then be replaced by:

$$P_M^2\left(\sum t_1 + \frac{1}{3}\sum t_k\right) = \sum P_1^2\, t_1 \tag{5.24}$$

based on the load cycle time t_1, the loads P_1 and the rest periods t_k. We will now examine the following two cases:

1. **Change of load during uninterrupted periodic operation** (Figure 5.29)

$$P_M = \sqrt{\frac{P_1^2\, t_1 + P_2^2\, t_2 + P_3^2\, t_3 + P_4^2\, t_4 + P_5^2\, t_5 + P_6^2\, t_6}{t_1 + t_2 + t_3 + t_4 + t_5 + t_6}} \tag{5.25}$$

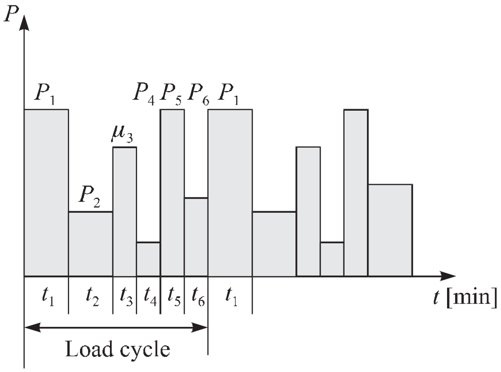


Figure 5.29 Change of load during uninterrupted periodic operation [62]

2. **Change of load and rest period between the load cycles** (Figure 5.30)

$$P_M = \sqrt{\frac{P_1^2\, t_1 + P_3^2\, t_3 + P_5^2\, t_5 + P_6^2\, t_6}{t_1 + t_3 + t_5 + t_6 + \frac{1}{3}(t_2 + t_4 + t_7)}} \tag{31}$$

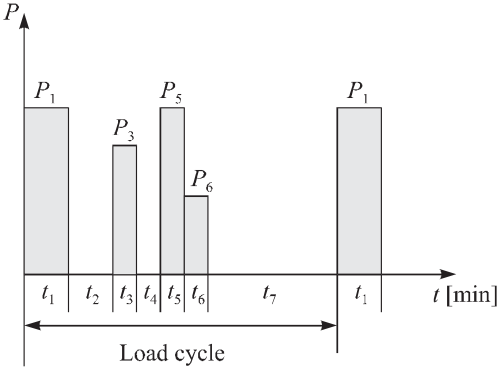
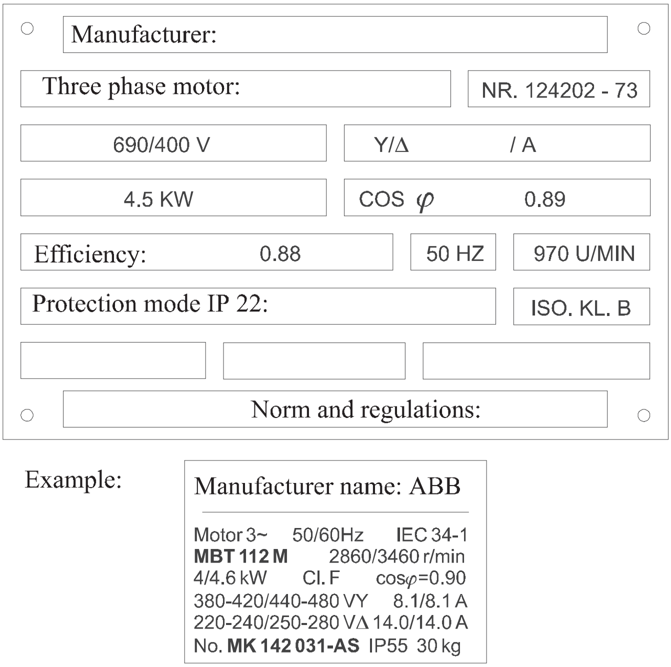


Figure 5.30 Change of load and rest period between the load cycles [62]

The motor nameplate (Figure 5.31) gives all characteristic values of a motor, such as the name of the manufacturer, type designation, production number, rated voltage, rated current, rated power, operating mode, type of protection, insulation class, rated torque and frequency, method of connection, efficiency, power factor, weight of the motor and standards complied with, e.g. VDE and IEC standards. All of these data are required for the planning and use of the motor.



Manufacturer:

Three phase motor:
NR. 124202 - 73

690/400 V
Y/Δ / A

4.5 KW
COS φ 0.89

Efficiency: 0.88
50 HZ
970 U/MIN

Protection mode IP 22:
ISO. KL. B

Norm and regulations:

Example:

Manufacturer name: ABB

Motor 3~ 50/60Hz IEC 34-1
MBT 112 M 2860/3460 r/min
4/4.6 kW Cl. F cosφ=0.90
380-420/440-480 VY 8.1/8.1 A
220-240/250-280 VΔ 14.0/14.0 A
No. **MK 142 031-AS** IP55 30 kg

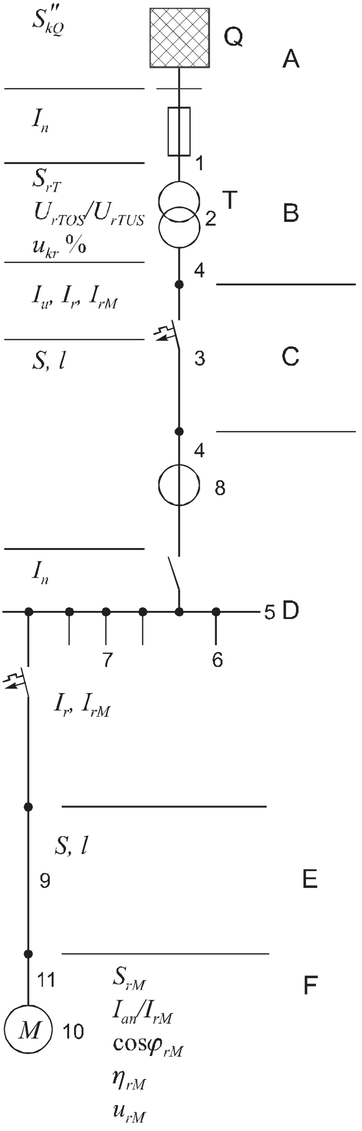
Figure 5.31 Nameplate of a motor [62]

The choice of the right type of protection is a necessary condition for ensuring that a motor can operate under difficult conditions over a long period of time. The type of protection is given, in accordance with IEC Publication 34-5, by the designation IP, followed by two numbers. Table 32 lists important rated motor values for the project planning of asynchronous motors. These values can differ slightly from one manufacturer to another.

Table 5.2: Rated motor values for $U_{rM} = 400\,V$ [11]

Choice of starters and rated motor values					
P_{rM} kW	**I_{rM}**	**Installation-B2 mm^2**	**Current setting (I_e) A**	**Direct startup (I_{rsi}} A**	**Y/△ startup A**
0.18	0.7	1.5	0.6–1.0	6	–
0.25	0.85	1.5	0.6–1.0	6	2
0.37	1.15	1.5	1.0–1.6	6	4
0.55	1.55	1.5	1.6–2.5	10	4
0.75	2	1.5	1.6–2.5	10	6
1.1	2.9	1.5	2.5–4	16	6
1.5	3.7	1.5	2.5–4	16	6
2.2	5.2	2.5	4–6	20	10
3	6.9	2.5	6–9	25	16
4	9	2.5	6–9	35	20
5.5	12	2.5	9–13	35	25
7.5	16	6	13–18	50	32
11	23	6	18–23	63	40
15	30	10	28–42	80	63
18.5	37	10	28–42	80	63
22	44	10	40–52	100	80
30	59	16	52–65	125	100
37	71	16	60–75	160	125
45	86	25	72–100	200	160
55	104	35	72–100	200	200
75	144	50	102–170	250	200
90	172	70	102–170	315	250
110	209	95	126–210	355	315
132	248	120	180–300	400	400
160	300	150	180–300	500	400
200	372	240	240–400	500	500
250	468	2 × 90	378–630	630	630
315	568	2 × 120	378–630	800	800

Figure 5.32 summarizes the most important data for the project planning of three-phase asynchronous motors.



A External network Q, Short circuit power

B Incoming-feeder transformer
  1 rated frequency 50 Hz or 60 Hz
    rated voltage, rated power,
    short circuit voltage
  2 low voltage winding in star or
    delta connection. If star connection:
    Neutral point grounded or free?

C Connection to switch gear
  3 Cable or open line? Length of line or
    open line operating capacitance,
    cable insulation (PE, PVC, Paper)
    type designation of cable
  4 Overvoltage protection provided
    on cable ends, at transformer,
    and on switch gear? Arresters, capacitors

D Switch gear
  5 Switchgear type, Busbar length
    between feed-in and motor switch cells
  6 Other, always connected loads on the busbar,
    Number and length of cables, Cable insulation,
    Type designation of cables
  7 Are there correction capacitors in the system,
    static correction capacitors or filter circuits?
  8 Number of current transformers

E Connection to drive
  9 bus or cable connection? Length of bus/cable,
    Type designation of cable, Operating capacitance,
    Cable insulation

F Drive
  10 Three-phase asynchronous motor, ated voltage,
     rated power, Insulation level (rated insulation level),
     motor type
  11 Overvoltage protection provided?
     (arresters, RC-elements)

Figure 5.32 Required planning data for three-phase asynchronous motors

5.5
Project Planning of Drives

During project planning it is necessary to match the motor to the power requirements and functional behavior of the drive. The correct dimensioning and the correct choice of a motor requires the following data for technically correct installation and use:

$\frac{M_K}{M_N}$	Overload conditions
$\frac{M_A}{M_N}$	Startup conditions
$\frac{I_A}{I_{rM}}$	Starting current conditions
P_{rM}	Rated power
$\cos \varphi_{rM}$	Rated power factor
η_{rM}	Rated efficiency
s	Slip
n	Speed of rotation
	Heating, ambient conditions, height of installation, type of attachment, type of construction and type of protection, control units

5.5.1
Example 1: Calculation With SIKOSTART

In this section we will calculate the torque, current and time characteristic of a motor with the SIKOSTART program [46], included on the CD-ROM accompanying this book (see Section 17.1.1). The motor torque changes with the square of the voltage ($M \sim U^2$) and the motor current linearly with the voltage applied ($I \sim U$). As a result, the acceleration torque and the starting current of the motor can be limited by controlling the effective value of the motor terminal voltage, i.e. only the voltage must be changed. Following startup, the thyristors are driven without phase control. The following values serve as the basis for calculation:

- the total moment of inertia of the drive
- the acceleration torque as the difference between the motor torque and the load torque.

To carry out the calculation for a motor, we first enter the required data.

1 Entering the motor data

Motor type	Waste water pump
Rotor class	16
Rated power	18.5 kW
Moment of inertia	0.1300 kg/m^2
Rated speed	1460 rpm

	Rated current	35 A
	Rated torque	121 Nm
2	Entering the load data	
	Type of load	Pump
	Required power	15 kW
	or load torque	0 Nm
	Speed	1460 rpm
	Mass moment of inertia	0.25 kg/m^2
	Torque characteristic	square law
3	Entering the starting parameters	
	Breakaway pulse	ON
	Breakaway pulse voltage	80 %
	Breakaway pulse time	0 ms
	Start ramp startup voltage	35 %
	Start ramp ramping time	3 second
	Limiting current	6535 A
	Limiting voltage	70%
	Limiting time	1 second
4	Calculation	
	Motor type	Waste water pump
	Breakaway pulse voltage	80 %
	Direct startup time	0.28 seconds
	Startup time with SIKOSTART	1.6 seconds
	Starting current	83 A
	Max. starting current	91 A

Table 5.3: Planning data

Motor data (direct startup)				**Load data**	
n	**M/M_N**	**n rpm**	**I/I_N**	**n_L rpm**	**M/M_L**
0	2.3	0	7	0	0.06
116	2.27	750	6	133	0.01
300	2.32	1050	5.09	265	0.04
570	2.5	1172	4.45	398	0.07
1050	2.94	1293	6.3	664	0.21
1200	2.97	1500	0.41	797	0.30
1394	2.11			1062	0.53
1460	1.0			1327	0.83
1500	0			1460	1.00

Results of the calculation

- Torque behavior (Figure 5.33) as a function of motor speed for direct startup and for starting with the startup parameters above, along with load.
- Current behavior (Figure 5.34) as a function of motor speed for direct startup and for starting with the startup parameters above.
- Time behavior (Figure 5.35) of motor terminal voltage, motor current and motor speed at startup with the startup parameters above.

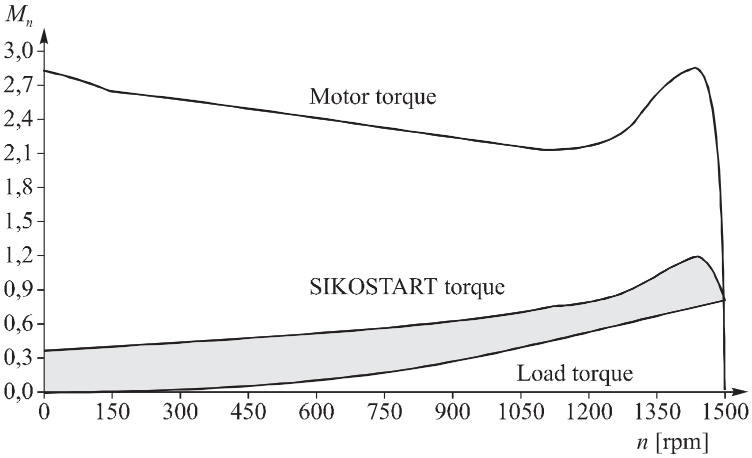


Figure 5.33 Torque behavior as a function of motor speed

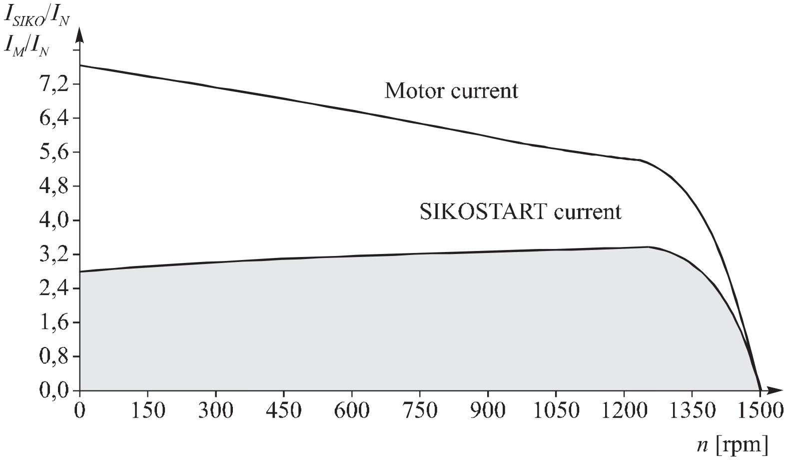


Figure 5.34 Current behavior as a function of time

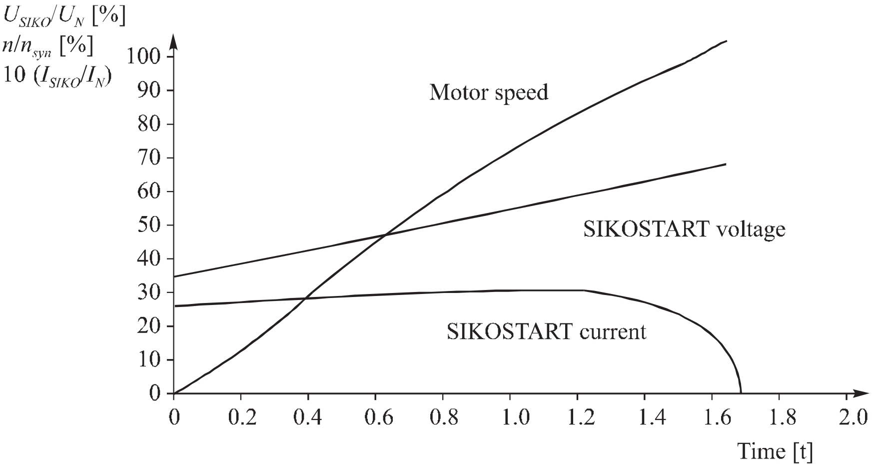


Figure 5.35 Time behavior of motor speed, terminal voltage and current with SIKOSTART

5.5.2
Example 2: Calculation of Overload and Starting Conditions

Given the following motor data:

P_{rM}	18.5 kW
U_{rM}	400 V
n	1460 min^{-1}
I_{rM}	35 A
M_A/M_N	2.5
I_a/I_{rM}	6
M_K/M_N	2.9

calculate all rated motor values for the star delta connection.

In the delta connection:

$$M_A = 2.5\,M_N$$

In the star connection:

$$M_A = \frac{2.5}{3}\,M_N = 0.83\,M_N$$

In the delta connection:

$$I_{a\Delta} = 6\,I_{rM} = 6 \cdot 35\text{A} = 210\text{A}$$

In the star connection:

$$I_{aY} = \frac{1}{3}\, I_{a\Delta} = \frac{1}{3} \cdot 210\text{A} = 70\text{A}$$

$$M_N = \frac{P_{rM}}{2\,\pi\, n_N} = \frac{18.5 \cdot 10^3 / \text{s} \cdot 60\ \text{s}/\text{min}}{2\,\pi \cdot 1460\,\text{min}^{-1}} = 121\text{Nm} \tag{5.27}$$

$$M_A = 2.5\, M_N = 2.5 \cdot 121 = 302.5\text{Nm} \tag{5.28}$$

$$M_K = 2.9\, M_N = 2.9 \cdot 121 = 350.9\text{Nm} \tag{5.29}$$

5.5.3
Example 3: Calculation of Motor Data

A three-phase asynchronous motor has the following rated values:
$P_{rM} = 400$ kW, $U_{rM} = 400$ V, 50 Hz, $I_{rM} = 750$ A, cos $\varphi = 0.86$, $n = 1448$ rpm, 4-pin

a) Calculate the slip s for the given rated motor speed.
b) Calculate the frequency of the rotor voltage f_L.
c) Calculate the efficiency η!

$$s = \left(1 - \frac{n}{n_s}\right) \cdot 100\,\% = \left(1 - \frac{1448}{1500}\right) \cdot 100\,\% = 3.46\% \tag{5.30}$$

$$f_L = \frac{f \cdot s}{100\,\%} = \frac{50\ \text{Hz} \cdot 3.46\,\%}{100\,\%} = 1.73 \tag{5.31}$$

$$P_1 = \sqrt{3}\, U_{rM}\, I_{rM} \cos\varphi \tag{5.32}$$

$$P_1 = \sqrt{3} \cdot 400\,\text{V} \cdot 750\,\text{A} \cdot 0.86 = 446.87\,\text{kW} \tag{5.33}$$

$$\eta = \frac{P_2}{P_1} = 400\ \frac{\text{kW}}{446.87\,\text{kW}} = 0.896 \tag{5.34}$$

5.5.4
Example 4: Calculation of the Belt Pulley Diameter and Motor Power

A three-phase motor is supposed to drive a circular saw blade with 550 mm diameter and a cutting speed of 36 m/s. The belt pulley on the saw blade has a diameter of 130 mm. The belt slip is 2.8%.

a) What diameter must the belt pulley on the motor have if its speed of rotation is 995 rpm?
b) How much power must the motor supply if a force of 340 N is required on the motor belt pulley?

Solution to a:

$$v_2 = \pi\, d\, n_2 \tag{5.35}$$

$$n_2 = \frac{v_2}{\pi\, d} = \frac{36\,\frac{\text{m}}{\text{s}}}{\pi \cdot 0.55\,\text{m}} = 20.84\,\frac{1}{\text{s}} \tag{5.36}$$

$$n_2 = 20.84\,\frac{1}{\text{s}} \cdot 60\,\frac{\text{s}}{\text{min}} = 1250.4\,\frac{1}{\text{min}} \tag{5.37}$$

with $n_1\, d_1 = n_2\, d_2$

$$d_1 = \frac{n_2\, d_2}{n_1} = \frac{1250.4\,\frac{1}{\text{min}} \cdot 130\text{mm}}{955\,\frac{1}{\text{min}}} = 170.21\,\text{mm} \tag{5.38}$$

Solution to b:

$$v = \pi\, d_1\, n_1 = \frac{\pi \cdot 170.21\,\text{mm} \cdot 955\,\frac{1}{\text{min}}}{60\,\frac{\text{s}}{\text{min}}} = 8.51\,\frac{\text{m}}{\text{s}} \tag{5.39}$$

$$P = F\, v_1 = 340\,\text{N} \cdot 8.51\,\frac{\text{m}}{\text{s}} = 2894\,\frac{\text{Nm}}{\text{s}} = 2.984\,\text{kW} \tag{5.40}$$

5.5.5
Example 5: Dimensioning of a Motor

A pump with a power of 19 kW, cos $\varphi = 0.8$ is supposed to run five times per hour operating for 60 seconds with a short-term load of 72 seconds. The ambient temperature is 50 °C; installation type C; $I_{an}/I_{rM} = 7$, loop resistance up to distribution 0.3 Ω; $l = 10$ m.

Determine the:

a) Current carrying capacity
b) Backup fuse
c) Voltage drop
d) Short circuit current
e) Current setting
f) Permissible break time

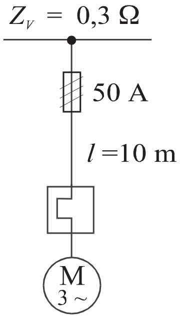


Figure 5.36 Calculation for a motor with operating modes

a) **Current carrying capacity**

For the load factor n:

$$n = \sqrt{\frac{1}{1-e^{-t_e/T}}}\ \text{, where } t_e = 60\,\mathrm{s}\,,\ T = 72\,\mathrm{s} \tag{5.41}$$

$$n = \sqrt{\frac{1}{1-e^{t_e/T}}} = \sqrt{\frac{1}{1-e^{60/72}}} = \sqrt{\frac{1}{1-\frac{1}{e^{0.833}}}} \tag{5.42}$$

$$n = \sqrt{\frac{1}{1-\frac{1}{2.3}}} = \sqrt{\frac{1}{1-0.434}} = 1.33 \tag{5.43}$$

The cross-section of the insulated lines depends on the minimum time value. For 72 seconds, a line of 4×4 mm^2 is chosen. The new current carrying capacity of the line is then:

$$I'_Z = n\, I_Z \tag{5.44}$$

$$I_Z = 34\mathrm{A} \tag{5.45}$$

$$I'_Z = 1.33 \cdot I_Z = 1.33 \cdot 34\mathrm{A} = 45.2\mathrm{A} \tag{5.46}$$

$$I_B = \frac{P}{\sqrt{3}\, U \cos\varphi} = \frac{19\,\mathrm{kW}}{\sqrt{3}\cdot 400\,\mathrm{V}\cdot 0.8} = 34.3\,\mathrm{A} \tag{5.47}$$

b) **Backup fuse:**

A 50 A fuse (gL) will provide sufficient short circuit protection.

c) **Voltage drop:**

$$\Delta U = \frac{\sqrt{3}\cdot I\, l\cdot 1.12\cos\varphi}{\kappa\, S} = \frac{\sqrt{3}\cdot 34.3\,\mathrm{A}\cdot 10\,\mathrm{m}\cdot 1.12\cdot 0.8}{56\frac{\mathrm{m}}{\Omega\,\mathrm{mm}^2}\cdot 4\,\mathrm{mm}^2} = 2.37\,\mathrm{V} \mathrel{\widehat{=}} 0.6\,\% \tag{5.48}$$

d) **Short circuit current:**

$$R_L = \frac{1.24 \cdot 2\, l}{\kappa\, S} = \frac{1.24 \cdot 2 \cdot 10\,\mathrm{m}}{56 \frac{\mathrm{m}}{\Omega \mathrm{mm}^2} \cdot 4\,\mathrm{mm}^2} = 0.11\,\Omega \tag{5.49}$$

$$Z_S = 0.3\,\Omega + 0.11\,\Omega = 0.41\,\Omega \tag{5.50}$$

$$I''_{k1} = \frac{c\, U_n}{\sqrt{3}\, Z_k} = \frac{0.95 \cdot 400}{\sqrt{3} \cdot 0.41\,\Omega} = 535.1\,\mathrm{A} \tag{5.51}$$

e) **Current setting:**

The motor protecting switch is set to the rated current of 34.3 A.

f) **Permissible break time:**

$$t_{zul} = \left(k\, \frac{S}{I''_{k1}}\right)^2 = \left(115\, \frac{A\,\sqrt{\mathrm{s}}}{\mathrm{mm}^2} \cdot \frac{4\,\mathrm{mm}^2}{535.1\,\mathrm{A}}\right)^2 = 0.74\,\mathrm{s} \tag{5.52}$$

6
Emergency Generators

Emergency generators (Figure 6.1) are used in order to provide consumers in the system entitled to standby service in the event of breakdown or shutdown of the normal power supply. They consist of the generator, the flywheel and the motor.

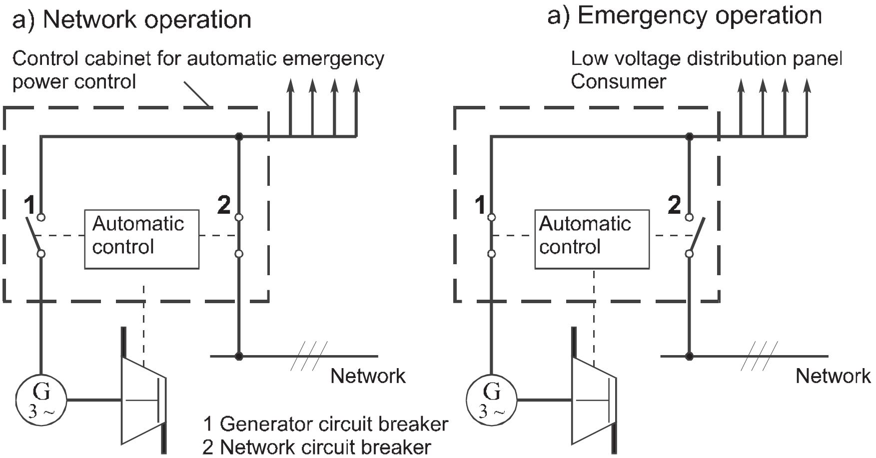


Figure 6.1 Schematic of circuit for standby generators

For the dimensioning of the generator power to supply a large number of consumers, the connected load with the coincidence factor must be taken as the basis. This connected load should be about 60 % of the rated load for the standby generator. The prime mover must be designed for the effective power and the generator for the apparent power. The feed-in of the network to the automatic standby power control takes place through the secondary distribution, to which other consumers are also connected. The functional and operational reliability of standby generators is ensured only when the planning takes account of all requirements for channeling air intake and exhaust air, room ventilation, sound attenuation and fuel supply. The main components are:

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- Generator
- Battery system
- Emergency standby control
- Fuel system
- Exhaust system with sound attenuation
- Fans for room ventilation
- Air intake and exhaust ducts

The starting power (Figure 6.2) and the correction factor (Figure 6.3) for consumers with a high starting power, taking into account the still permissible voltage dip, are calculated as follows and an additional 20 % reserve is planned to cover future energy requirements.

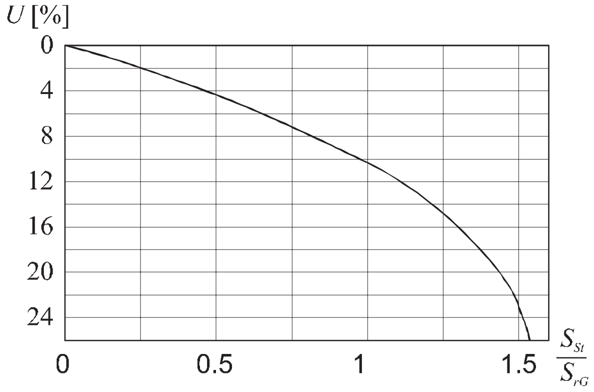

Figure 6.2 Starting power/rated standby generator power [42]

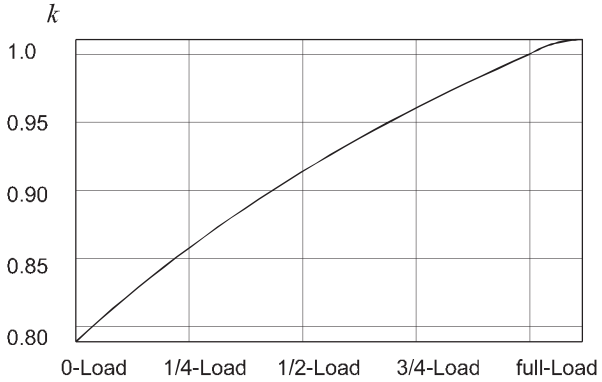

Figure 6.3 Correction factor k [42]

The starting power:

$$S_{st} = 1.3\, P\, \frac{I_A}{I_n}\, k \tag{6.1}$$

Generator power:

$$S_{rG} = \frac{P_{rM}\, \eta_{rG}}{\cos\varphi} \tag{6.2}$$

Motor drive power:

$$P_{rM} = \frac{S_{rG}\, \cos\varphi}{\eta_{rG}} \tag{6.3}$$

The meanings of the symbols are:

I_A	Starting current in A
S_{st}	Consumer starting power in kVA
I_n	Rated current in A
k	Correction factor for operating conditions
P	Effective power in kW
P_{rM}	Motor drive power in kW
S_{rG}	Generator power in kVA
$\cos\varphi$	Power factor

6.1
Generator-Specific Limiting Operational Values

- Range of application 1, Communal facilities After a switching time of maximum 15 seconds, 100% of the consumer power for the required safety equipment must be supplied (Table 6.1).

Table 6.1: Electrical installations in hospitals and communal facilities

Characteristic parameter	Communal facilities	in hospitals
Static frequency deviation	5 %	4 %
Dynamic frequency deviation	± 10 %}	± 10 %
Frequency adjustment time	5 s	5 s
Static voltage deviation	± 2.5 %	± 1 %
Dynamic voltage deviation	+20 %; –20 %	± 10 %
Voltage adjustment time	4 s	4 s
Steady state short circuit current	3 I_n (3 s)	3 I_n (3 s)
Total harmonic distortion of voltage	3 ~ < 5 %	3 ~ and 1 ~ < 5 %

- Range of application 1, Electrical installations in hospitals After a switching time of maximum 15 seconds, 80 % of the consumer power (consumers of the required safety equipment and operationally important consumers) in a maximum of two steps and after a further 5 seconds 100 % of the total consumer power must be supplied (Table 6.1). For inductive consumers the large starting current must also be considered (Table 6.2).

Table 6.2: Standard values for starting currents

Startup procedure	I_A/I_{rM}
Direct startup	4 ... 6
Squirrel cage rotor via star delta	2 ... 3
Squirrel cage rotor via frequency converter	1.5 ... 3
Squirrel cage rotor via phase control	2 ... 4

- Type classes 2 and 3 Connecting and disconnecting loads takes place in accordance with the regulations.

Table 6.3: Type class 2 and 3

Characteristic parameter	Class 2	Class 3
Static frequency deviation	5 %	3 %
Dynamic frequency deviation	± 10 %	± 7 %
Frequency adjustment time	5 s	3 s
Static voltage deviation	± 1 %	1 %
Dynamic voltage deviation	+ 22 %; –18 %	+ 20 %; –15 %
Voltage adjustment time	6 s	4 s
Steady state short circuit current	3 I_n (3 s)	3 I_n (3 s)
Total harmonic distortion of voltage	3 ~ < 5 %	3 ~ < 5 %

6.2
Planning a Standby Generator

The following features must be considered during the planning of standby generators:

1. Characteristic parameters of the network, such as type and number of active conductors of the feed-in, type of ground connections (mostly TN-S systems)
2. Determination of the power requirements with the coincidence factor
3. Expected three-pole and single-pole short circuit currents at the feed-in point
4. Distribution of phase loads for the operational equipment of the electrical system
5. Switching between network and standby power with mutual mechanical or electrical locking
6. Connection of the standby generator to the existing network takes place up to 125 A through a 5-pin CEE plug-and-socket device with H07RN-F line.
7. System ground can be in the form of a concrete footing electrode, ring conductor or buried grounding electrode.

6.3
Example: Calculation of Standby Generator Power

The following data are known for a three-phase motor:

Speed	1480 rpm
Rated power	22 kW
Rated current	42 A
Power factor	$\cos \varphi = 0.88$
Starting current	direct: factor 5.5
Starting current	star-delta: factor 2.3
Voltage dip	15 % in accordance with communal facility regulations

For the correction factor k, from Figure 6.3 we find a value of 0.97. Starting power with direct startup:

$$S_{st} = 1.3\,P\,\frac{I_A}{I_{rG}}\,k = 1.3 \cdot 22\,\text{kW} \cdot 5.5 \cdot 0.97 = 152.6\,\text{kVA}$$

Starting power with star delta connection:

$$S_{st} = 1.3\,P\,\frac{I_A}{I_{rG}}\,k = 1.3 \cdot 22\,\text{kW} \cdot 2.3 \cdot 0.97 = 63.8\,\text{kVA}$$

For 15 % voltage dip, from Figure 6.2 we find a factor of 1.25. The required standby power for the delta connection is:

$$S_{rG} = \frac{S_{st}}{x} = \frac{152.6\,\text{kVA}}{1.25} = 122\,\text{kVA}$$

and for the Y/Δ connection:

$$S_{rG} = \frac{S_{st}}{x} = \frac{63.8\,\text{kVA}}{1.25} = 51\,\text{kVA}$$

7
Equipment for Overcurrent Protection

This section will discuss all types of protection equipment, switching devices and interconnecting devices in low-voltage systems, including fuses, which in contrast to switching devices function only once and then melt in the event of a fault.

7.1
Electric Arc

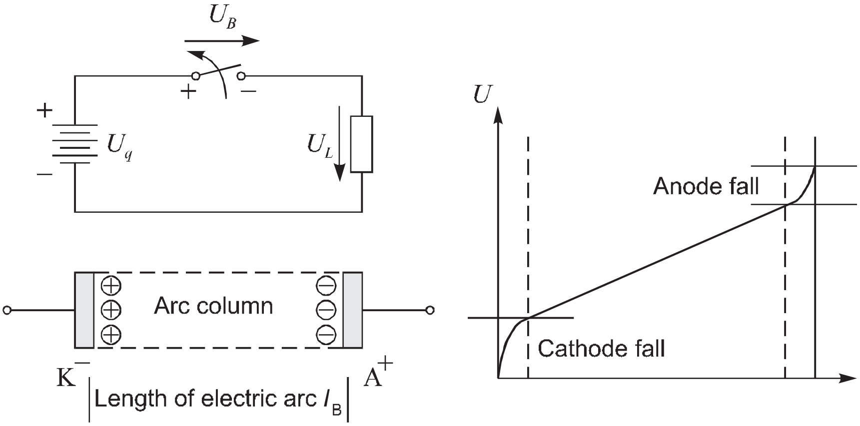

Figure 7.1 Origin of the electric arc

When the contacts of a current-conducting switch (Figure 7.1) are opened, the pronounced heating at the base points of the current with a large contact resistance results in an electric arc, which the voltage at the contacts then maintains. The electrons emitted from the hot cathode are accelerated by the electrical field and thus transported to the anode. At a high enough velocity, collisions occur between atoms and electrons, ionizing the atoms. The ions drift slowly to the cathode and the electrons quickly to the anode. An ion cloud forms in front of the cathode. The same process occurs in front of the anode, only in this case with electrons. Between these is the electric arc, consisting of a neutral plasma of ions and electrons. Positive ions

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ISBN: 3-527-30483-5

and the negative cathode form the cathode fall, with field strengths up to 10^5 V/cm, which are required to attract the electrons from the cathode and accelerate them. The cathode spot forms on the cathode. For low-voltage switching devices the cathode fall is the main feature, whereas high-voltage switching devices function with a cooled electric arc. A multiple of the cathode fall is obtained by dividing the arc gap into partial gaps, either by double-break contacts or through plates. The cooling is achieved by extending the arc (thermally or magnetically), blowing with air or gases, heat dissipation or with oil or water.

7.1.1
Electric Arc Characteristic

If an electric arc is formed in series in a circuit with a resistance (Figure 7.2), a falling characteristic results since with increasing current the ionization process is enhanced. The resistance is necessary to limit the current. There are two operating points, P1 and P2, such that P1 is stable and P2 labile. If the current of the arc burning at point P1 increases for any reason (e.g. poorer cooling), a negative induced voltage results which reduces the current at the point P1. In other words, the increasing current requires a voltage which exceeds the load line, i.e. the resistance of the arc must increase. If, on the other hand, the current decreases, again starting with point P1, or the voltage on the load lines increases and thus lowers the resistance, increasing the current. It is obvious that the conditions for point P2 are exactly the opposite, so that this point is labile.

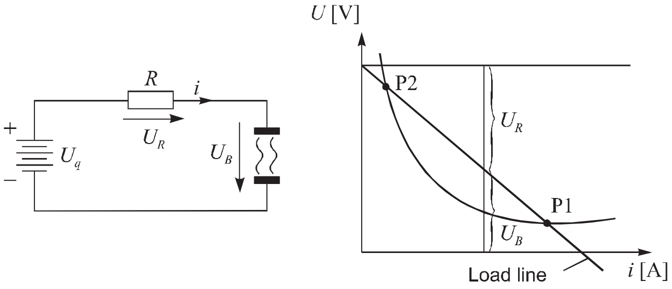


Figure 7.2 Electric arc characteristic

For systems engineering, there are then the following quenching possibilities:

1. Constant arc and changing resistance
2. Constant resistance in the circuit and changing arc, until the critical point is exceeded

For the DC arc, as expressed by the static characteristic, the energy is balanced and the energy supplied from the current and voltage compensates for the losses. For the AC current, on the other hand, the power supply – as a result of the driving voltage – must then cause a change in temperature and thus in the energy content and the losses. This gives rise to the dynamic characteristic (Figure 7.3). A change in the energy content results in a change in the power. With increasing current, the arc requires additional power for the temperature rise, whereas with decreasing current the losses can be compensated from the heat content of the arc. This means that for an increasing current the voltage must be greater than for a decreasing current, leading to the development of arc hysteresis. At higher frequencies, a straight line will result because the temperature is not able to follow the fast changes.

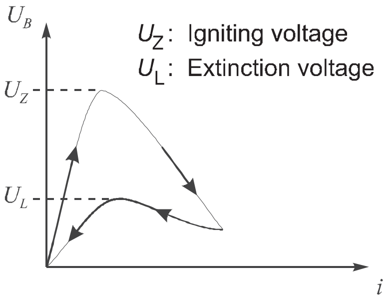


Figure 7.3 Dynamic characteristic

7.1.2
DC Cut-Off

The voltage and current of the electric arc will adjust themselves according to the static characteristic (Figure 7.4). If the cooling effect increases over time, the current then falls and the voltage rises. The switch must be able to withstand the temperature sufficiently to execute the cut-off cycle. DC switches present problems. It must also not be forgotten that the arc must be present in order to dissipate the energy stored in the inductivities. In order that no overvoltages arise, the value of $\mathrm{d}i/\mathrm{d}t$ must not be too great. So-called high-speed circuit breakers attain cut-off times of about 4 ms. The arc gradient is about 200 V/cm, so that DC high-voltage switches are generally not possible. The switches themselves function with thermal cooling and magnetic blowout.

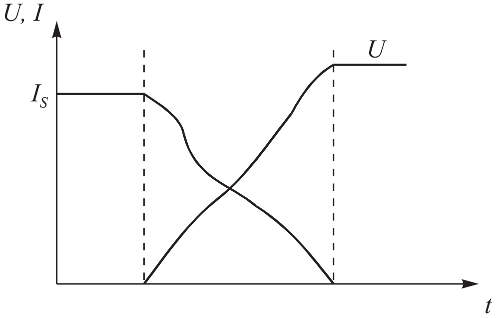


Figure 7.4 DC cut-off

7.1.3
AC Cut-Off

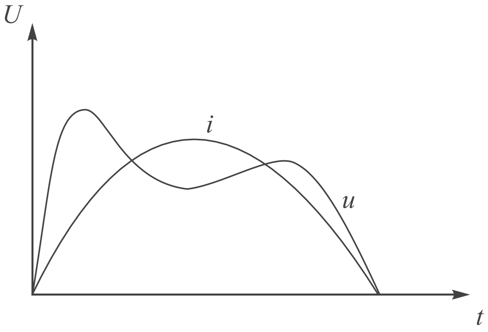


Figure 7.5 AC cut-off

For AC cut-off we must deal with the dynamic arc, i.e. the arc voltage is greater for increasing current than for falling current (Figure 7.5). After the zero current crossing there must be short pause without current until the voltage is attained which is required to re-ignite the arc. For phase-shifted values, however, during the zero current crossing the recovery voltage is immediately present with its corresponding instantaneous value. However, it cannot increase to this value in an infinitesimally short time, because as a result of the capacitances and inductances always present a transient process takes place. We will first discuss all AC circuit breakers without considering the transient process in order not to complicate matters. The voltage present at the contacts leads to a slight, hardly measurable post-arc current, comprised of the residual charge carriers of the electric arc which are only newly accelerated. This post-arc current is about 1/1000 of the short circuit current. It flows about 0.1 ms. Thus, with AC breakers two processes always take place:

1. The arc is cooled and the current therefore reduced. Finally, the charge carriers recombine and the remainder is taken up by the contacts. During the zero current crossing, the current extinguishes.
2. The recovery voltage loads the contact path and also causes a slight post-arc current.

Assuming the switch can withstand both stresses, the arc is then successfully extinguished.

Cut-off for large inductances

With increasing distance between contacts or with greater cooling, the arc voltage increases and the current decreases slightly until the igniting voltage is greater than the driving voltage (Figure 7.6). Cut-off is not easy for the unit because during the zero current crossover the peak value of the recovery voltage is present. This means that the arc will then re-ignite a few times more. We must try to design the cooling conditions for the first zero current crossing adequately to anticipate the first crossover. Inductive cut-off is practically a short circuit path, since here the circuit is largely inductive due to the generators, transformers and lines.

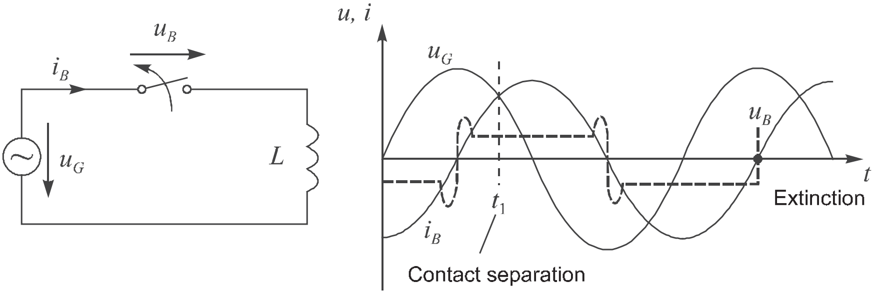


Figure 7.6 Cut-off for large inductances

Cut-off of pure resistances

Here, the current an voltage are in phase, the recovery voltage is practically zero and the switch is almost without voltage loading (Figure 7.7). The switches can therefore be constructed of a lightweight material.

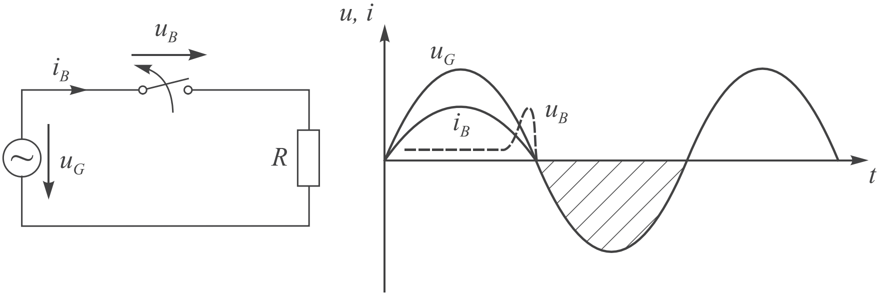


Figure 7.7 Cut-off of pure resistances

Cut-off of capacitances

Let us assume that the switch extinguishes during the first zero current crossing. The contact then lies on the capacitor voltage. Since there is no discharge path, the voltage remains. The recovery voltage follows the generator voltage. As a result, a difference voltage is formed at the switch contacts, which rises to double the peak value. This can easily lead to restriking, in turn causing overvoltages. The capacitive cut-off is therefore critical. It must always be checked whether the capacitive current from the particular switch can be controlled, even at low voltages (Figure 7.8).

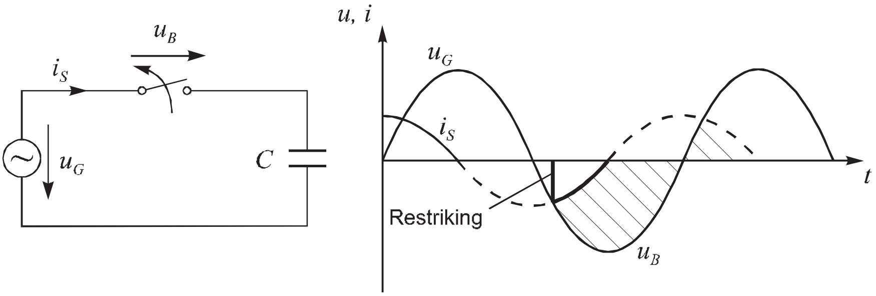


Figure 7.8 Cut-off of capacitances

Cut-off of small inductances

For small currents, that is especially for the magnetization currents of transformers in the no-load state, the cooling can interrupt the current already before the zero current crossover. Due to the rapidly changing current, a high induced voltage then results which, just as for the capacitances, adds to the generator voltage and can cause restriking. Here again, there is a danger of overvoltages. Since the switch is designed for the three-pole short circuit and not for the small magnetization currents, an overvoltage arrester should be connected to the transformer. The inductive currents for transformers in the no-load state are about 1 to 5 A.

7.1.4
Transient Voltage

The network consists of inductances and capacitances. The natural frequency can lie between 0.5 and 50 Hz, however the range from 1 to 5 kHz is rarely exceeded. A damping of the transient voltage is usually achieved with the use of a resistor. There is no difference compared with an AC cut-off, but there are some special considerations since the three currents do not pass through zero simultaneously. After the first zero current crossover, a two-pole short circuit remains. In detail, the result is as in (Figure 7.9):

1. At time t_1 the current flowing in line L1 is the first to pass through zero. It extinguishes during the first crossover.
2. The recovery voltage is shifted by 180° for both currents and in both cases has the value U_{star}.
3. After the first zero current crossover, a two-pole short circuit current remains at time t_2.

Of the many possible types of load, we will examine only two special cases here (Figure 7.9). In one case, this involves the coupling switch between two power stations or networks. If the coupling is opened because a fault has occurred, due to the voltage breakdown the synchronizing moment is no longer present because the active current of the load is missing. The generators then fall out of step. The systems rotate freely and during extinction can come to exactly opposite phases. This results in double the switching power as for normal three-pole cut-off. Between the circuit breaker and the location of the short circuit are several kilometers of line. For a short circuit at the end of the line the voltage at the switch is not zero, but increases according the distance away. Because of the different inductances on both sides of the switch, different transient values arise on the generator side and the fault side.

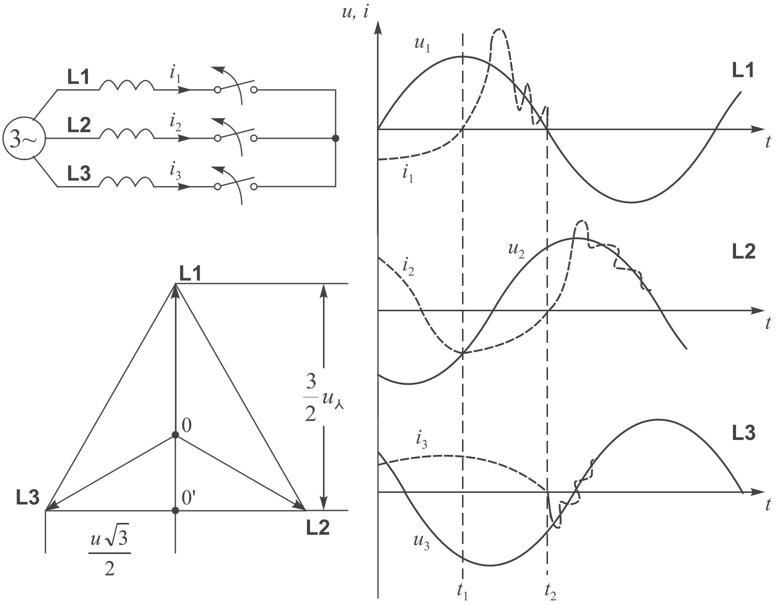


Figure 7.9 Transient voltage

The short-line fault is greater than the terminal short circuit. The terminal short circuit occurs in the immediate vicinity of the switch. The DC element decays with the time constant $T = \frac{L}{R}$, for which IEC 45 give 45 ms. In real networks and various operational equipment, this value oscillates between 10 ms and 450 ms.

7.2
Low-Voltage Switchgear

In switchgear and industrial systems, but also in any electrical systems, a wide range of switchgear is in use today for the reliable control of power, as well as its connection, interruption and servicing. Since the requirements for low-voltage and high-voltage switchgear are very different, e.g. mechanical problems are foremost with low-voltage units, while there is high electrical loading of high-voltage units, it is advisable to discuss such units separately. A classification of low-voltage switchgear and sizes follows for the connection, interruption and disconnection of circuits in the following way.

7.2.1
Characteristic Parameters

In accordance with IEC 947 - 2 we distinguish between the very different designations for the individual electrical parameters.

- Voltages
  1. Rated voltage
  2. Rated insulation voltage
  3. Operating voltage
  4. Fault voltage
  5. Touch voltage
- Currents
  1. Rated current
  2. Continuous current
  3. Dynamic current
  4. Thermal current
- Capacities
  1. Rated short circuit breaking capacity I_{cu}
  2. Rated service breaking capacity I_{cs}

Low voltage includes operating voltages up to 1000 V. For various reasons, DC equipment is also included here. The ratings of the individual equipment depends on their classification according to rated breaking capacity.

7.2.2
Main or Load Switches

Main or load switches are actuated without current. For their electrical dimensioning, in addition to the continuous current the limiting dynamic value is also of interest. The switches must be make-proof and must open by themselves even as a result of short circuit forces.

The dimensioning parameters are:

- Rated voltage and rated insulation voltage
- Rated current
- Continuous current
- Thermal current in kA as RMS value
- Dynamic current in kA as peak value

In the interest of saving space, fuses and disconnectors will be dealt with together. Disconnectors have a defined isolating distance for the protection of the operating personnel (line segment with a definite dielectric strength) and can conduct operating currents and overcurrents, but cannot switch these on or off. Load break switches are load switches with disconnection function. Switches for smaller currents for control circuits up to about 200 A have certain construction features. The dimensioning of the load switch is as for disconnectors, however in addition the cut-off current or the breaking capacity must be specified. The displacement power factor cos cos$\varphi = 0.7$ is defined by the test specifications. However, the motor power is mostly given as the per-unit quantity. Main switches or load switches are used in accordance with IEC 408 for switching operational equipment and system parts on and off under normal operating conditions.

7.2.3
Motor Protective Switches

IEC 292

Three-phase motors are most frequently used in industry, because of their simple design, ruggedness, favorable prices and operational reliability. Depending on the type of operation, they must be continuously switches (Figure 7.10) and protected (Figure 7.11). Motor protective switches are intended to execute a three-pole cut-off

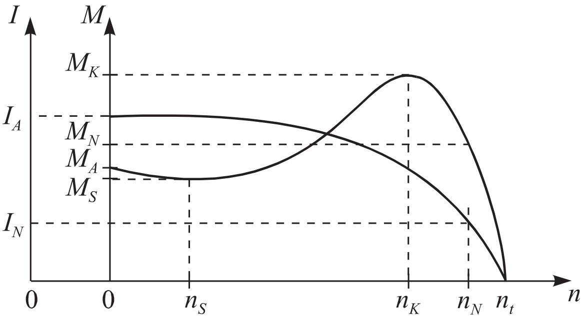


Figure 7.10 Switching of an asynchronous three-phase machine

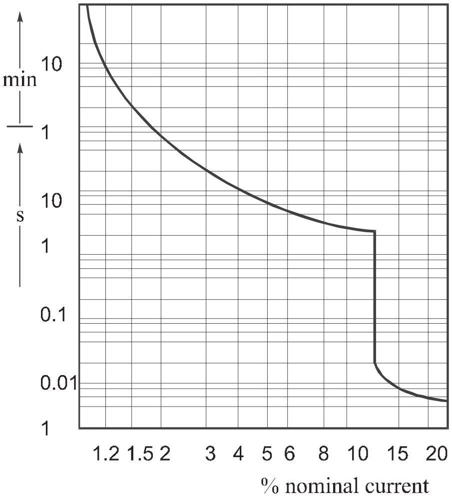


Figure 7.11 Protection of a three-phase asynchronous machine

in the event of a fault occurrence. They are mostly combined with a bimetallic and short circuit trip, which can also be replaced by a fuse. For the choice of starters, the rated current of the motor, the type of operation and the desired contact service life are decisive for the dimensioning. For direct switch-on the motor is loaded briefly with 5 to 6 times the rated current. For greater currents, the motor must be switched off in order to protect it from thermal destruction. Dangerous overcurrents arise during operation due to mechanical overloading over a longer time or external conductor breaks.

- Motor protection with fuses
  Overload protection is ensured by the motor protection relay, while the fuse is responsible for short circuit protection. The auxiliary switch responds through the overload release only after exceeding a definite time and initiates the all-pole tripping of the motor protection.
- Motor protection with circuit breakers
  Circuit breakers incorporate overload protection through bimetallic elements and short circuit protection through the instantaneous magnetic release. This switch has the properties of a disconnector and can be used as the main switch.

7.2.4
Contactors and Motor Starters

IEC 947-4-1

Conditions for fulfilling Classification 1:

- The contactor or starter must not endanger persons or systems in the event of a fault occurrence .
- The contactor or starter does not need to be suitable for continuing operation without repair and replacement.
- Damage to the contactor and overload relay is permissible.

Conditions for fulfilling Classification 2:

- The contactor or starter must not endanger persons or systems in the event of a fault occurrence.
- The contactor or starter must be suitable for continuing operation.
- There must be no damage to the overload relay or other parts.

Table 7.1 lists the utilization categories for typical applications in practice in accordance with IEC 947-4-1.

Table 7.1: Utilization categories for contactors

Utilization category	Load	$\frac{I_c}{I_e}$
AC1	Non-inductive or weakly inductive load Resistance furnace	1.5
AC2	Starting, switching off Slipring rotor motors	4.0
AC3	Starting, switching off while running Squirrel-cage rotor motors	8.0
AC4	Starting, braking by reversal, jogging Squirrel-cage rotor motors	10.0

I_c: Make and break current, I_e: Operating current

7.2.5
Circuit Breakers

IEC 898

Circuit breakers disconnect the short circuit current and are used for the protection of lines and cables. They are equipped with thermal and magnetic trip elements and are classified according to cross-sections. Different characteristics are necessary in order to optimally match the current-time behavior of the trip element to the current-time-thermal balance of the objects to be protected (Figure 7.12). The tripping current is standardized.

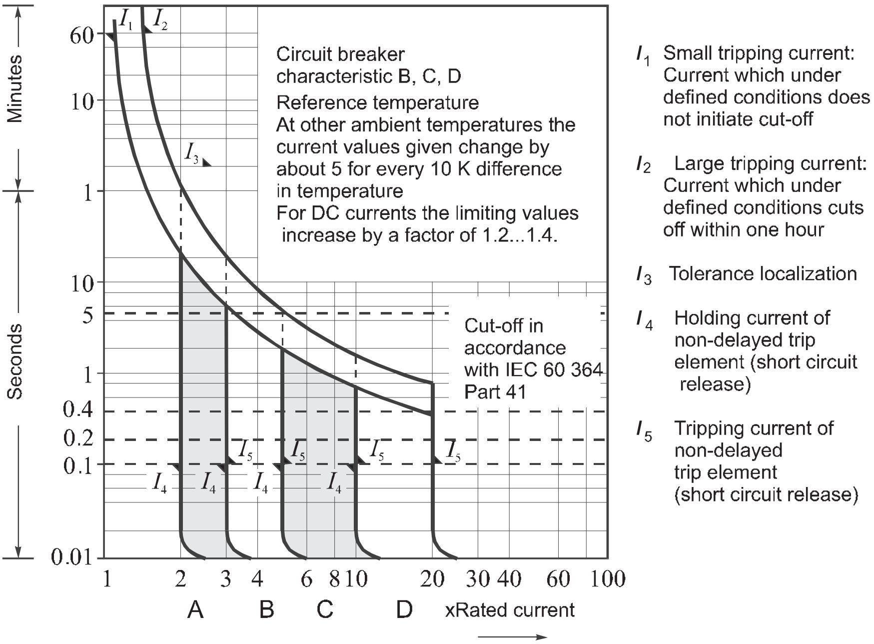


Figure 7.12 Time-current characteristics for circuit breakers in accordance with IEC 898 [52]

These protective devices are manufactured and used in single-pole or three-pole form. If the three-pole short circuit current at the site of the device is greater than the rated breaking capacity of the switch, it is necessary to install fuses ahead of the device (backup protection). Circuit breakers switch operating currents and function under fault conditions.

Table 7.2 gives the maximum permissible let-through values for different breaking capacities of the circuit breakers.

Table 7.2: Current limiting classes in A^2s

Breaking capacity A	Current limiting class 1	Current limiting class 3
3000	31000	15000
6000	100000	35000
10000	240000	70000

7.2.6
RCDs (Residual Current Protective Devices)

RCDs (residual current operated circuit breakers, Figure 7.13) consist of a summation current transformer with primary and secondary windings, tripping relay, contact system with latching mechanism, tripping device and housing. A tripping current circuit serves to control functioning. With the test key, a fault can be simulated and the function of the RCD be checked.

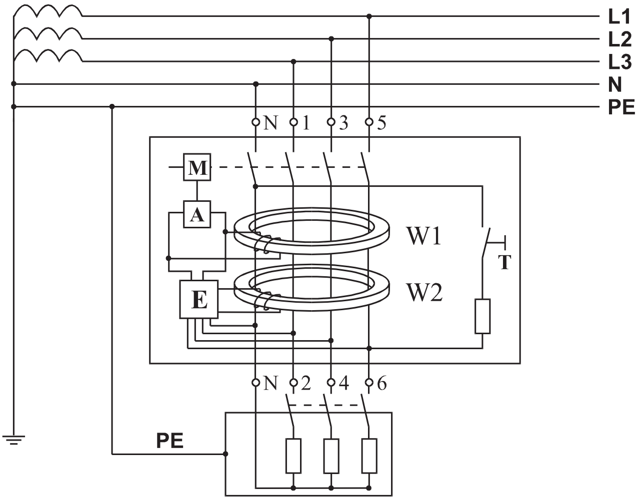


Figure 7.13 Principle of an RCD [49]

RCDs prevent injury to persons and damage to equipment due to electric current and within a small fraction of a second switch to 50 to 75 % of the rated fault current. RCDs enable protection against remaining excessive fault currents > 30 mA, protection against fires igniting for electrical reasons (maximum 300 mA) and protection in the event of direct contact (protection for persons) up to 30 mA, or better 10 mA because 10 mA lies below the human let-go current. In a fault-free electrical installation the operating current flows from the network through the summation current transformer to the consumer, and from there through the summation current transformer again and back to the network. The geometrical sum of the inward and outward currents in the transformer is zero. If in the event of a fault a current is led off to ground, then the current flowing to the consumer is proportionately greater than the outwardly flowing current. The current difference induces a magnetic field in the transformer, causing a current to flow in the secondary winding of the transformer which in turn causes the magnetic tripping element to respond and thus initiates an all-pole cut-off with the RCD.

RCDs can be used in TN-S, IT and TT systems. This requires that the neutral point of the network is grounded, the PEN conductor isolated before the RCD and the protective ground conductor is not led through the RCD. RCDs do not serve the purpose of cutting off overcurrents. It is therefore necessary to protect them using a suitable overload protection equipment, better to combine the two so that the system is also protected against overloading and short circuits. During planning it is necessary to take into account that the rated current of the overload protection equipment is not greater than that of the RCD. They must trip reliably when a pulsating DC current, such as occurs especially with such consumers as rectifiers, thyristors and triacs, flows to ground. For tripping the fault current must reach at least the value zero within a period.

Unintentional tripping of RCDs can be prevented by installing a delayed RCD of type designation S (selective) in addition to the non-selective RCDs following. This is especially recommended in regions in which there is a danger of lightning striking, as well as for consumers with long lines and for floor heating systems in which capacitive discharge currents arise during switch-on.

RCDs are firmly established in regulations for electrical installations (IEC 60 364) and international regulations. Figures 14 and 15 show different examples for planning with RCDs, in combination with circuit breakers.

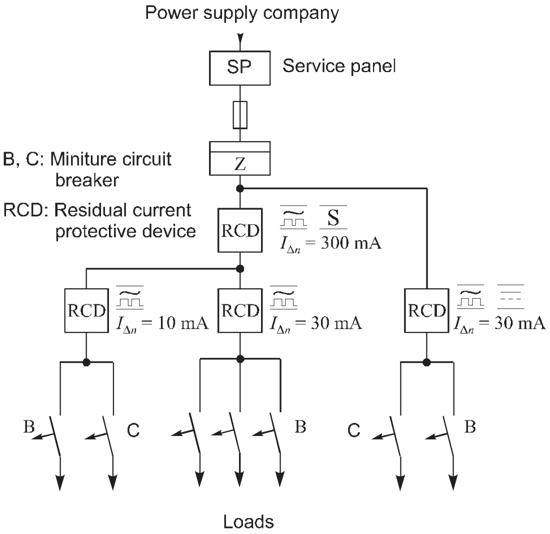


Figure 7.14 Planning with RCDs [49]

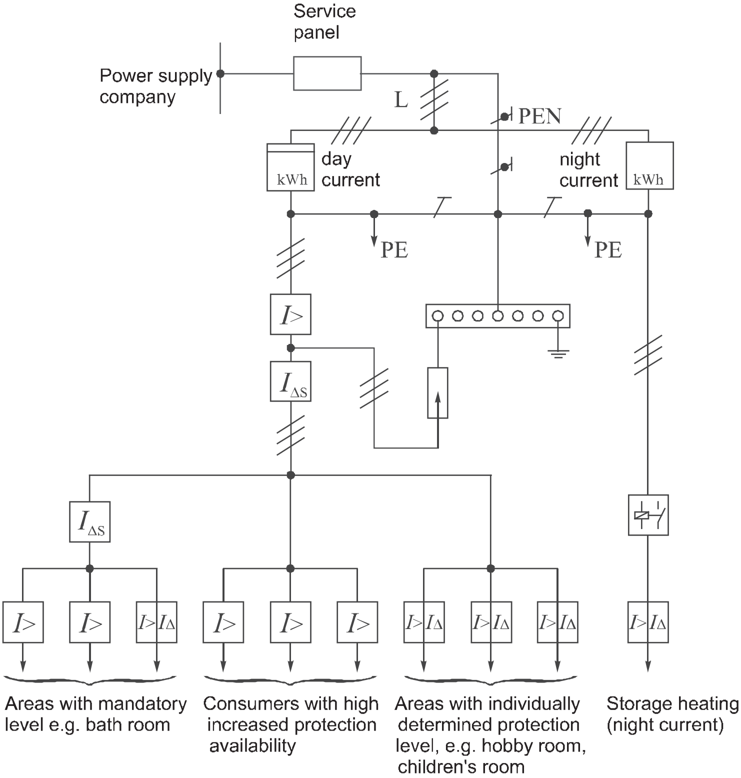


Figure 7.15 Planning with RCDs/circuit breakers [49]

7.2.7
Main Protective Equipment

This section describes primary protection equipment (single-pole or three-pole versions) in the form of SLS (selective circuit breakers). These overload protection devices may be used according to technical conditions for connection, power supply companies and utilities as line-side meter fuses in meter mounting boards or in the lower terminal housing instead of D02 and NH00 fuses (Figure 7.16). Their installation must be carried out according to the instructions of the power supply company or utility.

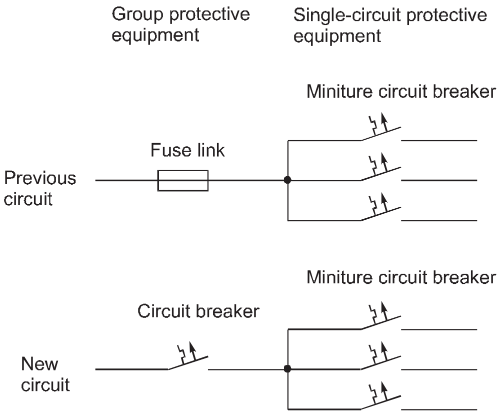


Figure 7.16 SLS breakers as group protective equipment

Properties of these breakers:

- Can be operated by untrained persons (safe operation), but not NH00
- Sealable
- Shock protection in accordance with the accident prevention regulations of the BG
- Backup protection for all overload protection equipment
- Selectivity of breakers among each other
- Disconnector properties with contact display
- Has selectivity to line fuses
- Can be installed without problems in meter mounting boards
- Fulfills the requirements of international and national testing standards for line protection equipment and offers full domain protection
- High making and breaking capacity (min. 25 kA) for meter mounting boards
- Direct installation on top-hat rails or on busbars using a high-quality adapter with special clamps
- Fast return to operation after occurrence of a fault
- The following versions are available: single-pole, double-pole or 3-pole, 25 A, 35 A, 50 A, 63 A, 80 A, 100 A

1. Design and function of the SLS breaker
   SLS breakers are comprised of the primary current circuit (1), the secondary current circuit (2) and the making current circuit (3) (Figure 7.17).

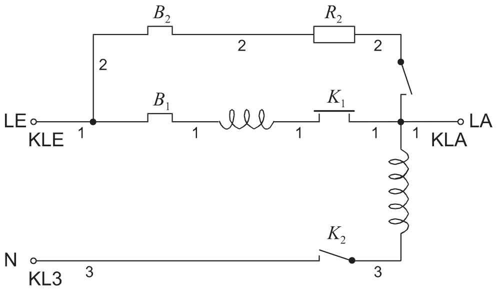


Figure 7.17 Design and function of the SLS breaker [54]

The primary current circuit includes the input terminal, bimetallic element, electromagnet, a movable double contact and an output terminal. The secondary current path is comprised of the bimetallic element, the pure resistance and the contact. The making current circuit includes an electromagnet, a movable contact and a terminal. In the event of overloading the bimetallic element releases latching mechanism S1, which then opens contact K2. With the occurrence of a short circuit, the electromagnet E1 releases latching mechanism S2, which the opens contact K1. The tripping characteristic is similar to that of the circuit breaker. In addition, there is also the tripping strip of the bimetallic element B2 in the secondary current circuit (Figure 7.18). In the event of a short circuit, the current commutates follow-

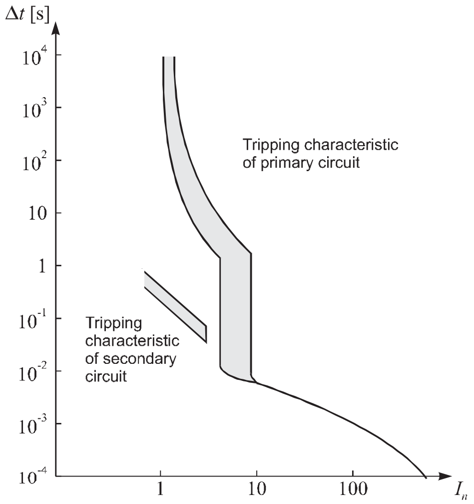


Figure 7.18 Tripping characteristic of SLS breakers [54]

ing tripping and extinction of the electric arc to the secondary current circuit. Figure 7.19 illustrates the current limiting for SLS breakers for clearing short circuits. The relative energy content for a 40 kA half-wave is $16 \cdot 10^6$ A^2s. The short circuit is initiated at $\alpha = 60°$ (unfavorable point). In 2.2 ms the SLS breaker disconnects the fault location from the network and limits the let-through energy to 112,500 A^2s. Figure 7.20 shows characteristics of SLS breakers and NH fuses for clearing short circuits.

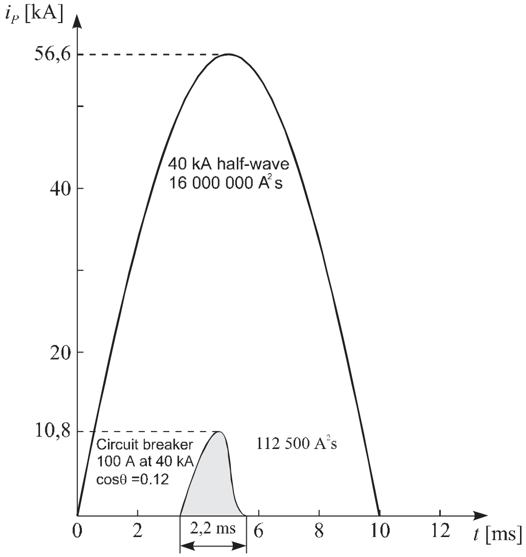


Figure 7.19 Current limiting for SLS breakers [54]

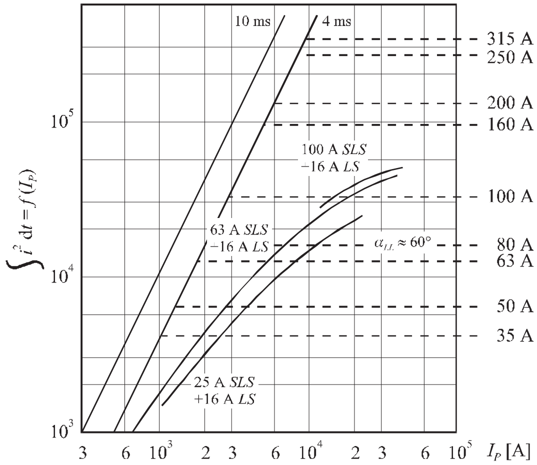


Figure 7.20 Comparison of SLS breakers with downstream circuit breakers and NH fuses for clearing short circuits [54]

2. Design and function of the automated main fuse assembly S700
   The design of the automated main fuse assembly S700 is shown in Figure 7.21. In the event of overloading, the first thermo-bimetallic element TB1 initiates tripping. With the occurrence of a short circuit the first electromagnet system, with impact anchor ES1, opens contact pieces K, so that a longer electric arc arises in the arc extinction chamber LL, limiting the magnitude of the short circuit current. In the normal case, this limited short circuit current is disconnected by the small downstream circuit breaker, closing the contacts of S700 again. If the short circuit occurs before the circuit breaker, then a partial current flows through the second thermo-bimetallic element TB2. This element bends and closes the circuit for the second electromagnet system ES2. Cut-off thus takes place through the contact mechanism S. The time-current characteristics of the main automated fuse assembly are shown in Figure 7.22.

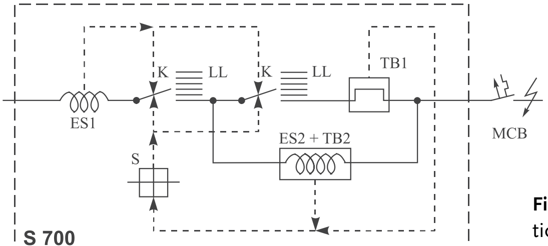


Figure 7.21 Design and function of the main automated fuse assembly S700 [62]

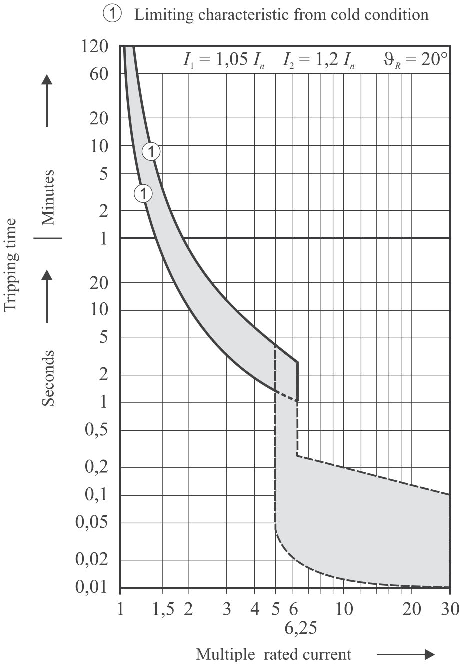
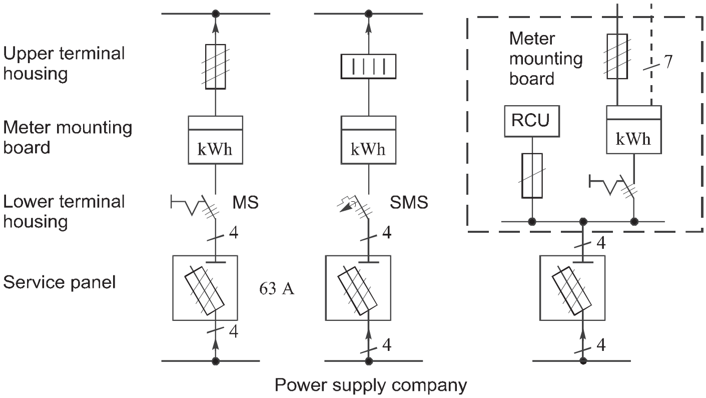


Figure 7.22 Time-current characteristic for main automated fuse assembly S700 [62]

7.2.8
Meter mounting boards with main protective switch

It is possible to install main automated fuse assemblies and selective circuit breakers on meter mounting boards in the following ways:

1. Single-rate connection up to 63 A loading capacity (Figure 7.23)
   Connection takes place in accordance with service panel regulations. A three-pole main switch is provided in the lower terminal housing and a main branch circuit terminal / summation fuse in the upper terminal housing or an overcurrent protective device as a switchable disconnecting device, e.g. a selective main branch circuit breaker in the lower terminal housing and a main branch circuit terminal in the upper terminal housing.



MS : Main switch
SMS: Selective main protective circuit breaker
RCU: Rate control unit

Figure 7.23 Single-rate connection up to 63 A loading capacity

2. Multi-rate connections for 63 A to 100 A loading capacity (Figure 7.24)
   Connection takes place in accordance with service panel regulations. A three-pole main switch is provided in the lower terminal housing and summation fuses in the upper terminal housing or an overcurrent protective device as a switchable disconnecting device, e.g. a selective main branch circuit breaker in the lower terminal housing and a main branch circuit terminal in the upper terminal housing.

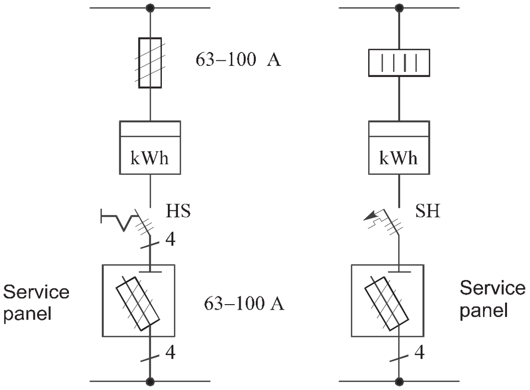


Figure 7.24 Multi-rate connections for 63 A to 100 A loading capacity

3. Multi-rate connections for more than 100 A loading capacity (Figure 7.25) Group fuses up to 100 A are outside of the meter cabinet, a three-pole main switch in the lower terminal housing and summation fuses in the upper terminal housing or an overcurrent protective device as a switchable disconnecting device, e.g. a selective main branch circuit breaker in the lower terminal housing and a main branch circuit terminal in the upper terminal housing.

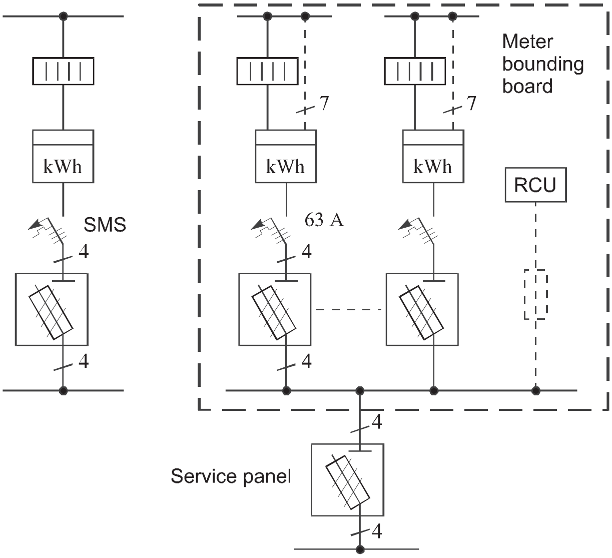


Figure 7.25 Multi-rate connections for more than 100 A loading capacity

7.2.9
Fuses

Fine compacted sand serves as the quenching medium for the electric arc. The threshold current melts or vaporizes the conductor. The electric arc which arises maintains the current. The arc in turn melts the sand. For this a certain Joule heat pulse $\int i^2 \, \mathrm{d}t$ is necessary.

The fuse always interrupts large short circuit currents by current limiting before reaching i_p and without waiting for the natural zero current crossing. The electric arc voltage of the fuse must be greater than the overvoltage produced in order to ensure quenching. The type of characteristic determines the function class of the fuse and its external construction its construction type. The current-dependent characteristic of the fuse follows from the simplified equation

$$\int i^2 \, \mathrm{d}t = c\, m\, \Delta\theta \tag{7.3}$$

The assignment of a function class to an object to be protected determines the duty class of a fuse. Fuses are current-limiting switching devices. The peak short circuit current is limited to the let-through current. Here it is necessary to distinguish between overloading and short circuits. In the event of overloading, the left section of the characteristic (Figure 7.26, 7.27), a fusible element detects the overload condition, whereas the melting of the bottleneck section interrupts a short circuit. The complete fuse consists of the base with adapter ring, adapter screw, indicator, screw cap and plug head.

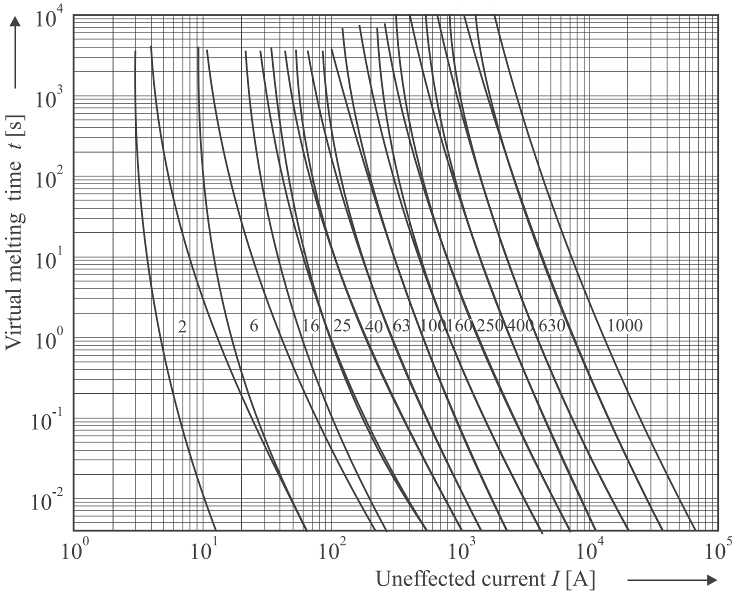


Figure 7.26 Fuse characteristics from 2 A to 1000 A

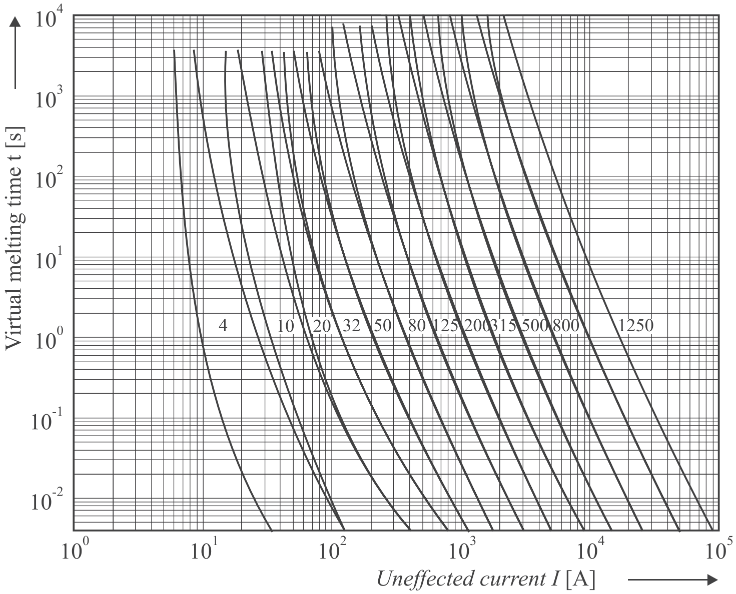


Figure 7.27 Fuse characteristics from 4 A to 1250 A

The rated current of the fuses for motor circuits should be about twice the rated current of the motor under normal startup conditions. In practice, there are graduated tables for the rated currents of fuses which function selectively. At the node points of the meshed networks the fuses are selective, as long as the largest partial current does not exceed approximately 0.8 times the summation current.

Rated parameters for fuses:

1. Let-through current: The maximum value of the short circuit current is not reached, so that it is sufficient here to use the let-through current.
2. Short circuit strength: The fuse must not explode or even blow out due to the short circuit.

Color coding of fuses in accordance with Table 7.4

The dimensioning follows from the:

- Rated voltage
- Rated current
- Short circuit strength
- Let-through current
- Time-current characteristic

Table 7.3: Color coding of fuses

Rated current A	Color
2	pink
4	brown
6	green
10	red
16	gray
20	blue
25	yellow
35	black
50	white
63	copper
80	silver
100	red
125	yellow
160	copper
200	blue

Types of construction

Here we distinguish between three types of construction:

- Screw-type fuses
  These are characterized by the non-interchangeability of the fuse unit and the protection against electric shock. These fuses can be operated by untrained personnel. The bases of screw-type fuses are constructed to accommodate adapter rings.
- Fuses with blade contact
  These consist of a lower fuse part, the replaceable fuse element and the operating element for replacing the fuse element. Untrained personnel cannot operate these fuses. A low-capacity fuse disconnector ensures safe conditions while replacing the fuse elements. It is possible to install and remove fuses with the system under load.
- Operation classes of the fuses
  These duty classes are identified by two letters, of which the first indicates the function class and the second the object to be protected.
- Function classes
  1. Function class
     g Full domain protection (protection against overload and short circuits)
     a Subdomain fuses (protection against short circuits)
  2. Defined objects of protection for fuses:
     G Cables and lines (general applications)
     L Cables and lines

M	Switchgear
T	Transformers
R	Semiconductors
B	Mining systems

The rated current ranges for NH fuse elements are listed in Table 7.4. According to the rated current intensities there are different thread sizes for fuse systems (Table 7.6).

Table 7.4: Rated current ranges for NH fuse elements

Size	**NH fuse elements**				**NH fuse bases**	**Switching strips**
	500 V **gL** **A**	**660 V** **gL** **A**	**500/660 V** **aM** **kVA**	**400 V** **gT** **A**	**A**	**A**
00	6–100	6–100	35–100	–	160	160
1	80–250	80–250	80–250	–	250	250
2	125–400	125–400	125–400	50–250	400	400
3	315–630	315–500	315–630	250–400	630	630
4a	500–1250	500–800	630–1250	400–1000	1250	–

Table 7.5: Threads of fuses

Thread of D fuses		
E27	2 A to 25 A	D2
E33	36 A to 63 A	D3
R1.24 inches	80 A to 100 A	D4H
Thread of D0 fuses		
E14	2 A to 16 A	D01
E18	20 A to 63 A	D02
M30x2	80 A to 100 A	D03

The cut-off behavior of fuses in the overload region is determined by the small (no cut-off in the specified checking time) and the large (cut-off during the specified checking time) tripping currents. Table 7.6 summarizes the tripping currents.

The time-current characteristics for gG fuses are shown in Figure 7.26, from 2 A to 1250 A. NH fuses of duty class gL protect electrical operational equipment against overloading and short circuits. With corresponding classification, they can also be used to protect motors against short circuits.

Table 7.6: Tripping currents of fuses

Duty class	Rated current in A	Small tripping current I_1	Large tripping current I_2	Checking time
Tripping currents of NH fuses				
gG	< 4	$1.5\ I_n$	$2.5 I_n$	1 h
	4–10	$1.5\ I_n$	$1.9\ I_n$	1 h
	10–25	$1.4\ I_n$	$1.75\ I_n$	1 h
	25–63	$1.3\ I_n$	$1.6\ I_n$	1 h
	63–160	$1.3\ I_n$	$1.6\ I_n$	2 h
	160–400	$1.3\ I_n$	$1.6\ I_n$	3 h
	> 400	$1.3\ I_n$	$1.6\ I_n$	4 h
aM	all of the I_n	$4\ I_n$	$6.3\ I_n$	60 s
Tripping currents of D0 fuses				
gG	bis 4	$1.5\ I_n$	$2.1\ I_n$	1 h
	4–10	$1.5\ I_n$	$1.9\ I_n$	1 h
	10–25	$1.4\ I_n$	$1.75\ I_n$	1 h
	25–63	$1.3\ I_n$	$1.6\ I_n$	1 h
	63–100	$1.3\ I_n$	$1.6\ I_n$	2 h

The current limitation diagrams for gG fuses are drawn in Figure 7.28. Before reaching the peak short circuit current, the short circuit current I_k is disconnected.

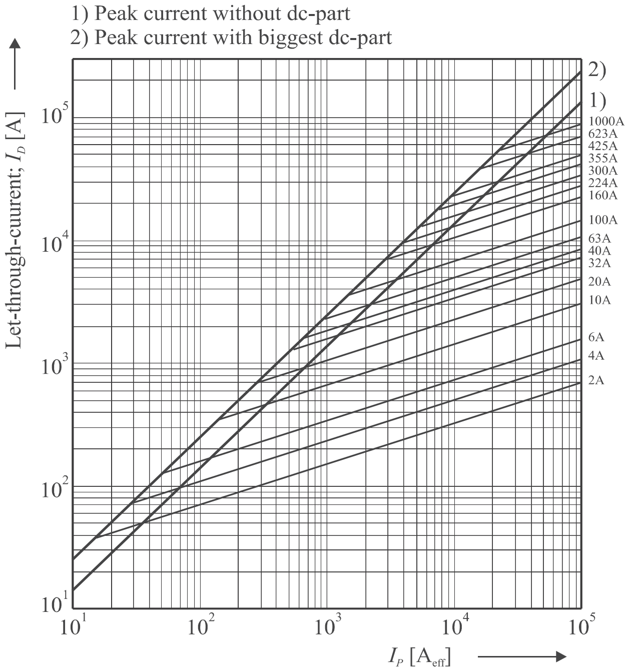


Figure 7.28 Let-through curves for gG fuses

D0 fuses are frequently found in industrial and residential installations.

Figure 7.29 gives the time-current characteristics. The rated breaking capacity is 50 kA for these fuses.

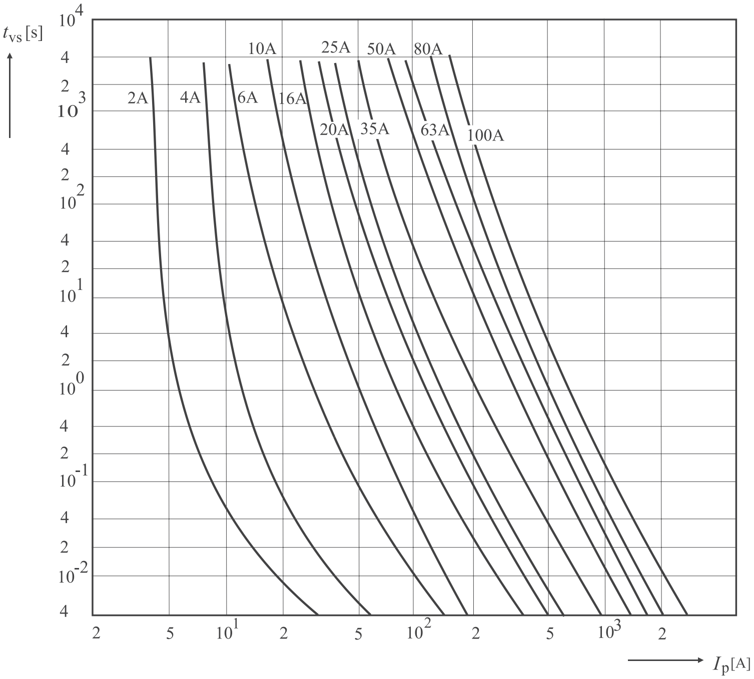


Figure 7.29 Time-current characteristics for D0 fuses

7.2.10
Power Circuit Breakers

IEC 947

In accordance with IEC 947 a power circuit breaker is a mechanical switching device which under normal operating conditions for a given circuit switches on, directs and switches off current. In addition, under unusual circumstances such as a short circuit the device directs and switches off current. Power circuit breakers are switching devices for the repeated switch-on and switch-off of circuits in normal operation and under fault conditions. Power circuit breakers always release in three-pole form. Following the occurrence of a fault they are switched on again. Signalling with remote on or off is possible without problems. Power circuit breakers have a limited breaking capacity and are selective under one another only with certain restrictions. The making and breaking capacity increases linearly with the rated current. The response time of modern power circuit breakers is between 2 and 10 ms for both making and breaking. The large switching forces required are supplied from compressed air, hydraulic or spring-loaded drives, which must have certain properties such as:

- An actuated switch must always be ready for switch-off
- A switch-on action must be completed once begun.

Power circuit breakers must be able to control equipment under normal operating conditions as well as under fault conditions, i.e. they must be able to cut off reliably at any time. Their breaking capacity is dimensioned according to the effective value of the unaffected prospective short circuit current. For the making and breaking capacity according to short circuit category P2, a cut-off and two make-break switches with two interruptions at 1.1 times the rated voltage and the appropriate power factor are required. The power factor is 0.15. For the tests which demonstrate the making and breaking capacity, the test switching sequence must be complied with. Today, all power circuit breakers are designed according to the building block principle, which enhances the breaking power, divides the applied voltage and reduces the chamber loading through multiple chambers. The puffer is the most important element of a power circuit breaker. During cut-off, it is drawn back by a force. This compresses the gas. At the same time, a switching contact coupled to the puffer, which joins the two contact tubes and closes to the make state, is displaced. This results in breaker gap between the upper contact tube and the contact piece. The voltage over the breaker gap the drops, causing an electric arc. The line current at first continues to flow. The compressed gas flows into the breaker gap and cools the electric arc (heat dissipation). The current is interrupted, and a transient voltage begins between the line connections, which must be checked for its reliability when dimensioning the switches (recovery voltage). The length of the arc sustained in the contact tube becomes larger. Since the resistance of the arc also increases, the current and the supplied power are reduced. As we already know, the current extinguishes during the zero current crossing. A current chopping (tolerated only up to 4 A) is not permissible before this quenching, since otherwise large overvoltages would arise according to the law of induction. At switch-on the puffer and the switch contact are displaced upwards within 30 ms. The voltage along the breaker gap drops. Today, power circuit breakers are manufactured up to 80 kA, and in high-voltage applications power circuit breakers with several chambers per pole are used. Figure 7.30 gives the tripping characteristics for different power circuit breakers.

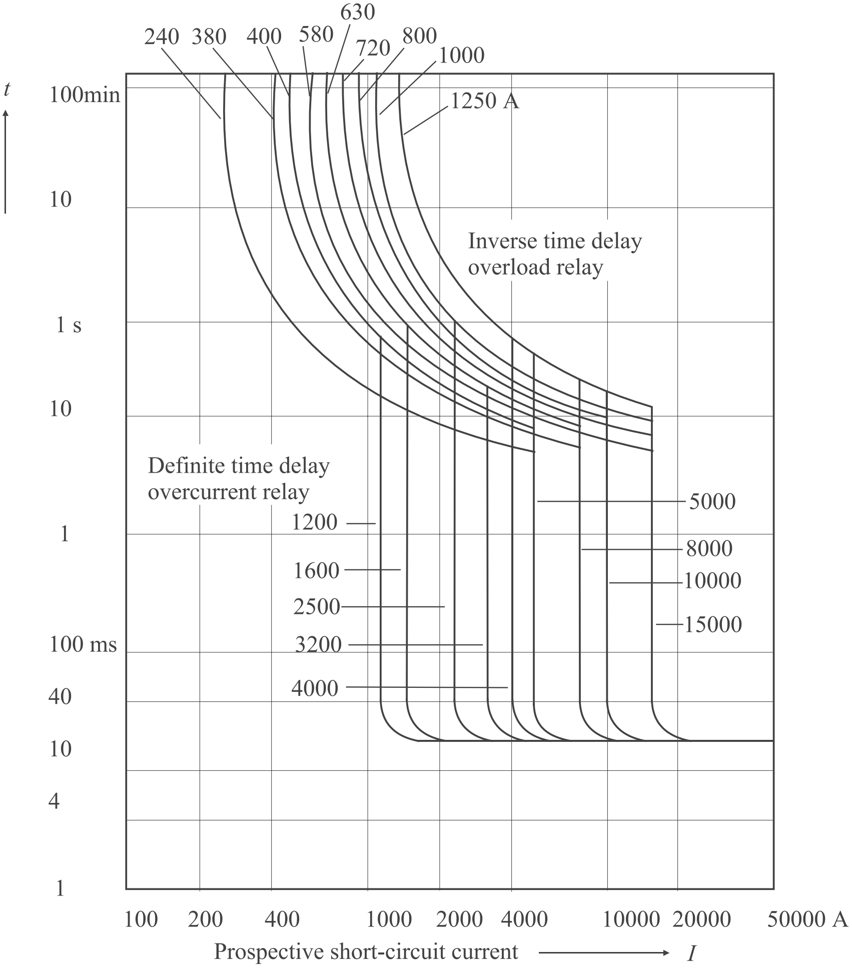


Figure 7.30 Time-current characteristics of power circuit breakers [53]

Short circuit categories in accordance with IEC 947

- Short circuit category 1
  old: P-1, Application for Short Circuits
  new: Icu in accordance with IEC 947
  I_{cu} rated ultimate short circuit breaking capacity
  Switching sequence for testing the rated ultimate short circuit breaking capacity:
  $O - t - CO$: suitable only for reduced operation,
  insignificant displacement of characteristic for rated ultimate short circuit breaking capacity

- Short circuit category 2
  old: P-2, Application for frequent high short circuits
  new: Ics in accordance with IEC 947
  I_{cs}: service short circuit breaking capacity
  Switching sequence for testing the service short circuit breaking capacity:
  $O - t - CO - t - CO$: suitable for normal operation without servicing, no displacement of characteristic
  The meanings of the symbols are:
  O switch-off
  CO On-Off sequence (onto the short circuit)
  t time (waiting interval of 3 minutes)

Breaker types

We differentiate between the following breaker types, according to the arc extinguishing medium:

- Liquid-level circuit breakers: The breaking gaps are under oil in a tank. The oil serves as an insulating material and as the arc extinguishing medium. Heat is extracted from the electric arc through vaporization, expansion following an increase in pressure and through thermal conduction. This requires large amounts of oil. This type of breaker is no longer manufactured today, since the oil is flammable and represents an environmental hazard.
- Compressed air or compressed gas circuit breakers: The arc extinguishing medium flows independently of the current to be interrupted into the arc space. Following successful quenching, the cold gas under high pressure rapidly produces a surge-proof breaking gap. Today, only type SF6 is still used. The gas is not toxic and is odorless, inflammable and a good thermal conductor.
- Vacuum circuit breakers: These breakers find use in low-voltage and medium-voltage systems and have very good insulating properties. They require little servicing and have a large number of operating cycles. Due to the absence of an arc extinguishing medium, flashing and contact wear result. The contacts are slit obliquely in order to prevent these difficulties. Copper-chrome alloys are used in order to produce metal vapor and to keep the chopping current small.
  Properties of vacuum circuit breakers:
  - Can be switched on again immediately
  - Large number of operating cycles
  - High reliability
  - No open arc
  - Long electrical life
  - High short circuit breaking capacity
  - Requires little servicing.

7.2.11
Load Interrupter Switches

IEC 408
In medium-voltage networks, load interrupter switches are often used together with fuses and combined with disconnectors. Switch disconnectors are also used in order to save costs. Only the load is switched and a breaking gap is produced. The power factor is $\cos\varphi = 0.7$. Load interrupter switches are switching devices which fulfill the same switching functions as switch disconnectors.

7.2.12
Disconnect Switches

Disconnect switches are necessary in order to de-energize system components, so that these are accessible for checking. The main problems with disconnect switches are the heating of the contact surfaces and disengaging of the contact elements with the occurrence of abrupt short circuit loading. They have no elements for extinguishing the electric arc, but must still be capable of quenching small currents.

A distinction is made between:

- center-break disconnectors
- automatic disconnectors
- pantograph disconnectors

Disconnector drives:

- manual drives
- motor drives
- compressed air drives

Compressed air drives are no longer manufactured. Disconnectors, grounding electrodes and circuit breakers must be provided with interlocks. Disconnectors must be switched only with the circuit breakers in the OFF position. On the other hand, the grounding electrodes must be actuated only with the disconnectors open.

7.2.13
Fuse Links

This section gives the characteristics for fuse links which provide protection against short circuits on the medium-voltage side of the transformer. They are used at 6 kV up to 150 A and at 30 kV up to 40 A (Figure 7.31, 7.32).

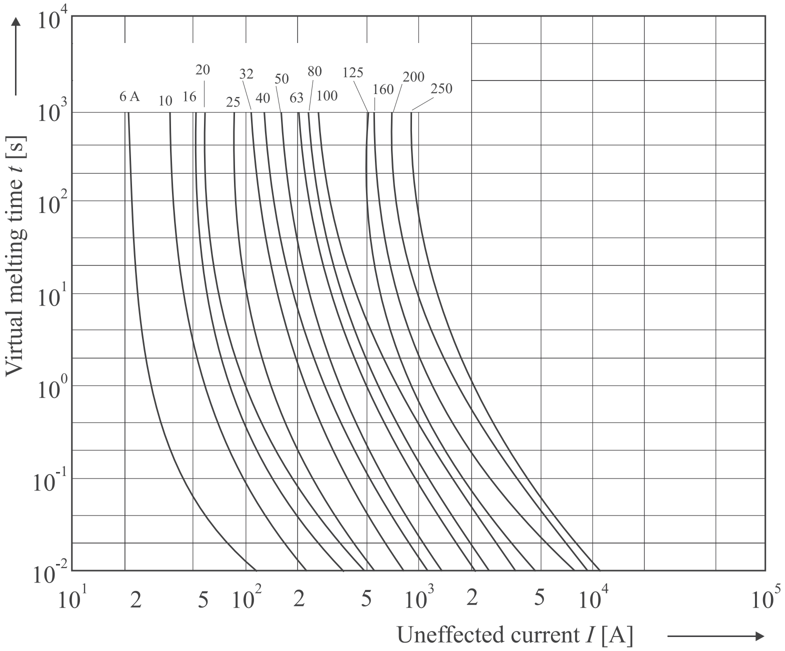


Figure 7.31 Time-current characteristics for fuse links

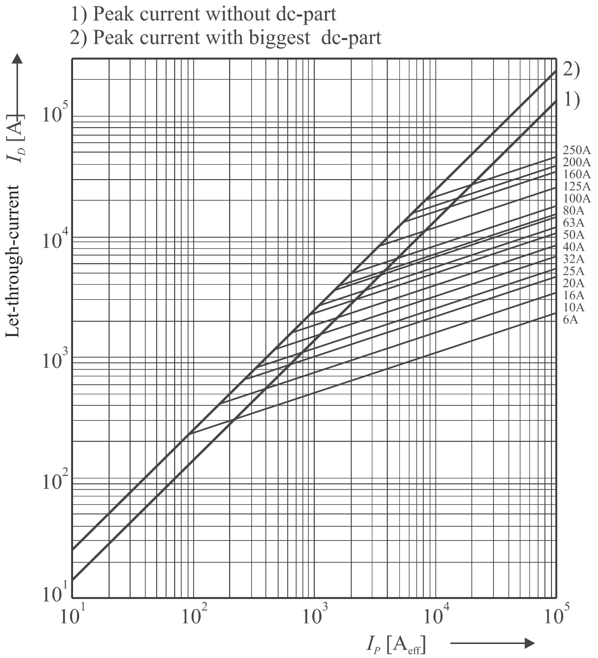


Figure 7.32 Let-through-current for HH-fuses

7.2.14
List of Components

This section summarizes position units (PU) for the most common built-in units and terminals. From the sum of the position units, with sufficient reserve positions, it is then possible to determine the cabinet types and distributions (Table 7.7). For each field width for the installation of the built-in units 12 position units are available. One position unit has the dimensions 150 mm × 180 mm.

Table 7.7: Determining the position requirements for distribution cabinets

Type	PU	Type	PU
Circuit breaker 0.5 to 63 A		Staircase circuit breaker	1
1-pole	1	Time switch analog day	3
2-pole	2	Time switch analog week	4
3-pole	3	Time switch digital 2-channel	2
		Time switch digital 3-channel	4
Fuse element			
63 A	1.5	Air-break contactor 24A, AC	2
25 A	2.4	Air-break contactor 40-63A, AC	3
Neozed fuse element			
100 A	2.6	three-point terminal	0.35
63 A	1.5	Modular terminal 4 mm^2	0.35
16 A	1.5	Modular terminal 16 mm^2	0.6
Breaker 16 A, 1-,2- and 3-pole	1	Modular terminal 50 mm^2	1.2
Breaker 25 A, 3-pole	1	N isolating terminal, blue, 4 mm^2	0.35
One-way switch 63-80 A, 3-pole	2.5	N isolating terminal, blue, 16 mm^2	0.6
One-way switch 63-100 A, 3-pole	3	PE terminal 4 mm^2	0.45
Master switch 63 A, 3-pole	3	PE terminal 16 mm^2	0.7
Master switch 100 A, 3-pole	4		
Fuse switch disconnector 16 A 1-pole	1	Servo relay	1
Fuse switch disconnector 63 A 1-pole	1.5	Phase monitor	2
Fuse switch disconnector 16 A 3-pole	3	Dimmer	3
Fuse switch disconnector 63 A 1-pole	4.5	Load disconnecting relay	1
Fuse switch disconnector 16 A 4-pole	4	Remote control switch 16 A, 2-pole	10
Fuse switch disconnector 63 A 4-pole	4.5	Remote control switch 16 A, 1-pole	1
Power circuit breaker 6 to 6300 A	24	Photo-electric controller switch	4
RCD 16 to 63 A, 2-pole	2	Network rectifier	6
RCD 25 to 63 A, 4-pole	4	Miniature transformer 8-24 V	4
Pushbutton and control lamp	1	Incorporated transformer 100 VA	6
Grounding type outlet	2.5	Doorbell transformer 8-12 V, 8 VA	2

8
Selectivity and Backup Protection

8.1
Selectivity

Electrical operational and consumer equipment must be protected against stresses resulting from short circuit circuits by the selective disconnection of the faulty systems. IEC 60 364, Part 56 requires selectivity in low-voltage networks. The most important selectivity conditions for protective devices are described. An electrical system is equipped with several overcurrent protective devices connected in series such as fuses and circuit breakers, which are selective because in the event of a fault only the overcurrent protective device located directly before the fault location in the direction of current flow responds. Investigating the selectivity conditions requires a comparison of the time-current characteristics for the overcurrent protective devices or the fuse melt integrals with one another. In the following the most important selectivity cases are described.

In electrical systems, different overcurrent protective devices are used for overload and short circuit protection. The effects of these faults can be significantly reduced when the protective devices are correctly chosen.

Figure 8.1 illustrates time-current characteristics for different possible devices in a low-voltage network.

Current selectivity is obtained through the use of protective devices with different tripping currents. Time selectivity is obtained by delaying the release of the upstream protective devices.

Conditions for the selectivity of fuses:

- The characteristics must not coincide at any point.
- This is achieved when the upstream fuse has at least 1.6 times the rated current of the downstream fuse.
- With less than 1.6 times the rated current, no protection exists.
- The deviations of the scatter vary by ± 7 %.
- The cut-off time t_A is the sum of the melting time t_S and the arc extinction time t_L.

Analysis and Design of Low-Voltage Power Systems. Ismail Kasikci

ISBN: 3-527-30483-5

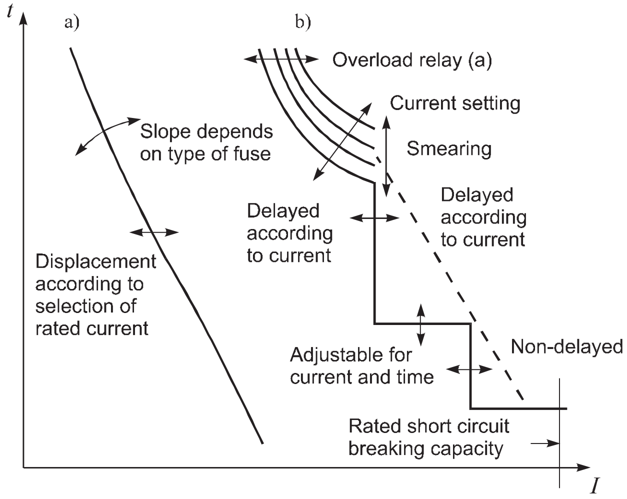


Figure 8.1 Tripping characteristics of NH fuses (a) and power

- For short circuit currents ≥ 20 times the rated current of the fuse and melting times ≤ 10 ms, characteristics cannot give reliable information. In such cases, it is necessary to check the i^2 dt values.

Advantages and disadvantages of fuses:

- The short circuit breaking capacity of fuses is sufficient for nearly all network conditions.
- Fuses cannot be adjusted.
- After cut-off fuses cannot be used again.
- Planning with fuses is simple.
- Systems in which the power levels are not yet known can be adapted to later requirements by simply changing the fuses.

A system with a transformer has a power of 1200 kVA, 6 % short circuit voltage and a 50 kA short circuit current at the feed-in (Figure 8.7). Conditions for the selectivity of power circuit breakers:

- Time or current grading is possible.
- Power circuit breakers are selective under one another only with certain restrictions.
- The total cut-off time t_A of the downstream switching device must be less than the minimum command time t_m of the upstream switching device.of the upstream switching device.
- The total cut-off time t_A is the sum of the contact parting time $t_{"OV}$ and the arcing time t_L.
- The delay time is about 50 ms.

- The interrupting current is 1.2 times the current setting I_e.
- The short circuit current is 12 times the rated current I_n.
- The power circuit breaker must be able to control the maximum short circuit current at the location of installation.

Advantages and disadvantages of power circuit breakers:

- Power circuit breakers have a limited short circuit breaking capacity.
- For a small rated current the breaking capacity is also smaller.
- For correct planning of a system with power circuit breakers it is necessary to calculate the short circuit currents.

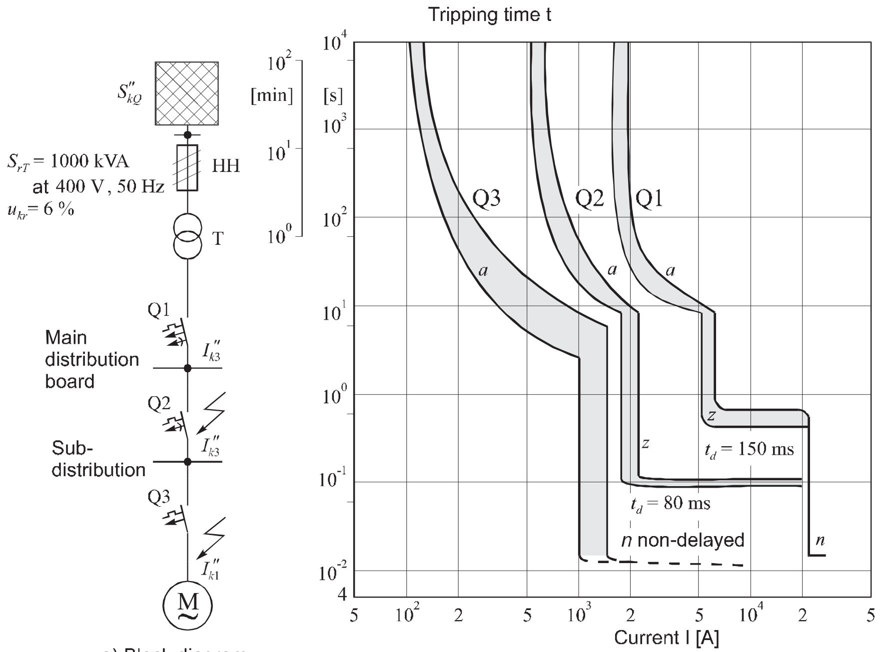
Important remarks about power circuit breakers and fuses:

- The grading time between a power circuit breaker and the fuse must be at least 100 ms.
- The let-through capacity of the fuse must be greater than that of the power circuit breaker.
- The breaking capacity of the power circuit breaker must always be taken into account.
- With fuses it is necessary to consider the type, state, aging, manufacture and characteristics.

Current selectivity is obtained through grading of the response currents and non-delayed short circuit tripping when the short circuit currents at the installation location differ greatly (Figure 8.7). The non-delayed short circuit tripping device can be set to the calculated short circuit values. To test the selectivity, another possibility is to compare the tripping characteristics with each other.

When the short circuit currents of the upstream and downstream power circuit breakers in a system are approximately equal, it is not possible to make use of time selectivity (Figure 8.2). The delay time must then be chosen so that a downstream power circuit breaker has the required time to cut off by itself.

Selectivity in the overload region is provided only when the characteristic of the fuse does not touch the characteristic of the power circuit breaker (Figure 8.3 to Figure 8.5). For larger short circuit currents the fuse responds so quickly that the power circuit breaker with 100 ms delay time never cuts off. Downstream fuse links switch selectively to a power circuit breaker when the operating current of the overload relay in the breaker has 4 to 5 times the value of the rated current for the fuse (Figure 8.6).



a) Block diagram

Q1 Power circuit breaker
Q2 Power circuit breaker for protection of system
Q3 Power circuit breaker for protection of motor

b) Staggered characteristics
a Current-dependent delayed overload relay
n Non-delayed electromagnetic overload relay
z Short-time-delay overload relay

Figure 8.2 Time selectivity of two power circuit breakers in series [30]

The primary side of the transformers is mostly protected with HH fuses and combined load disconnector switches. On the low-voltage side, power circuit breakers are used. The HH fuses are standardized, depending on the power of the transformer, and provide protection against short circuits only on the medium-voltage side. For selectivity it is necessary to take the manufacturers' data and scatter ranges of both characteristics into account. Power circuit breakers with a protective relay are used in place of HH fuses and provide the best protection. Figure 8.8 illustrates a motor exit cable with a short circuit current of 20 kA connected directly to the busbar of a transformer station and its short circuit current, which is supplied from two feeder circuit breakers with 10 each. Here, the trigger characteristic is shifted by a factor of two to the right on the current scale.

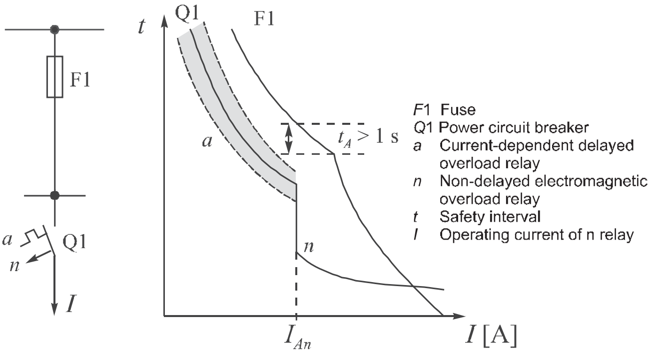


Figure 8.3 Selectivity in the overload region: Fuse upstream from power circuit breaker [30]

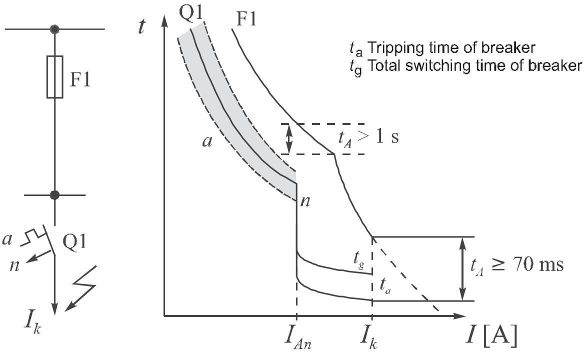


Figure 8.4 Selectivity in the short circuit region: Fuse upstream from power circuit breaker [30]

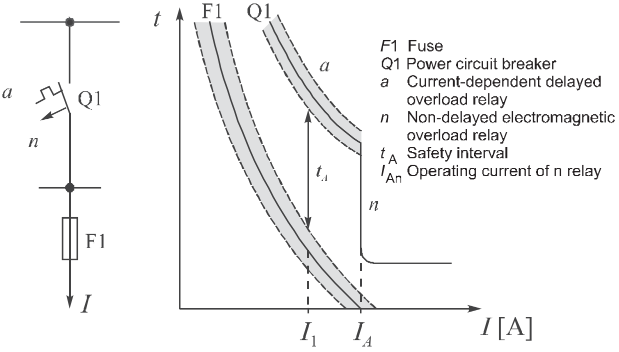


Figure 8.5 Selectivity in the overload region: Power circuit breaker upstream from fuse [30]

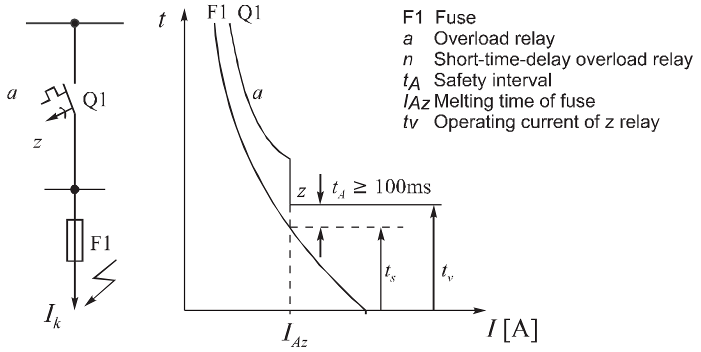
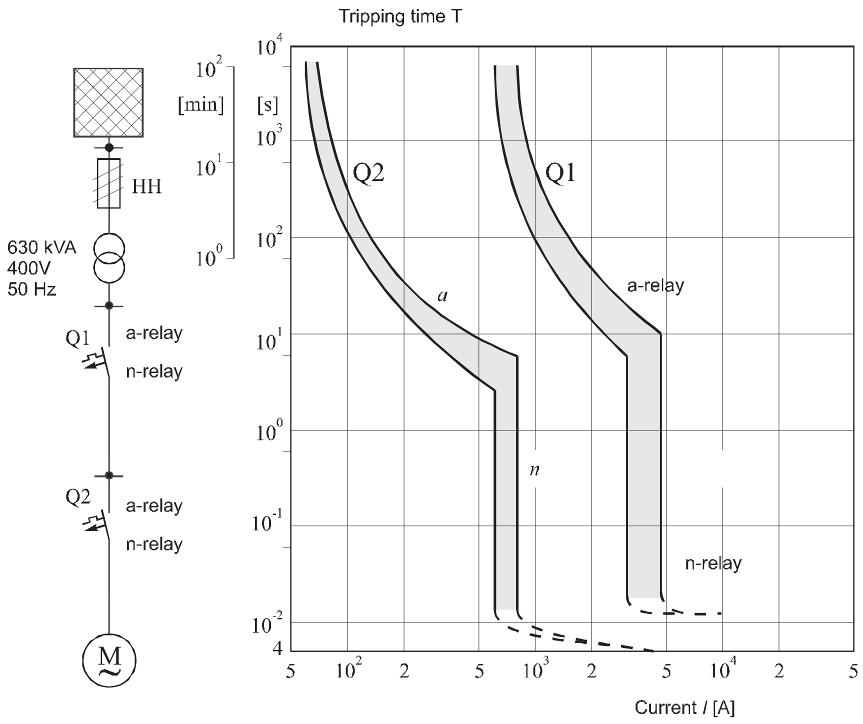


Figure 8.6 Selectivity in the short circuit region: Power circuit breaker upstream from fuse [30]

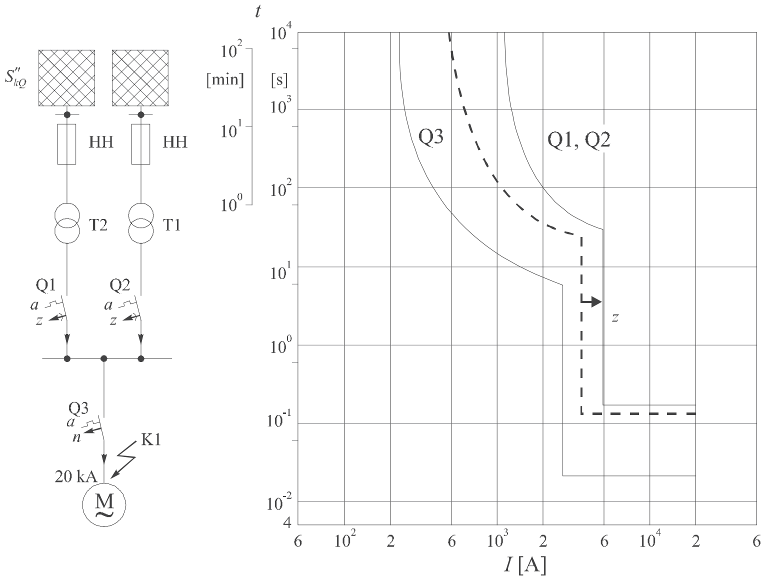


a) Block diagram

b) Tripping characteristics

Q1 Power circuit breaker (zero-current interrupter)
Q2 Power circuit breaker for protection of motor (current-limiting)
a Current-dependent delayed overload relay
n Non-delayed electromagnetic overload relay

Figure 8.7 Current selectivity for two power circuit breakers in series [30]



a) Block diagram

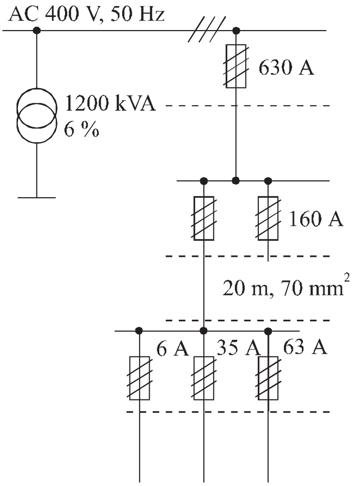
b) Tripping characteristics

Q1 Feeder circuit breaker
Q2 Feeder circuit breaker
Q3 Power circuit breaker for protection of motor

a Current-dependent delayed overload relay
z Short-time-delay overload relay

Figure 8.8 Selectivity in a system with two transformers [30]

The breaking capacity of the fuses is over 100 kA. The calculation of the short circuit currents at the installation location is not necessary. The selectivity is provided, since the upstream fuse element has ≥ 1.6 times the rated current of the downstream fuse element. Figure 8.9 shows a system with fuses. On the basis of the melting time characteristics for the fuse elements, we have proof of selectivity (Figure 8.10).



Network 400 V, 50 Hz
Maximum short circuit current
at main distribution board 50 kA

Questions:

Do the fuses have sufficient breaking capacity?

Is the system selective?

Figure 8.9 Evaluation of a system with fuses

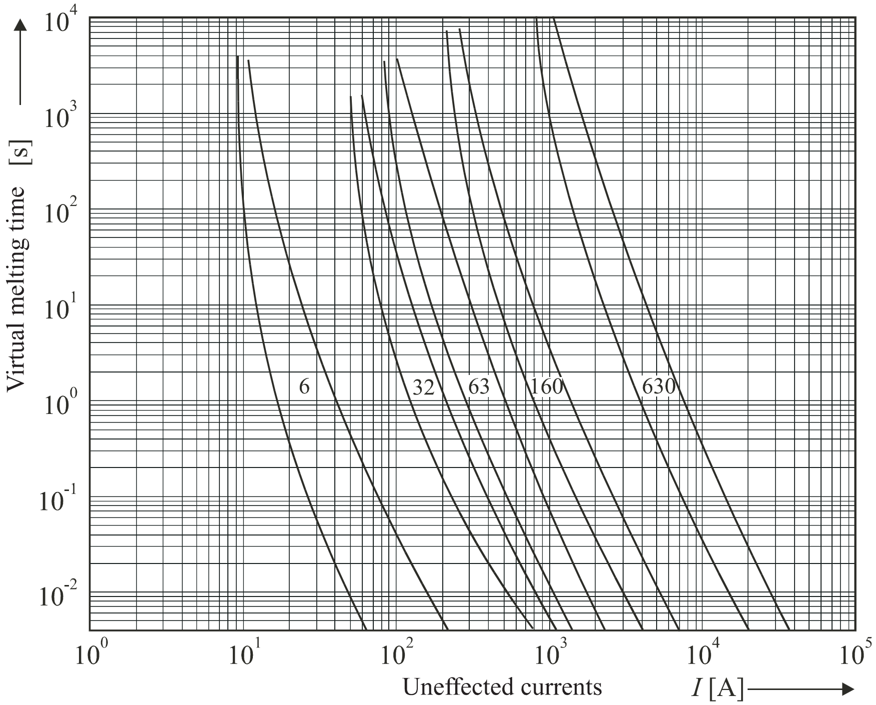


Figure 8.10 Time-current characteristics for fuses

At the installation location of the power circuit breaker a calculation of the short circuit current is always necessary in order to be able to choose the correct power circuit breaker and current setting. It is always possible to use either a compact power zero-current interrupter (Figure 8.11). The zero-current interrupter quenches the electric arc only during the natural passage of the current through zero. It must be able to withstand the dynamic and thermal short circuit stresses of its full breaking capacity for a short time. If the short circuit current is interrupted by a current-

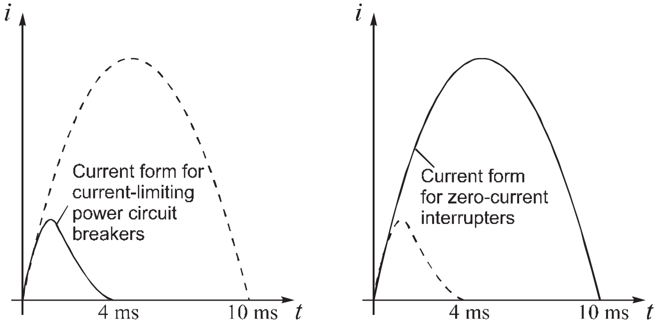


Figure 8.11 Current form for breaking a short circuit

limiting power circuit breaker the contacts then open very quickly, so that already after only a few milliseconds an arc is ignited which represents an additional resistance that rapidly increases and limits the short circuit current to the curve form shown with the continuous line. This is a considerable relief for the system and breaker.

In the following example (Figure 8.12) power circuit breakers with the same rated values are used in place of fuses. Referring to the characteristic in Figure 8.13 , we see that the power circuit breakers are too similar in their characteristics to be selective. The, we see that the power circuit breakers are too similar in their characteristics to be selective. The 630 A breaker is chosen with a z n release. The z release is delayed by 80 ms and the n release set to infinity. This makes the breaker selective with respect to the others. Since in the sub-distributions the short circuit currents are > 6 kA, a backup protective device must be installed there.

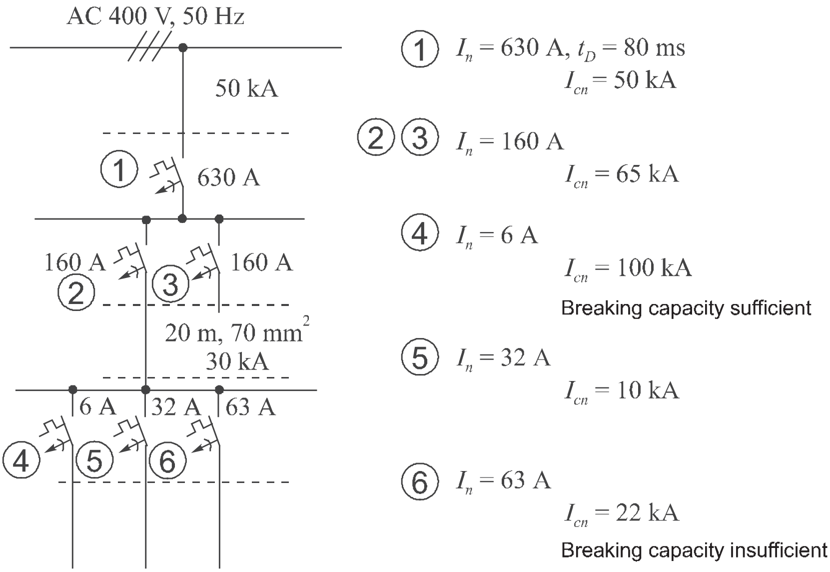


Figure 8.12 Evaluation of a system with power circuit breakers

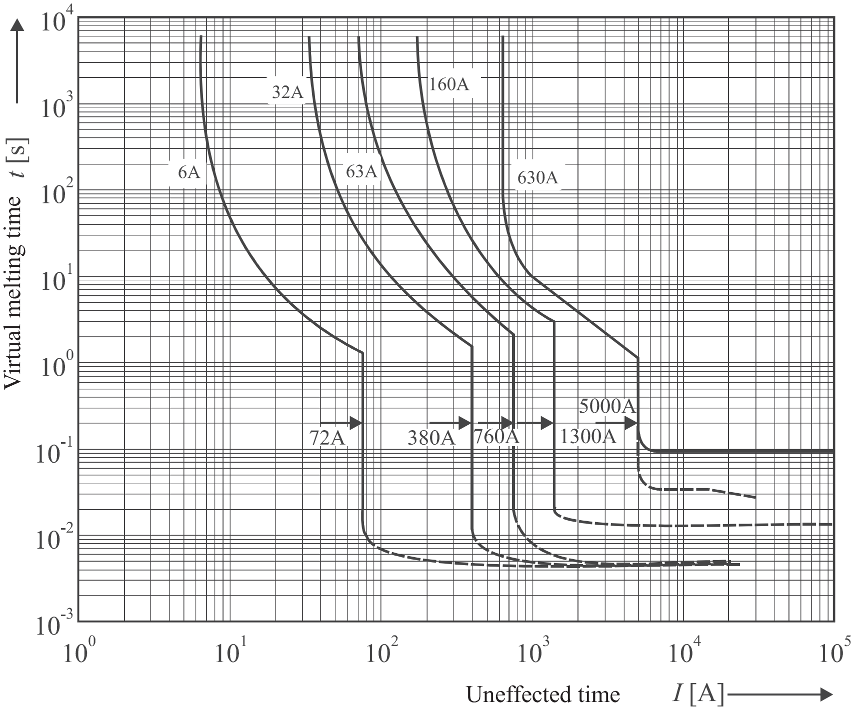


Figure 8.13 Time-current characteristics for power circuit breakers

8.2
Backup Protection

Back-up protection is ensured when in the event of a short circuit a downstream overcurrent protective device is protected by an upstream overcurrent protective device (Figure 8.14). This means that the rated breaking capacity of the downstream breaker can be smaller than the short circuit current at the installation location. The

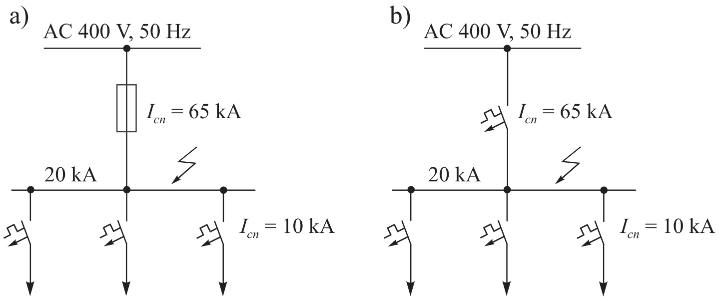
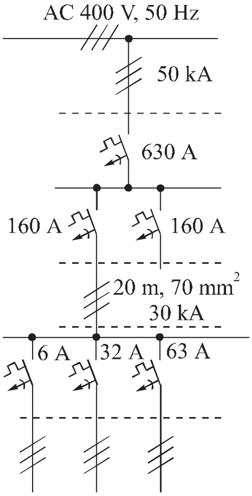


Figure 8.14 Back-up protection in a system

three-pole short circuit current must be determined at the installation location and the rated breaking capacity of the protective devices chosen checked with respect to whether backup protection is required or not. The selectivity limits and the backup protection can also be taken from the manufacturers' information.

Figure 8.15 shows a complete system with different branches. The following power circuit breakers are chosen:



Nominal current 630 A, time 80 ms
breaking capacity 50 kA

Nominal current 160 A,
breaking capacity 65 kA

Nominal current 6 A,
breaking capacity 65 kA

Nominal current 32 A,
Back-up protection up to 35 kA
Selectivity up to 10 kA

Nominal current 63 A,
Back-up protection up to 35 kA
Selectivity up to 10 kA

Figure 8.15 Selectivity and backup protection for a system with power circuit breakers

For the 6 A branch we choose a power circuit breaker with a breaking capacity of 100 kA. Back-up protection is not necessary. For the 32 A branch, with a breaking capacity of 10 kA, backup protection of 65 kA is required. For the 63 A branch, with a breaking capacity of 22 kA, 65 kA backup protection is already provided. The backup protection into account is sufficient to enable the power circuit breakers to keep the required 30 kA short circuit current under control.

9
Switchgear Combinations

EN 60439-1-2-3-4-5

Until 1996 the installation of ”non - factory assembled switchgear combinations” on the system site was permitted. From 1967 it was possible to manufacture “factory-assembled switchgear combinations” in industrial production. Since 1984, switchgear combinations are no longer produced on the system site. For the planning of distribution systems it is necessary to differentiate between the regulations for installation in accordance with IEC 60 364 and the design requirements in accordance with IEC 947-1. This in turn leads to:

1. in accordance with consumer units and meter panels regulations
   - Small distribution boards and meter mounting boards up to 63 A
   - Units with load circuits having $I_n < 63$ A
   - Protection type IP 31 or 3X (national standard)
2. in accordance with EN 60439, Part 1
   - Low-voltage switchgear combinations
3. in accordance with EN 60439-3
   - replaces for factory-assembled installation distribution systems.

9.1
Type-Tested Switchgear Combinations (TSC)

EN 60439, Part 1

Type-tested low-voltage switchgear combinations are identified by the complete system of the manufacturer, such as for cabinets, rails, modules and units. These switchgear combinations can be regarded as type-tested when their assembly is carried out according to the instructions of the manufacturer so that the equivalence with the original type or system for compliance with the standard is ensured.

Analysis and Design of Low-Voltage Power Systems. Ismail Kasikci

ISBN: 3-527-30483-5

9.2
Partially Type-Tested Switchgear Combinations (PTSC)

EN 6043

Partially type-tested low-voltage switchgear combinations include both type-tested and non-type-tested modules, assuming that the latter are derived (e.g. by calculation) from type-tested modules which have satisfied the corresponding testing. Such combinations result from the installation of units or modules not included in the type testing of the manufacturer, such as

- Compensation systems (on supporting plate)
- Electronic units
- Door installations
- On-site busbar supports
- Noncompliance with manufacturer's installation instructions

Partially type-tested switchgear combinations require the mandatory verification of the system installer in regard to:

- Temperature rise limits
- Short circuit behavior
- Leakage paths and clearances in air
- Short circuit calculation for the busbars
- Calculation of heat loss.

9.3
Proof of Short Circuit Strength

The proof of short circuit strength with respect to mechanical and thermal stresses of the electrical system follows in accordance with IEC 60 909 and IEC 865. This proof is not required:

- in auxiliary circuits with transformers
- with current-limiting overload protection equipment ($I_{cu} \leq 15$ kA),
- with a prospective rated short circuit current ($I_{cu} \leq 15$ kA).

For the mechanical short circuit stresses of the switchgear combinations, the peak short circuit current i_p , together with the initial symmetrical short circuit current I_k'' and the withstand ratio n must be determined in (Table 9.1).

A switchgear combination encompasses several circuits or a part of these. The term "rated diversity factor" has been introduced, which takes into account the changing and not simultaneous loading of the individual main circuits and which is important for the dimensioning of power supply feeders and busbars (Table 9.2). The factor n applies for all operational equipment for which the power dissipation is proportional to the current, such as switches, pushbuttons and indicator lights. The factor n' applies for all operational equipment for which the power dissipation is proportional to the square of the current, such as circuit breakers, contactors, load disconnection switches and fuse elements.

Table 9.1: Withstand ratio for different values of i_p and $\cos\varphi$

Effective value of peak short circuit current in kA	**cos φ**	**Withstand ratio n**
$i_p \leq 5$	0.7	1.5
$5 < i_p \leq 10$	0.5	1.7
$10 < i_p \leq 20$	0.3	2
$20 < i_p \leq 50$	0.25	2.1
$i_p > 50$	0.2	2.2

Table 9.2: Rated withstand ratio as a function of the number of main circuits

Number of main circuits	**TSC (n)**	**n′**
Power supply feeders	3	1
2 and 3	0.9	0.64
4 and 5	0.8	0.49
6 to 9	0.7	0.36
10 and more	0.6	0.25

9.4
Proof of Compliance With Upper Temperature Limits in Partially Type-Tested Switchgear Combinations

The calculation procedure for the evaluation of the upper temperature limit is very difficult and complicated. Proof of compliance can be shown with the use of special software and tables [55, 7].This section deals with the principles for the proof of compliance with upper temperature limits.

Computer-based evaluation (without ventilation) is used to determine the characteristics of the air overtemperature in the housing/enclosure. This is comprised of the ambient temperature of the switchgear combination (outside the housing) and the air overtemperature inside the housing. As a result of the calculation, it can be seen whether the operational equipment in the partially type-tested switchgear combination is able to function without problems for the rated currents used as the basis for the power loss and for the calculated overtemperature of the air within the housing. This determination concerns both the built-in switchgear and also the electrical connections, such as rails and isolated lines. As long as no other conditions are specified, the ambient temperature (average over 24 hours) is taken as 35 °C and the inner temperature of the cabinet 55 °C. In addition, the following conditions must also be fulfilled:

- The power losses must be approximately uniformly distributed within the housing.
- The air circulation must not be impeded.
- In a partially type-tested switchgear combination or in a field subdivided by partitions, there must be no more than three horizontal partitions.

- For air ducts, the cross-section of the exhaust air ducts must be at least 10 % greater than the cross-section of the air intake ducts.
- The built-in operational equipment is designed for DC and AC voltages up to 60 Hz and for a maximum power supply feeder current intensity of 3150 A.

The following points must be known in order to calculate the overtemperature:

- Smart I/O card protection type and protection class
- Type of installation of housing/enclosure
- Dimensions of housing/enclosure
- Type of construction (wall-mounted or floor-mounted distribution board)
- Equipment installed, heat losses, determination of space
- Location of installation (height, width and depth)
- Structure of lines
- Number of inner partitions
- Type selection
- Parts list, drawings
- Reserve space.

9.5
Differentiation of Power Losses

The power losses of the different operational equipment are taken from the manufacturers' information and added.

If the equipment is operated with a load current which deviates from the rated current, the power losses can then be described as in the following four groups:

1. Power losses proportional to the square of the current, e.g. main circuits of equipment, busbars and lines:

$$P_v = P_{Vr} \left(\frac{I_B}{I_r}\right)^2 . \tag{9.1}$$

2. Power losses which are nearly proportional to the current, e.g. rectifiers and thyristors:

$$P_v \sim P_{Vr} \frac{I_B}{I_r} . \tag{9.2}$$

3. Power losses which show a non-uniform behavior:

$$P_v = P_{Fe} + P_{Cu} \left(\frac{I_B}{I_r}\right)^2 . \tag{9.3}$$

4. Power losses which remain constant, e.g. magnetic coils for contactors and light bulbs:

$$P_v = P_{Vr} . \tag{9.4}$$

Here, the meanings of the symbols are:

P_V	Power loss
P_{Vr}	Power loss of equipment
I_B	Load current
I_r	Rated current
P_{Fe}	Iron losses
P_{Cu}	Copper losses

9.6
Checklist

All manufactured components are subject to a type check in accordance with IEC 439-1 and IEC 439-3 as well as EN 60439-1, which must be repeated for all modifications and in definite intervals of time. Prior to commissioning, the testing of all equipment for safe operation is required.

Table 9.8 presents an overview of all testing procedures for installation distribution systems.

Table 9.3: Checklist

Type testing	**Section EN 60439-1**
Proof of compliance with upper temperature limits by testing	8.2.1
Proof of dielectric strength by testing	
Proof of short circuit strength by testing	
Effectiveness of protective conductor PE	8.2.4
Proof of faultless connection between elements of the switchgear combination and the PE circuit by control or resistance measurement	
Proof of short circuit strength of the PE circuit by testing	
Proof of leakage paths and clearances in air	8.2.5
Proof of mechanical function	8.2.6
Proof of smart I/O card protection type	8.2.7
Proof of construction type and nameplates	8.2.8
Proof of impact strength	8.2.9
Proof of resistance to rusting	8.2.10
Proof of stability of insulating material against heat	8.2.11
Proof of stability of insulating material against extraordinary heat and fire resulting from internal electrical processes	8.2.12
Routine test	
Visual inspection of switchgear combination, including wiring, electrical function test as required	8.3.1
Insulation testing	8.3.2
Testing of protective measures, continuity of protective conductor connection	8.3.3

9.7
Notes on Project Planning

IEC 339-1 and EN 60439, Part 1 describe different constructions, such as:

- Open construction
- Tabular construction
- Closed construction
- Cabinet construction
- Desk-type construction
- Multi-box construction.

According to the material of the housing we differentiate between:

- Insulation material distribution systems
- Cast iron distribution systems
- Steel plate distribution systems
- Busbar distribution systems
- Stationary and mobile installation distribution systems.

The planning of low-voltage switchgear, distribution and control systems must meet certain criteria [31]. The purpose of the system must first be known, e.g.:

- Transformer stations up to 24 kV and 1250 kVA
- Low-voltage main distribution boards
- Main distribution boards
- Sub-distributions
- Motor distribution systems
- Lighting circuit distribution systems
- Power distribution systems
- Busbar distribution systems
- Distribution cabinets for reactive power compensation
- Weak current distribution systems.

9.8
Example: Computer Evaluation of Temperature Rise

Electrical operational equipment in switchgear and distribution systems give off current heat losses to the surroundings. In order to ensure the proper functioning of the built-in equipment, it is necessary to determine the upper temperature limits. The following example (Figure 9.16) illustrates the procedure for proving compliance with the upper temperature limits.

A system with the block wiring diagram shown in Figure 9.16 is located in a distribution cabinet with the dimensions H × W × T (2200 × 1000 × 600). The housing is a stand-alone construction and IP 5X on all sides, with no air ducts and without horizontal partitions inside.

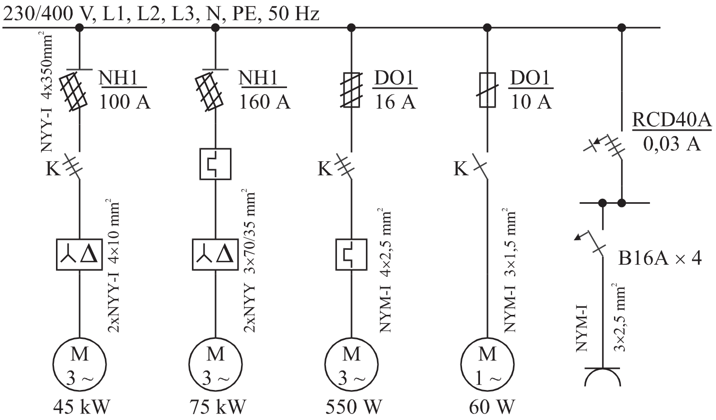


Figure 9.16 Block wiring diagram

The objective is to prove compliance with the upper temperature limits.

1. Determination of power loss from built-in equipment
   - 1 busbar system Cu 20 × 5 with $P_{Vr} = 63$ W
   - 1 power circuit breaker with $I_n = 100$ A, $I_B = 70$ A
   - 1 NH1 fuse switch disconnector with $I_n = 100$ A, $I_B = 80$ A, $P_{Vr} = 15.60$ W.

$$P_V = P_{Vr}\left(\frac{I_B}{I_n}\right)^2$$

$$P_V = 15.60\,\text{W}\left(\frac{70\,\text{A}}{100\,\text{A}}\right)^2 = 7.644\,\text{W}$$

- 1 NH1 fuse switch disconnector with $I_n = 160$ A, $I_B = 144$ A, $P_{Vr} = 20$ W.

$$P_V = 20\,\text{W}\left(\frac{144\,\text{A}}{160\,\text{A}}\right)^2 = 16.2\,\text{W}$$

- 1 D01 with $I_n = 16$ A, $I_B = 1.55$ A, $P_{Vr} = 2.61$ W.

$$P_V = 2.61\,\text{W}\left(\frac{1.55\,\text{A}}{16\,\text{A}}\right)^2 = 0.024\,\text{W}$$

- 1 D01 with $I_n = 10$ A, $I_B = 1.5$ A, $P_{Vr} = 2.61$ W.

$$P_V = 2.61\,\text{W}\left(\frac{1.5\,\text{A}}{10\,\text{A}}\right)^2 = 0.058\,\text{W}$$

- 1 RCD with $I_n = 40$ A, $I_B = 35$ A, $P_{Vr} = 13.81$ W.

$$P_V = 13.81\,\text{W}\left(\frac{35\,\text{A}}{40\,\text{A}}\right)^2 = 10.57\,\text{W}$$

- 1 circuit breaker B16 A with $I_n = 16$ A, $I_B = 8$ A, $P_{Vr} = 4.73$ W.

$$P_V = 4.73\,\mathrm{W}\left(\frac{8\,\mathrm{A}}{16\,\mathrm{A}}\right)^2 = 1.18\,\mathrm{W} \cdot 4 \; = 4.73\,\mathrm{W}$$

- 1 contactor with $P_{Vr} = 15.7$ W
- 3 relays with $P_{Vr} = 3.10$ W
- 3 star-delta switches with $P_{Vr} = 28.6$ W
- 1 external conductor with 2 × 4 × 10 mm^2, at 35 °C, $P_{Vr} = 4.82$ W
- 1 external conductor with 2 × 3 × 70/35 mm^2, at 35 °C, $P_{Vr} = 8.40$ W
- 1 external conductor with 4 × 2.5 mm^2, at 35 °C, $P_{Vr} = 3.50$ W
- 1 external conductor with 3 × 1.5 mm^2, at 35 °C, $P_{Vr} = 2.09$ W
- 1 external conductor with 3 × 2.5 mm^2, at 35 °C, $P_{Vr} = 3.50$ W
- 1 external conductor with 4 × 25 mm^2, at 35 °C, $P_{Vr} = 6.25$ W
- The total of all power losses for the built-in equipment and lines is then 108.936 W.

2. Determination of the effective cooling surface A_e

Table 9.4: Determination of the effective cooling surface

	A_0 m × m	**A_0 m^2**	**Surface factor *b***	**A_e Column 3·4**
1	2	3	4	5
Top surface	1 × 6	0.6	1.4	0.840
Front side	1 × 2.2	2.2	0.9	1.980
Back side	1 × 2.2	2.2	0.9	1.980
Left side surface	0.6 × 2.2	1.320	0.5	0.660
Right side surface	0.6 × 2.2	1.320	0.5	0.660
	$A_e\ \Sigma\ (A_0\ b)$ = total 6.12			

The individual surfaces are calculated from the dimensions of the housing. The appropriate surface factors *b* can be taken from Table 9.4.

3. The determination of the air overtemperature in the housing at half the height $\Delta\, t_{0.5}$ follows from the relationship

$$\Delta t_{0.5} = k\, d\, P_v^x$$

Factor *k*: It follows from Figure 9.2 for housings closed on all sides with $A_e >$ 1.25 m^2 that $A_e = 6.12\ \mathrm{m}^2$ and $k = 0.140$.
Factor *d*: It follows from Table 9.5 for housings closed on all sides with $A_e >$ 1.25 m^2 and 0 horizontal partitions that $d = 1.0$.

Table 9.5: Factor *d* for an effective cooling surface A_e 1.25 m^2

Number of horizontal partitions	Blower without air duct	Blower with air duct
0	1.00	1.00
1	1.05	1.05
2	1.15	1.10
3	1.30	1.15

Table 9.6: Exponent *x* for housing closed on all sides with an effective cooling surface A_e

Housing	*x*	
	$A_e > 1.25\ m^2$	$A_e < 1.25\ m^2$
Without air ducts	0.804	0.804
With air ducts	0.715	

Exponent *x*: It follows from Table 9.6 for housings closed on all sides with $A_e > 1.25\ m^2$ that $x = 0.804$. Substituting these values in the relationship above,

$$\Delta t_{0.5} = k\,d\,P_v^x = 0.140 \cdot 1.0, \cdot 219.912^{0.804} = 10.69\text{K}$$

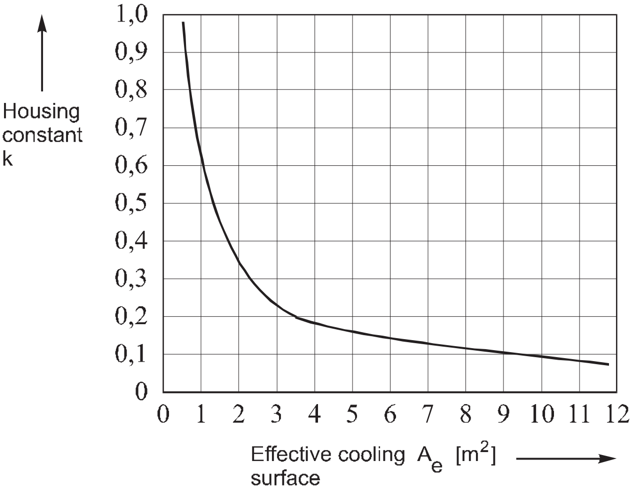


Figure 9.17 Housing constant k for housings without air ducts [55]

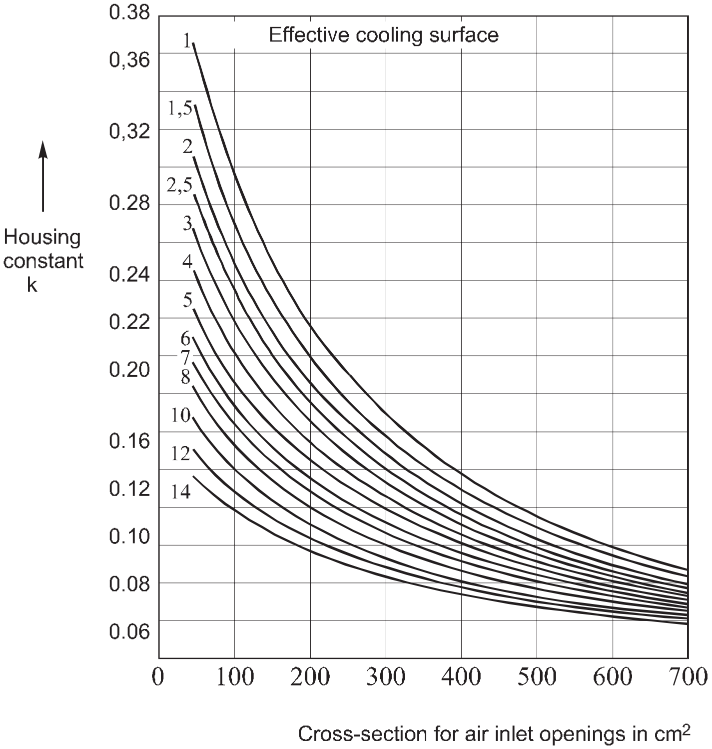


Figure 9.18 Housing constant *k* for housings with air ducts [55]

4. The determination of the air overtemperature in the housing on the top surface $\Delta t_{1.0}$ follows from the relationship

   $$\Delta t_{1.0} = c\,\Delta t_{0.5}$$

   The factor c is taken from Figure 9.4 for housings closed on all sides with $A_e > 1.25\ \text{m}^2$. This requires a knowledge of the variable

   $$f = \frac{(H\,\text{in}\,\text{m})^{1.35}}{A_G\,\text{in}\,\text{m}^2}$$

   $$= \frac{2.2^{1.35}}{1.0\cdot 0.6} = 4.832$$

   With this, from curve 3 (stand-alone medium housing) $c = 1.37$. Substituting this value in the relationship above, we obtain:

   $$\Delta t_{1.0} = c\,\Delta t_{0.5} = 1.37 \cdot 10.69\ \text{K} = 14.65\ \text{K}$$

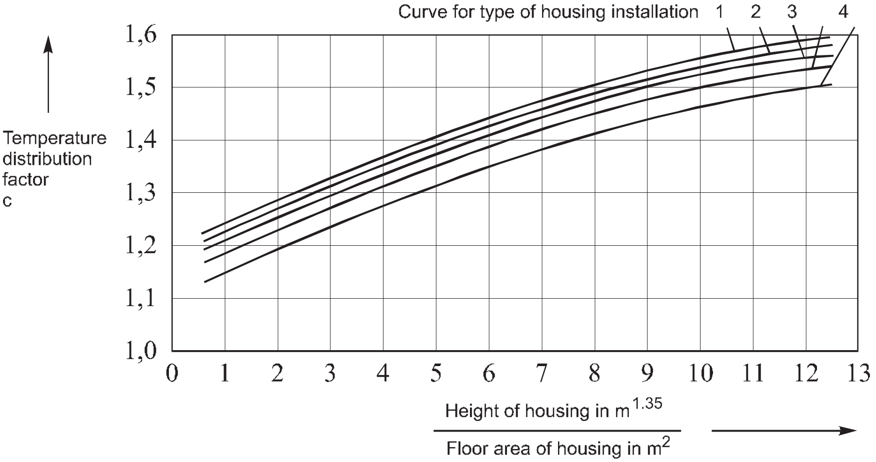


Figure 9.19 Temperature distribution factor *c* with air ducts for $A_e > 1.25^2$ [55]

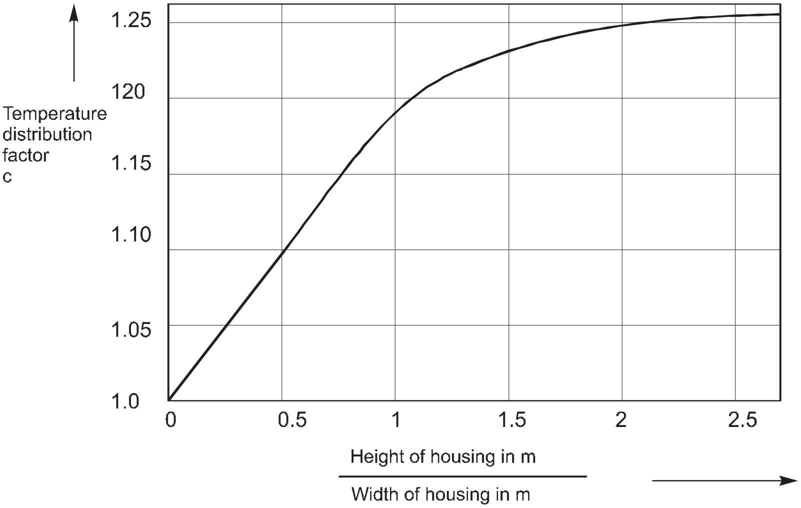


Figure 9.20 Temperature distribution factor *c* without air ducts for $A_e < 1.25^2$ [55]

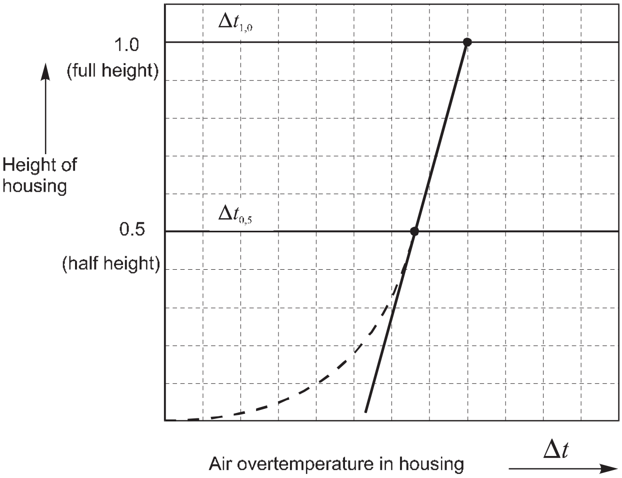


Figure 9.21 Temperature rise characteristic for housings with $A_e > 1.25^2$ [55]

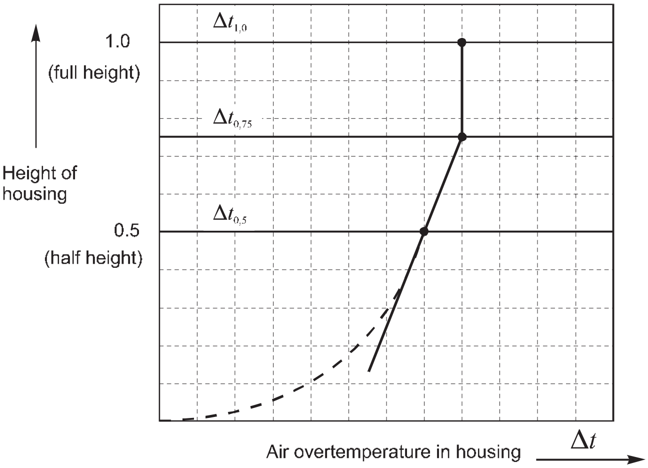


Figure 9.22 Temperature rise characteristic for housings with $A_e < 1.25^2$ [55]

For the calculated temperature of 14.65 K, at an ambient temperature of 35 °C a cabinet temperature of 49.65 °C will set in. Since (according to information of the manufacturer) a temperature of 55 °C is permissible, this constitutes proof that the upper temperature limits are satisfied.

Here the symbols have the meanings:

A_e	Effective cooling surface of the housing
A_0	Individual areas of the outer housing parts
H	Height of housing
A_G	Floor area of housing
b	Area factor
c	Temperature distribution factor
d	Factor for temperature rise with horizontal partitions inside housing
k	Housing constant
n	Number of horizontal partitions inside housing (maximum 3)
P	Effective power loss of operational equipment built into housing
x	Exponent
Δt	Overall air overtemperature in housing
$\Delta t_{0.5}$	Air overtemperature at half height within housing
$\Delta t_{0.75}$	Air overtemperature at 3/4 height within housing
$\Delta t_{1.0}$	Air overtemperature within housing at upper edge of housing

10
Protection Against Electric Shock

Protection against electric shock in accordance with IEC 60 364, Part 41 is a very important pilot standard within the harmonization document HD 384.4.41 S2 and IEC 364-4-41. It can be ensured by way of the following measures:

- Through protection under both normal operating conditions and under fault conditions (protection against both direct and indirect contact)
- Through protection under normal operating conditions (protection against direct contact, or basic protection) or
- through protection under fault conditions (protection against indirect contact, or fault protection)

10.1
Voltage Ranges

This standard redefines voltage ranges (Table 10.1) and cut-off times (Table 10.2 and 10.4).

Definition of voltage ranges according to the rated voltage of the network:

Voltage range I: Protection against electric shock is ensured by the value of the voltage. The voltage is limited for functional reasons.

Voltage range II: These are the voltages in household installations, as well as commercial and industrial systems, in public supply systems etc.

Table 10.1: Voltage ranges

	For AC currents		
Voltage range	Grounded networks		Isolated or ungrounded networks between external conductors
	External conductor-ground	Between external conductors	
I	U ≤ 50 V	U ≤ 50 V	U ≤ 50 V
II	50 V < U ≤ 600 V	50 V < U ≤ 1000 V	50 V < U ≤ 1000 V
	For DC currents		
I	U ≤ 120 V	U ≤ 120 V	U ≤ 120 V
II	120 V < U ≤ 900 V	120 V < U ≤ 1500 V	120 V < U ≤ 1500 V

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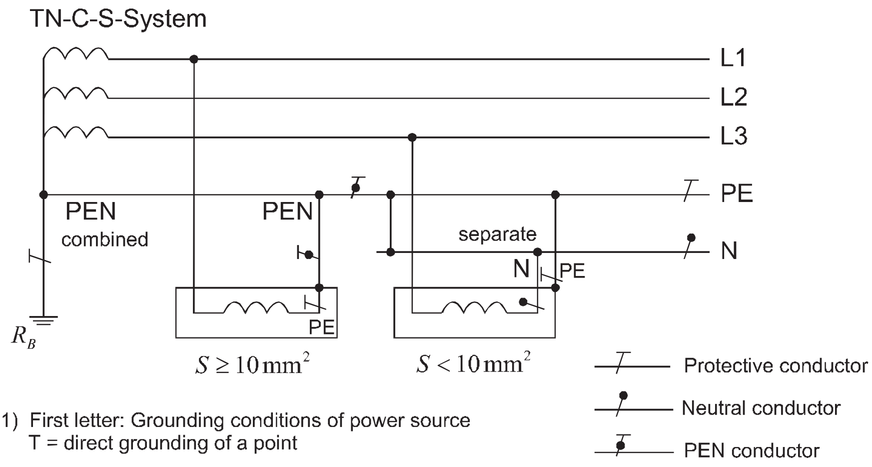
ISBN: 3-527-30483-5

10.2
Protection by Cut-Off or Warning Messages

This section deals with protection against electric shock under fault conditions. Persons and useful animals must be protected from the hazards of dangerous currents passing through the body. For this purpose, the coordination of systems with overcurrent protective equipment is of greatest importance. The protective measures of protection through cut-off in accordance with IEC 60 364, Part 41 for TN and TT systems or through warning for IT systems with equipotential bonding find use here.

10.2.1
TN-Systems

In TN systems (Figure 10.1), a large short circuit current must flow in order for the cut-off to take place within the specified time (0.2 s, 0.4 s and 0.5 s) (Table 10.2). If the tripping condition cannot be met, it is then necessary to lower the rated current of the overcurrent protection device or provide for an RCD or additional equipotential bonding.



1) First letter: Grounding conditions of power source
T = direct grounding of a point

2) Second letter: Grounding conditions of exposed conductive parts of electrical system
N = direct connection of exposed conductive parts through PEN or PE to operational ground electrode (in AC networks, generally the neutral point)
S = Neutral conductor and protective conductor functions through separate conductors
C = Neutral conductor and protective conductor functions combined in a single conductor (PEN conductor)

3) Permissible circuit breakers
Overcurrent protection equipment
RCDs

Figure 10.1 Circuitry of a TN system

Table 10.2: Rated voltages and maximum cut-off times for TN systems

Voltage U_0 in V	**Cut-off time in s**
230	0.4
400	0.2
> 400	0.1

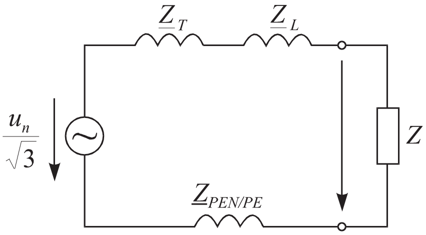


Figure 10.2 Equivalent circuit for a TN system

For the TS system, from Figure 10.2 we obtain the following cut-off conditions:

- Loop impedance

$$Z_S \leq \frac{U_0}{I_a} \tag{10.1}$$

- Single-pole short circuit current

$$I''_{k1} = \frac{U_0}{Z_v + \sum Z'\,l} \tag{10.2}$$

Here the meanings of the symbols are:

Z_s	Loop impedance
U_0	Line-to-ground voltage
I_a	Cut-off current of the overcurrent protective device
Z_v	Source impedance
Z'	Per-unit impedance
l	Length of cable or line

The relationship

$$I''_{k1} \geq I_a \tag{10.3}$$

must always hold true.

In accordance with IEC 909, for the single-pole short circuit current:

$$I''_{k1} = \frac{\sqrt{3}\, c_{min}\, U_n}{|\underline{Z}_1 + \underline{Z}_2 + \underline{Z}_0|} \tag{10.4}$$

In accordance with IEC 60 364, Supplement 5 we obtain:

$$I''_{k1} = \frac{\sqrt{3}\, c_{min}\, U_n}{3\sqrt{(2\,R_L + R_v)^2 + (2\,X_L + X_v)^2}} \tag{10.5}$$

With $R_L = l\,R'_L$ and $X_L = l\,X'_L$, it follows that:

$$I''_{k1} = \frac{\sqrt{3}\, c_{min}\, U_n}{3\sqrt{(2\,l\,R'_L + R_v)^2 + (2\,l\,X'_L + X_v)^2}} \tag{10.6}$$

With an impedance phase angle of 28°, we then obtain:

$$R_v = Z_v \cos 28^\circ \tag{10.7}$$

$$X_v = Z_v \sin 28^\circ \tag{10.8}$$

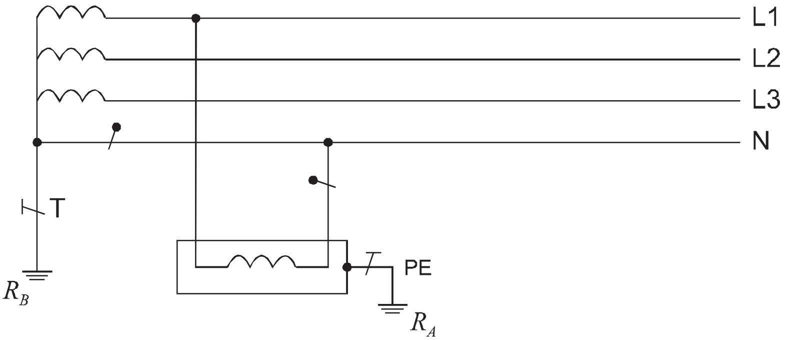
This averaged impedance phase angle is applicable for power supply companies and industrial networks.

Here, the symbols have the meanings:

c_{min}	Voltage factor
U_n	Rated voltage
I''_{k1}	Single-pole short circuit current
R_v	Resistance per unit length
X_v	Reactance per unit length
Z_v	Loop impedance of supply network from current source to overcurrent protective device

10.2.2
TT-Systems

TT systems (Figure 10.3) are characterized by the grounding of the source current and the operational equipment. Cut-off with overcurrent protective equipment is difficult to achieve due to the required low-resistance grounding resistor. As a result, predominantly RCDs are used.



First letter: Grounding conditions for current source
T = direct grounding of a point
Second letter: Grounding conditions for exposed conductive parts of electrical system
T = direct grounding of the operational equipment
Permissible circuit breakers
RCD = RCDs
Overcurrent protective equipment

Figure 10.3 Circuitry of a TT system

For TT systems, from Figure 10.4 we obtain the following conditions:

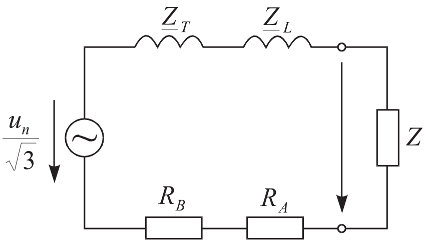


Figure 10.4 Equivalent circuit for a TT system

- Grounding resistor with protective equipment

$$R_A \leq \frac{U_L}{I_a} \tag{10.9}$$

- Grounding resistor with RCD

$$R_A \leq \frac{U_L}{I_{\Delta n}} \tag{10.10}$$

- Grounding resistor with selective RCD

$$R_A \leq \frac{U_L}{2\, I_{\Delta n}} \tag{10.11}$$

- Grounding resistance for several RCDs in parallel
  The total grounding resistance of the system is calculated considering Table 10.3

$$R_A \leq \frac{U_L}{g \sum I_{\Delta n}} \tag{10.12}$$

  In distribution circuits, a cut-off time of ≤ 1 s is permissible to obtain selectivity. Cut-off with protective equipment must take place without delay or, for a short trigger time with rising current, within a maximum time of 5 s.

Table 10.3: Coincidence factor

Number of RCDs	***g***
2 to 4	0.5
5 to 10	0.35
More than 10	0.25

- Single-pole short circuit current
  For a short circuit to an exposed conductive part, the fault current becomes a single-pole short circuit current. The following relationships apply:

$$I''_{k1} = \frac{U_n}{\sqrt{3} \cdot Z_s} \tag{10.13}$$

$$I''_{k1} = \frac{\sqrt{3} \cdot U_n}{2 \cdot \underline{Z} + \underline{Z}_0} \tag{10.14}$$

  Assuming that the grounding resistances are larger than the network impedances, then (Figure 10.4):

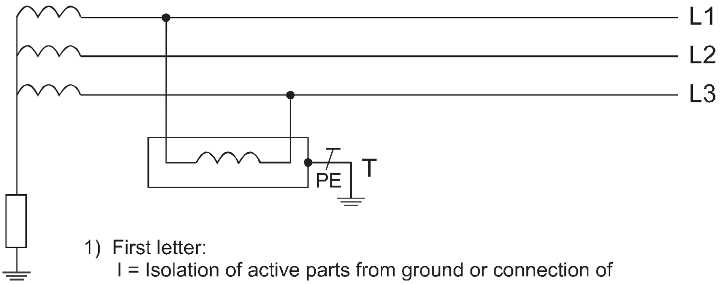
$$II''_{k1} = \frac{U_n}{\sqrt{3} \cdot (R_A + R_B)} \tag{10.15}$$

Here, the symbols have the meanings:

R_A	Sum of resistances of grounding electrode and protective conductor
R_B	Operating impedance
$\underline{Z}_s$	Loop impedance
$\underline{Z}$	Positive-sequence impedance
$\underline{Z}_L$	Line impedance
$\underline{Z}_{0T}$	Zero-sequence impedance of the transformer
U_L	Touch voltage
I_a	Cut-off current of protective device
$I_{\Delta n}$	Rated differential current of RCD

10.2.3
IT Systems

For IT systems the current source is not grounded, i.e. isolated from ground or connected through a high impedance to ground. The operational equipment must be connected to a grounding electrode (Figure 10.5). The leakage current is very small and can be taken from Figure 10.7. The first fault is indicated by the isolating equipment and can be localized, i.e. no cut-off may take place here. The second fault must lead to a cut-off. IT systems must be used for example in hospitals (rooms according to class of application) and in mining.



1) First letter:
I = Isolation of active parts from ground or connection of active parts through impedance to ground (indirect grounding)

2) Second letter:
Grounding conditions for exposed conductive parts of electrical system
T = exposed conductive parts grounded directly, independently of current source

3) Permissible protective and monitoring devices:
Isolation monitoring devices
Overcurrent protective devices
Fault current protective device

Figure 10.5 Circuitry of an IT system

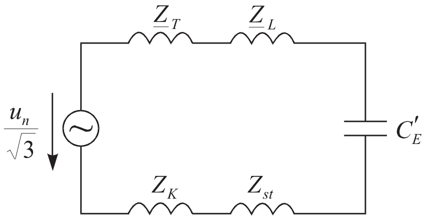


Figure 10.6 Equivalent circuit for an IT system

For IT systems, from Figure 10.6 we obtain the following cut-off conditions:

- Grounding resistor

$$R_A \leq \frac{U_L}{I_d} \tag{10.16}$$

Table 10.4: Rated voltages and maximum cut-off times for IT systems (second fault)

Rated voltage of electrical system in V	Cut-off time in s Neutral conductor not distributed	Cut-off time in s Neutral conductor distributed
230/400	0.4	0.8
400/690	0.2	0.4
580/1000	0.1	0.2

The following condition must be satisfied if the neutral conductor is not distributed:

$$Z_S \leq \frac{U}{2\,I_a} \tag{10.17}$$

The following condition must be satisfied if the neutral conductor is distributed:

$$Z_S' \leq \frac{U_0}{2\,I_a} \tag{10.18}$$

- Fault current

$$I_F = \frac{\sqrt{3}\,U_n}{3\,Z_F - \frac{1}{w\,C_E'\,l}} \tag{10.19}$$

$$Z_F = Z_K + Z_{st} \tag{10.20}$$

$$Z_0 = -\frac{1}{w\,C_E'\,l} \tag{10.21}$$

This results in:

$$I_F = \frac{\sqrt{3}\,U_n}{Z_0 + 3\,Z_F} \tag{10.22}$$

The meanings of the symbols are:

R_A	Grounding resistance
U_L	Touch voltage
I_d	Leakage current
C_E'	Capacitance to ground
Z_F	Fault impedance
Z_0	Zero-sequence impedance
Z_k	Impedance of exposed conductive parts
Z_{st}	Site impedance
Z_S	Impedance of fault loop, consisting of external conductor and protective conductor of the circuit

Z'_S Impedance of fault loop, consisting of neutral conductor and protective conductor of the circuit
U_0 Rated AC voltage between external conductor and neutral conductor
U Rated AC voltage between external conductors

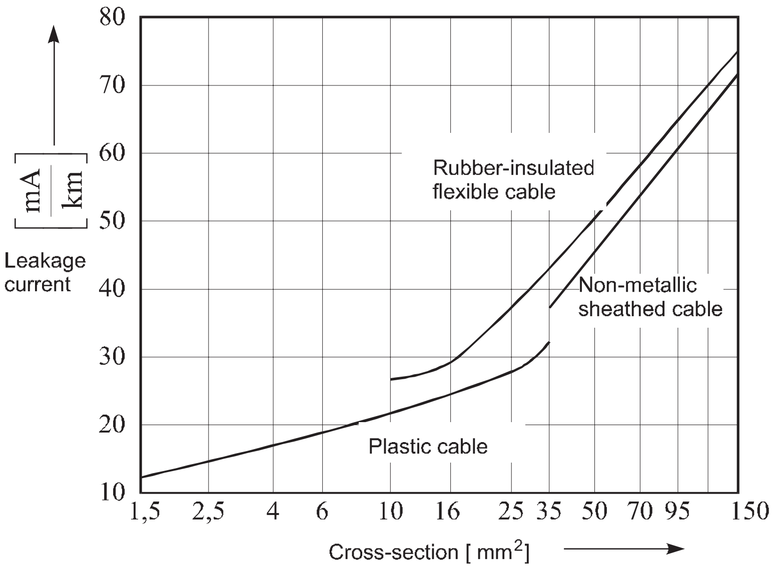


Figure 10.7 Leakage current in an IT system

During or following installation every system must, before the user begins operation, be inspected, tested and measured. The requirements of the following standards must be fulfilled:

- IEC 60 364, Part 61: Measurements for the testing of protective measures in heavy current systems before initial startup
- IEC 60 364 Part 701: Measurements for the testing of protective measures for electrical equipment
- IEC 60 364 Part 702: Measurements for the testing of protective measures following repairs or modifications
- EN 50110-1: Measurements for the testing of protective measures for requalification tests.

The measurements must take the errors in measurements of the measuring instrument and the method of measurement into account. For measuring instruments it is also necessary to consider the operating error. Along with the operating error, systematic errors (fundamental errors in the method of measurement) must also be considered (Table 10.5).

Table 10.5: Summary of measurement errors and measuring instrument errors

	Error in %
Resistance for 80 °C line temperature $R_x = R_{20°}\,[1+\kappa\Delta\vartheta]$	24
Error of measuring instrument	± 5
for loop impedance measurement	+30
for single-pole short circuit current measurement	–30

10.2.4
Summary of cut-off times and loop resistances

Table 10.6 summarizes the cut-off currents and loop resistances in a TN system. These values can be used as the basis for the measurement and calculation of electrical systems. They apply at 80 °C line temperature. When measurements are performed at other temperatures it is necessary to correct for the loop resistance. In addition, the operating error of the measuring instrument must be considered (Table 10.5).

Table 10.6: Summary of overcurrent protective equipment and loop resistances in TN systems

	Rated currents of overcurrent protective equipment										
I_n	6	10	16	20	25	35	50	63	80	100	160
Low-voltage fuses of duty class gG in accordance with IEC 269-1											
Cut-off currents in A											
I_a (0.2s)	60	100	148	192	250	372	578	750	990	1310	2080
I_a (0.4s)	48	80	140	180	210	300	450	600	800	1000	1850
I_a (5s)	28	46	70	85	118	173	260	350	452	573	995
Loop resistances in Ω											
Z_S (0.2s)	3.7	2.2	1.5	1.2	0.9	0.6	0.4	0.3	0.22	0.17	0.11
Z_S (5s)	7.8	4.7	3.2	2.6	1.9	1.3	0.8	0.6	0.5	0.4	0.22
Circuit breakers in accordance with IEC 898, B characteristic Cut-off current $I_a = 5 \cdot$ rated current of overcurrent protective device											
I_a	30	50	80	100	125	175	250	315	400	500	800
Z_S	7.3	4.4	2.8	2.2	1.8	1.3	0.886	0.55	0.44	0.28	
Circuit breakers in accordance with IEC 898, C characteristic Power circuit breakers in accordance with EN 60439-1 for corresponding setting Cut-off current $I_a = 10 \cdot$ rated current of overcurrent protective device											
I_a	60	100	160	200	250	350	500	630	800	1000	1600
Z_S	3.6	2.2	1.4	1.1	0.88	0.63	0.45	0.35	0.27	0.22	0.14
Circuit breakers in accordance with IEC 898, K characteristic Motor starter in accordance with EN 60439-1, Parts 102 and 104 Cut-off current $I_a = 15 \cdot$ rated current of overcurrent protective device											
I_a	90	150	240	300	375	525	750	945	1200	1500	2400
Z_S	2.4	1.5	0.9	0.7	0.6	0.4	0.29	0.23	0.18	0.15	0.09

10.2.5

Example 1: Checking Protective Measures

On the basis of Figure 10.8, check the protective measures for a series resistor of R_V = 0.6 Ω.

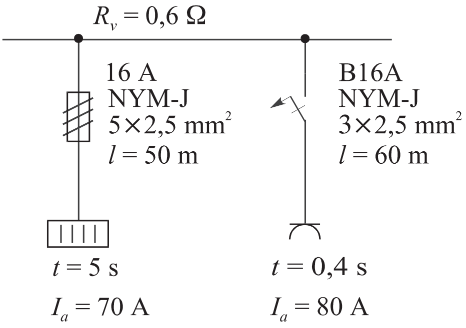


Figure 10.8 Protective measure with heating unit and electrical outlet

a) With an electrical outlet

Loop resistance:

$$R_S = R_V + R_L = 0.6\,\Omega + 1.24\,\frac{2\cdot 60\,\text{m}}{56\frac{\text{m}}{\Omega\,\text{mm}^2}\cdot 2.5\,\text{mm}^2} = 1.66\,\Omega$$

According to Table 10.6, the cut-off current for B16A is 80 A. With 0.4 seconds cut-off time, the fault current is given by:

$$I_F = \frac{230\,\text{V}}{1.66\,\Omega} = 138.5\,\text{A}$$

$$I_F > I_a \longrightarrow 138.5\,\text{A} > 80\,\text{A}$$

The cut-off condition is therefore fulfilled.

b) With a heating unit

$$t_a \leq 5\,\text{s}$$

$$R_S = R_V + R_L = 0.6\,\Omega + 1.24\,\frac{2\cdot 50\,\text{m}}{56\frac{\text{m}}{\Omega\,\text{mm}^2}\cdot 2.5\,\text{mm}^2} = 1.485\,\Omega$$

From Table 10.6, the cut-off current is 70 A for gL16A.

$$I_F = \frac{230\,\text{V}}{1.485\,\Omega} = 154.88\,\text{A}$$

$$I_F > I_a \longrightarrow 154.88\,\text{A} > 70\,\text{A}$$

The cut-off current is less than the fault current. This fulfills the cut-off condition.

10.2.6
Example 2: Determination of Rated Fuse Current

In a circuit the loop resistance is measured to be $R_S = 1.8\,\Omega$ with $U_0 = 230\,\text{V}$. Find the rated current of the fuse for 0.4 seconds and 5 seconds.

$$I''_{k1} = \frac{U_0}{R_S} = \frac{230\text{V}}{1.8\,\Omega} = 127.7\,\text{A}$$

For cut-off times of 0.4 seconds and 5 seconds, from the time-current characteristic (Figure 7.28) for *D*02 gL fuse elements we find the rated currents:

$$0.4\,\text{s} \Rightarrow I_n = 20\,\text{A} \qquad 5\,\text{s} \Rightarrow I_n = 25\,\text{A}$$

10.2.7
Example 3: Calculation of Maximum Conductor Length

Given:
Rated current of fuse $I_n = 25\,\text{A}$
Line-to-ground voltage $U_0 = 230\text{V}$
Cross-section of conductor $S = 4\,\text{mm}^2$

The cut-off times can be read from the time-current characteristic (Figure 7.28): for 0.4 seconds: $I_a = 170\,\text{A}$; for 5 seconds: $I_a = 80\,\text{A}$
Calculation of the loop resistance:

$$R_S = \frac{U_0}{I_a} = \frac{230\,\text{V}}{80\,\text{A}} = 2.875\,\Omega$$

$$R_S = \frac{U_0}{I_a} = \frac{230\,\text{V}}{170\,\text{A}} = 1.35\,\Omega$$

Calculation of the length:

$$l_{5s} = \frac{R_S\,\kappa\,S}{2} = \frac{2.875\,\Omega \cdot 56\,\frac{\text{m}}{\Omega\,\text{mm}^2} \cdot 4\,\text{mm}^2}{2} = 322\,\text{m}$$

$$l_{0.4s} = \frac{R_S\,\kappa\,S}{2} = \frac{1.35\,\Omega \cdot 56\,\frac{\text{m}}{\Omega\,\text{mm}^2} \cdot 4\,\text{mm}^2}{2} = 151.2\,\text{m}$$

10.2.8
Example 4: Rated current for a TT System

Determination of the rated current for the overcurrent protective device of a TT system:

Given:
Touch voltage $U_L = 50\,\text{V}$
Ground resistance $R_A = 2\,\Omega$
The cut-off current is then:

$$I_a \leq \frac{U_L}{R_A} = \frac{50\,\text{V}}{2\,\Omega} = 25\,\text{A}$$

With this cut-off current, we can obtain the rated currents for the fuses from the time-current characteristic (Figure 7.28):

for 5 seconds: $I_n = 10\,\text{A}$; for 0.4 seconds: $I_n = 6\,\text{A}$

With no RCD this overcurrent protective equipment must be installed. With an RCD $(0.03\,\text{A})$ a resistance of results.

$$R_A \leq \frac{U_L}{I_{\Delta n}} = \frac{50\,\text{V}}{0.03\,\text{A}} = 1666\,\Omega$$

The determination of the overcurrent protective device then follows as for the TN system.

10.2.9
Example 5: Cut-Off Condition for an IT System

A warning message is given for:

1. Errors reported by the isolation monitoring and cut-off
2. Errors due to tripping of the overcurrent protection device.

Calculation of the loop resistance with a cut-off current of 80 A:

$$Z_S \leq \frac{\sqrt{3}\,U_0}{2\,I_a} = \frac{\sqrt{3}\cdot 230\text{V}}{2\cdot 80\,\text{A}} = 2.48\,\Omega \qquad \text{without neutral conductor}$$

$$Z_S \leq \frac{U_0}{2\,I_a} = \frac{230\text{V}}{2\cdot 80\,\text{A}} = 1.43\,\Omega \qquad \text{with neutral conductor}$$

10.2.10
Example 6: Protective Measure for Connection Line to a House

On a service panel for the connection line to a house the PEN conductor is not properly connected, so that a contact resistance remains. On the house service panel itself, however, the PE is grounded, with $R_{B2} = 10\,\Omega$ (Figure 10.9).

1. What is the touch voltage U_B which occurs for breakage of the PEN conductor when a load with $P = 4\,\text{kW}$ is operated?
2. What is the touch voltage which occurs for a contact resistance of $1\,\Omega$ when a load with $P = 4\,\text{kW}$ is operated?
3. What is the short circuit current which flows for a total short circuit to conductive parts (neglect line impedances)?

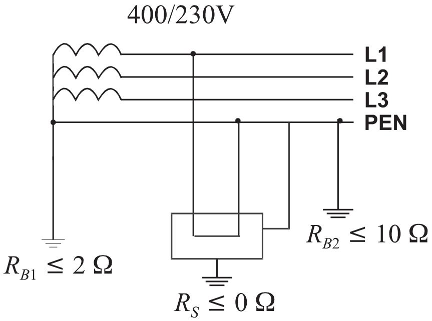


Figure 10.9 Protective measure for connection line to a house

Solution 1:

$$P = U\,I$$

$$I = \frac{P}{U_0} = \frac{4\,\text{kW}}{230\,\text{V}} = 17.4\,\text{A}$$

$$R = \frac{230\,\text{V}}{17.4\,\text{A}} = 13.2\,\Omega$$

$$I_F = \frac{U_0}{R_G} = \frac{230\text{V}}{13.2\,\Omega} = 17.4\,\text{A}$$

$$U_B = 10\,\Omega \cdot 17.4\,\text{A} = 174\,\text{V}$$

Solution 2:

$$R_{Total} = 2\,\Omega + (10\,\Omega + 2\,\Omega)||1\,\Omega = 12.92\,\Omega$$

$$I_1 = \frac{230\,\text{V}}{12.92\,\Omega} = 17.8\,\text{A}$$

$$U = 17.8\,\text{A} \cdot 12.92\,\Omega = 230\,\text{V}$$

$$I_2 = \frac{230\text{V}}{12\,\Omega} = 19.16\,\text{A}$$

$$U_B = 19.16\,\text{A} \cdot 10\,\Omega = 191.6\,\text{V}$$

Solution 3:

$$I_k = \frac{U}{R} = \frac{230\text{V}}{12\,\Omega} = 19.17\,\text{A}$$

10.2.11
Example 7: Protective Measure for a TT System

With a ground resistance of $R_E = 1\,\Omega$ and a resistivity of $\rho_E = 300\,\Omega$ (Figure 10.10) find:

a) The length of the grounding strip

$$R_E \leq \frac{U_L}{I_a} \leq \frac{50\,\text{V}}{50\,\text{A}} \leq 1\,\Omega$$

$$R_E \approx \frac{3\,\rho_E}{l}\ (\text{for } l > 10\,\text{m})\ \textit{(in accordance with HD 637 S1)}$$

$$l \approx \frac{3{\cdot}300\,\Omega\,\text{m}}{1\,\Omega} = 900\,\text{m}$$

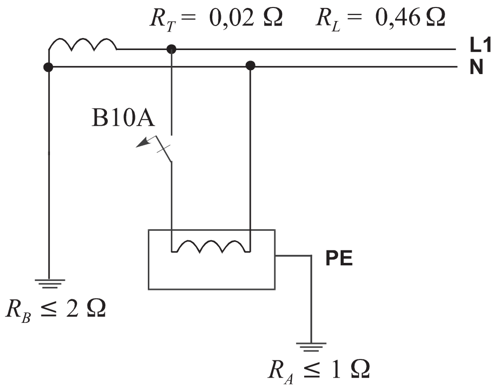


Figure 10.10 Protective measure for a TT system

b) The fault current

$$I_F = \frac{230\,\text{V}}{(0.02{+}0.46{+}1{+}2)\,\Omega} = 66.1\,\text{A}$$

c) The voltage on the grounding strip

$$U_E = I_F\,R_A = 66.1\,\text{A}\cdot 1\,\Omega = 66.1\,\text{V}$$

The larger the value of I_a, the more difficult it is to obtain the ground resistance. Here it is necessary to use an RCD.

11
Current Carrying Capacity of Conductors and Cables

IEC 60 364, Part 43, IEC 523

11.1
Terms and Definitions

- Overcurrent:
  Overcurrent refers to every overload current and every short circuit current which is greater than the maximum permissible current carrying capacity I_z.
- Overload:
  The overload is greater than the rated current and arises during the fault-free operating condition. High loading of a motor or the simultaneous use of several loads can lead to overloading of the cable or the line.
- Short circuit:
  The terms short circuit and ground fault are used to describe faults in the functional isolation of operational equipment when energized parts are shunted out as a result. In accordance with IEC 60 909, a short circuit arises through a fault, accidentally or intentionally, between active lines under voltage standing in opposition, through a low resistance or impedance.
- Short circuit current:
  In accordance with IEC 60 909, a short circuit current flows as a result of a fault for the duration of the short circuit. Here it is necessary to distinguish between short circuit current at the fault location and the transferred short circuit currents. Lines and cables must be protected against excessive temperature rises as a result of an overcurrent (overload and short circuit protection) with overcurrent protective equipment.
- Load carrying capacity:
  The load carrying capacity defines, under certain conditions, the highest permissible currents.
- Loading:
  Loading describes the currents to which a cable or line is subjected through a particular mode of operation or a fault condition.

Analysis and Design of Low-Voltage Power Systems. Ismail Kasikci

ISBN: 3-527-30483-5

- Current carrying capacity:
  The current carrying capacity of a cable or a line depends on the type of installation, the grouping of lines and cables, the ambient temperature, the operating temperature, the number of core wires and the insulation material, which must be considered in the form of correction factors for the dimensioning of lines and cables.
- Rated short-time current density:
  This value is the effective value of the current density which a cable is able to withstand the rated short circuit duration.
- Rated short-time current:
  This value is the effective value of the current which electrical operational equipment, under predefined conditions, is able to withstand over the rated short circuit duration. The rated short-time current and the related rated short circuit duration are determined by the manufacturer of the operational equipment.

The difference between overload and overcurrent lies in the cause of the fault. For a short circuit, the overcurrent arises as a result of a defect or a wrong operation. The overload causes a current which exceeds the maximum current carrying capacity.

The choice of circuit breaker follows on the basis of the tripping behavior and the breaking capacity, which is matched to the tripping behavior. The lines in heavy current systems are made of copper (Cu) and aluminum (Al).

The effective electrical cross-section is taken as the cross-section of the line. The resistivity for copper at 20 °C is $\varrho_{20} = 0.017241\,\Omega\,\mathrm{mm}^2/\mathrm{m}$. The temperature coefficient is $3.93{\cdot}10^{-3}/\mathrm{K}$ and increases or decreases with the conductivity. The resistivity for aluminum at 20 °C is $\varrho_{20} = 0.028264\,\Omega\,\mathrm{mm}^2/\mathrm{m}$. The temperature coefficient is $4.03 \cdot 10^{-3}/\mathrm{K}$ and increases or decreases with the conductivity, as with copper.

The temperature dependence of the resistivity is:

$$R_{\vartheta} = R_{20^{\circ}\mathrm{C}}\,[1 + \alpha\,(\vartheta - 20^{\circ}\mathrm{C})] \tag{11.1}$$

The symbols have the meanings:

α Temperature coefficient
ϑ Temperature

11.2
Overload Protection

The matching of overload protection equipment for cables and lines must be based on the following conditions (IEC 60 364, Part 43):

- Nominal current rule
  The overload protection equipment should be chosen so that its rated current I_n or current setting I_e for power circuit breakers is less than or equal to the current carrying capacity I_z of the cable or line:

$$I_b \leq In \leq Iz \tag{11.2}$$

- Tripping rule
  The conventional tripping current I_2 must not exceed 1.45 times the current carrying capacity of the cable or line:

$$I_2 \leq 1.45\, I_z \tag{11.3}$$

Here, the meanings of the symbols are:

I_b	Operating current
I_n	Nominal current
Iz	Permissible current carrying capacity
I_2	Conventional tripping current

The overload protection can be determined:

- from tables
- by calculation
- from the current carrying capacity of the line or cable.

Layout of overload protection equipment:

1. Overload protection devices must be installed at all places for which the current carrying capacity is reduced.
2. Overload protection devices are required at the beginning of the circuit.
3. Overload protection devices can be staggered as long as this does not endanger the overload protection of the circuit.
4. Overload protection can be neglected if the occurrence of an overload is not expected.
5. Overload protection must not be implemented if interruption of the circuit can pose a danger.

11.3
Short Circuit Protection

Short circuit currents must be interrupted before they can damage the insulation of lines, connections and terminal connections or even operational equipment. Here a short-term overtemperature is permissible. The parameters affecting this short-term short circuit strength and which determine the required cables and lines are:

- Current
- Length of time
- Voltage drop
- Power transferred
- Protective measures
- Electrical resistivity

- Operation temperatures of the system
- Permissible operating temperature of the cable or line
- Cross-section of the cable or line
- Specific thermal capacity
- Corrosive stress
- Regulations to be observed.

The short circuit protection can be determined:

- in accordance with IEC 60 909
- from tables
- from measurements in the system based on instructions from the power supply company
- from the current carrying capacity of the line or cable.

Layout of overload protection equipment:

1. Overload protection devices must be installed at all places for which the current carrying capacity is reduced.
2. Overload protection equipment against short circuits can be moved along the line or cable if the part of the line between the reduced cross-section and the overload protection device is not more than 3 m long and there is no reason to expect a fire hazard and injury to persons, or the occurrence of a short circuit is not expected. Here it is necessary to make sure that the electrical installation is well grounded and secure against short circuits.

Selection of overload protection equipment:

1. Common overload protection device against short circuits and overloading
2. Calculation of the permissible cut-off time
3. Limitation of the line length

Short circuit currents must be interrupted by overload protection devices before the temperature limits for lines and cables are reached. The calculation of the permissible cut-off time up to 5 seconds can be done as follows:

$$t_2 = \left(\frac{k\,S}{I''_{k1}}\right)^2 \tag{11.4}$$

When the calculated cut-off times are below 0.1 seconds, the matching of power circuit breakers and circuit breakers must then be according to the following equation:

$$k^2\,S^2 > I^2\,t \tag{11.5}$$

This condition is always satisfied when the cross-section of the line is at least 1.5 ^{2} and the source fuse is 63 A.

It must always hold true that

$$t_1 < t_2 \tag{11.6}$$

The meanings of the symbols are:

t_1 Cut-off time of the overload protection device in seconds
t_2 Permissible cut-off time or short circuit duration in seconds
I_f Fault current (smallest short circuit current) in A
k Material factor or specific conductor factor in $\frac{\mathrm{A}\sqrt{\mathrm{s}}}{\mathrm{mm}^2}$ after Table 11.3
S Line cross-section in mm^2

The matching of reference values for lines an overload protection equipment is illustrated in Figure 11.1.

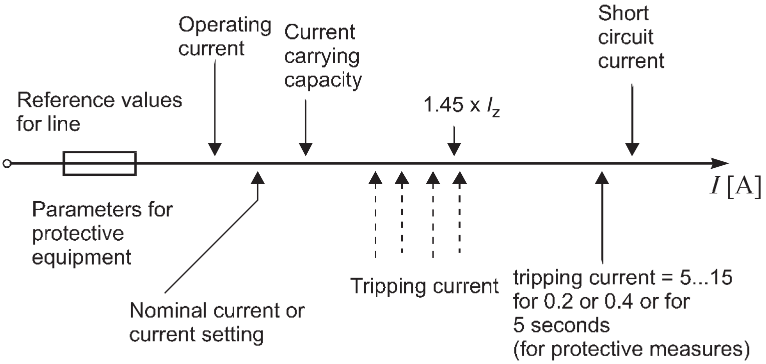


Figure 11.1 Matching of reference values for lines and overload protection equipment

Table 11.1, can be used for the current carrying capacity of cables or lines and for the selection of overcurrent protective equipment for protection in the event of overloading in a building wiring installation at 30 °C.

For disconnecting the overload and the short circuit current it is necessary to determine the overload and short circuit tripping devices (Table 11.1).

Table 11.1: Overload protection equipment, conventional tripping current and cut-off currents

OPE	Delayed thermal tripping device (overload protection) I_2	Short-time delay magnetic tripping device (short circuit protection) I_5
A	1.45 I_n	3 I_n
B	1.45 I_n	5 I_n
C	1.45 I_n	10 I_n
D	1.45 I_n	15 I_n
Z	1.2 I_n	3 I_n
K	1.2 I_n	20 I_n
E	1.2 I_n	6.25 I_n

It is also possible to determine the let-through energy of a circuit breaker from the energy equation [59]

$$m\,c\,\Delta\vartheta = R\int i^2\,\mathrm{d}t \tag{11.7}$$

The temperature rise of the conductor is then given by:

$$\Delta\vartheta = \frac{\rho\frac{l}{S}\int i^2\,\mathrm{d}t}{l\,S\,\rho_m\,c} \tag{11.8}$$

$$\Delta\vartheta = \frac{\int i^2\,\mathrm{d}t}{S\,\rho_m\,c} \tag{11.9}$$

The meanings of the symbols are:

$\rho_m\,l\,S$ Mass of conductive material

ρ_m Density of conductive material

c Specific thermal capacity of conductive material

$\Delta\vartheta$ Temperature rise

$R = \frac{\rho_m\,l}{S}$ Resistance of conductor

For copper:

$$\rho = 0.017241\,\frac{\Omega\,\mathrm{mm}^2}{\mathrm{m}}$$

$$\rho_m = 8.92\,\frac{\mathrm{kg}}{\mathrm{dm}^3}$$

$$c = 380\,\frac{\mathrm{Ws}}{\mathrm{kg\,K}}$$

$$\Delta\vartheta = 5.16\cdot 10^{-3}\frac{\int i^2\,\mathrm{d}t}{S^2}\cdot\frac{\mathrm{mm}^4}{\mathrm{A}^2}\,\mathrm{K}$$

For a known cross-section of the conductor and a known maximum temperature rise, we obtain the maximum per-unit energy which a protective device can pass in the event of a short circuit without overloading the line:

$$i^2\,\mathrm{d}t = 194\,S^2\,\Delta\vartheta\,\frac{\mathrm{A}^2\mathrm{s}}{\mathrm{mm}^4\,\mathrm{K}} \tag{11.10}$$

In general a single-pole short circuit can be assumed, and this must be interrupted within 0.4 seconds for outlet circuits up to 35 A or within 5 seconds at 35 A for permanently connected circuits.

For a short circuit the following must hold true:

- The rated breaking capacity of the overcurrent protective device I_{cn} must be greater than the three-pole short circuit current at the beginning of the line I''_{k3}.
- The current setting for the short circuit tripping device I_{rm} must be less than or equal to the single-pole short circuit current at the end of the line I''_{k1}.

As overcurrent protective devices the following can be used:

1. Devices which protect against overloading
2. Devices which protect against short circuits
3. Devices which protect against both overloading and short circuits.

11.3.1
Designation of Conductors

The conductors are described by the

- Construction type symbol
  This always begins with the letter *N* (standard type). Deviations from the standard are set in parentheses. If *N* is not given, for this conductor there is no building construction code.
- Number of cores × rated cross-section in mm^2
- Number of cores × rated cross-section of distributed protective conductor in mm^2
- Rated voltages for conductor in or

Example for a line: PVC-sheathed line NYM-J 3 × 2.5
Here the meanings of the symbols are:

N	Standard type
Y	PVC insulation
M	sheathed conductor
J	Green-yellow core (PE)
3	Three cores
2.5	Rated cross-section of conductor in mm^2

The description of harmonized lines is made up of three parts. The first part describes the range of validity and the rated voltage of the line. The second part characterizes the structural elements. The third part gives the number of cores and the rated cross-section, with or without green-yellow core.

Example of a line: Flexible PVC sheathed cable H05 VV-F 3 × G1.5
Here the symbols have the meanings:

H	Harmonized type
05	Rated voltage 300/500 V
V	PVC insulation
V	PVC sheath
F	Fine-wire conductor
3	Three cores
G	With green-yellow core
1.5	Rated cross-section of conductor in mm^2

11.3.2
Designation of Cables

The cables are designated with

- Construction type symbol
  This always begins with the letter *N* (standard type). Deviations from the standard are set in parentheses. If *N* is not given, for this line there is no building construction code.
- Symbol for form and type of conductor
- Rated cross-section of shielding (if present)
- Number of cores × rated cross-section in mm^2
- Number of cores × rated cross-section of distributed protective conductor in mm^2
- Rated voltages of conductor in V or kV, U_0/U

Construction type symbols for cables and line forms (Figure 11.2):

RE = eindrähtiger Rundleiter

SE = eindrähtiger Sektorleiter

RM = mehrdrähtiger Rundleiter

SM = mehrdrähtiger Sektorleiter

Figure 11.2 Conductor forms

Example of a cable: PROTODUR cable NAYCWY 3 × 150 SE/150

Here, the symbols have the meanings:

N	Standard type
A	Aluminum conductor
Y	PVC insulation
CW	Wave-shaped concentric conductor
Y	PVC sheath
3	Three cores
150	Rated cross-section of conductor in mm^2
SE	Single-core sector-shaped conductor
150	Rated cross-section of concentric conductor in mm^2

11.4
Current Carrying Capacity

The selection of the line cross-section is made according to the capacity of the cable or line under normal operating conditions and under fault conditions. The current carrying capacity *Iz* of the line must always be greater than the operating current I_b, and this must be true for all operating modes.

Recommended values for current carrying capacities of cables and lines in buildings are found in IEC 523. The matching of protective equipment has been redefined in IEC 60 364, Part 43. The temperature is assumed to be 30 °C. Protective equipment is standardized for all cross-sections.

11.4.1
Loading Capacity Under Normal Operating Conditions

The current load must be limited so that at every point of the cable and line the heat produced can be dissipated under controlled conditions to the environment.

The parameters for the current carrying capacity are:

- Rated cross-section of cable and line
- Line material
- Number of cores under load
- Insulation material
- Type of installation of cable and line
- Grouping of cables
- Deviating ambient temperatures
- Mode of operation.

For the dimensioning of cables and lines, conventional operating conditions such as operating mode, installation conditions and ambient temperatures are the basis for the rated currents I_r. For other operating conditions, correction factors are used to determine the current carrying capacity, such as for underground installations:

$$I_z = I_r f_1 f_2 \Pi f \tag{11.11}$$

and for overhead installations:

$$I_z = I_r \Pi f \tag{11.12}$$

The selection of the line cross-section under normal operating conditions follows from the relationship:

$$I_z \geq I_b \tag{11.13}$$

Here, the meanings of the symbols are:

Iz	Current carrying capacity
I_r	Load capability for conventional operating conditions
f_1	Correction factor, e.g. for deviating temperature
f_2	Correction factor, e.g. for grouping
Πf	Product of all other correction factors required, e.g. multi-core conductors
I_b	Load under normal operating conditions

11.4.2
Loading Capacity Under Fault Conditions

With a short circuit, lines and cables are subjected to both thermal and mechanical stresses. Lines must not heat up to above the permissible short circuit temperature. The initial temperature and the duration of the short circuit must be considered in the calculation. The thermal stressing of the lines depends on the magnitude, the behavior over time and the duration of the short circuit. In accordance with IEC 865, the thermal equivalent short circuit current, with the time-dependent thermal effect of the DC and AC current components of the short circuit current, is used as the basis for testing the short circuit strength:

$$I_{th} = I_k'' \sqrt{m+n} \tag{11.14}$$

The factor m is the thermal effect resulting from the DC component. It can be read from Figure 11. or calculated with the following equation for $f = 50$ Hz:

$$m = \frac{1}{2\pi\, T_k \ln(\kappa - 1)} \left[e^{4\,f\,T_k \ln(\kappa-1)} - 1 \right] \tag{11.15}$$

For a short circuit lasting a time $T_k > 1$ second, we can set $m = 0$.

The factor n is the thermal effect resulting from the AC component. For a far-from-generator short circuit $n = 1$.

Electrical operational equipment has a sufficient thermal short circuit strength when:

for $T_k \leq T_{kr}$

$$I_{th} \leq I_{thr} \tag{11.16}$$

for $T_k \geq T_{kr}$

$$I_{th} \leq I_{thr} \sqrt{\frac{T_{kr}}{T_k}} \tag{11.17}$$

For the calculation of the thermal short circuit strength for lines, instead of the current the thermal equivalent short circuit current density can also be used, provided that the following condition is satisfied:

$$S_{th} \leq S_{thr} \sqrt{\frac{T_{kr}}{T_k} \frac{1}{\eta}} \tag{11.18}$$

The factor η takes account of the heat dissipated to the insulating material during the time of the short circuit.

The rated short circuit current density S_{thr} is given by:

$$S_{thr} = \sqrt{\frac{\kappa_{20}\, c\, \rho}{\alpha_{20}\, T_{kr}} \ln \frac{1+\alpha_{20}\,(\vartheta_{\mathrm{e}}-20°\mathrm{C})}{1+\alpha_{20}\,(\vartheta_{\mathrm{b}}-20°\mathrm{C})}} \tag{11.19}$$

The meanings of the symbols are:

I_k''	Initial symmetrical short circuit current in kA
I_{th}	Thermal equivalent short circuit current in kA
I_{thr}	Rated short-time current in kA
T_{kr}	Rated short circuit duration in seconds
T_k	Short circuit duration in seconds
S_{thr}	Rated short circuit current density in A/mm^2
S_{th}	Thermal equivalent short circuit current density in A/mm^2
ϑ_e	Temperature of line at end of short circuit in °C
ϑ_b	Temperature of line at beginning of short circuit in °C}
ρ	Density of conductive element in g/cm^3
κ	Withstand ratio
α	Temperature coefficient for electrical resistance in 1/°C
η	Factor for heat dissipated to insulating material

The factors for Equation (32) are taken from (Table 11.2).

Table 11.2: Parameters for the rated short circuit current density

Material	**c** $\frac{\mathrm{J}}{\mathrm{g\,K}}$	ρ $\frac{\mathrm{g}}{\mathrm{cm}^3}$	κ $\frac{\mathrm{m}}{\Omega\mathrm{mm}^2}$	α_{20} $\frac{1}{\mathrm{K}}$
Copper	0.39	8.9	56	0.0039
Aluminum	0.91	2.7	34.8	0.0040
Steel	0.48	7.85	7.25	0.0045

For the limiting temperature curve the material coefficient k for the line can be taken from Table 11.3 or calculated. Table 11.4 gives the permissible line temperatures for a short circuit, according to the insulating material of the cable. Table 11.5 gives the short circuit temperatures for overhead lines.

Table 11.3: Factor k

	PVC	R	XLPE, EPR
Cu	115	135	143
Al	76	87	94

Table 11.4: Short circuit temperatures for cables in °C

	PVC	R	XLPE, EPR
Temperature at beginning T_a	70	60	90
Temperature at end T_e	160	200	250

Table 11.5: Short circuit temperatures T_e for overhead lines in °C

Single-conductor materials				Composite materials	
Al	Aldrey	Cu	St	Aldrey/Steel	Al/St
130	160	170	200	160	160

The symbols have the meanings:

PVC	Polyvinyl chloride insulation
XLPE	Cross-linked polyethylene insulation
EPR	Ethylene-propylene rubber insulation
G	Rubber insulation

Figure 11.3 shows the rated short circuit current density as a function of line temperature for copper.

Figure 11.4 shows the rated short circuit current density as a function of line temperature for aluminum.

For planning conforming to standards it is also necessary to take account of the information in Table 11.6.

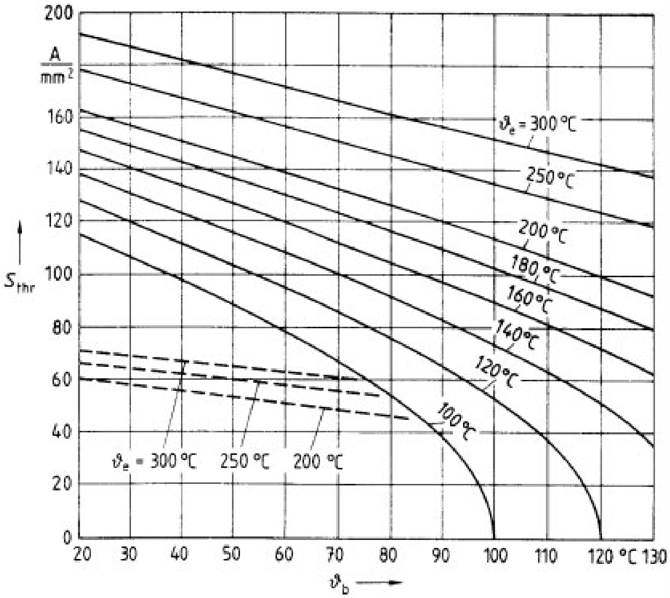


Figure 11.3 Rated short circuit current density ($T_{kr} = 1$ second) as a function of line temperature for copper (solid lines) and for flat profile of unalloyed steel and steel wire (dashed lines) [55]

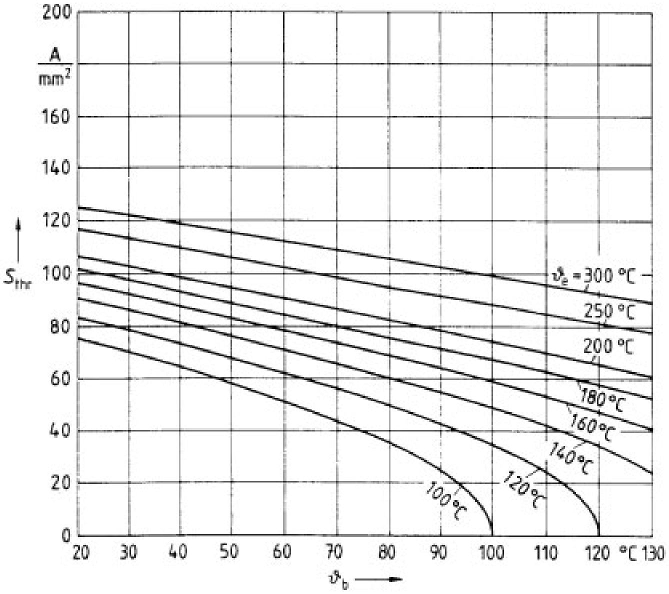


Figure 11.4 Rated short circuit current density ($T_{kr} = 1$ second) as a function of line temperature for aluminum, aluminum alloy (AlMgSi), for wires with and without steel component [55]

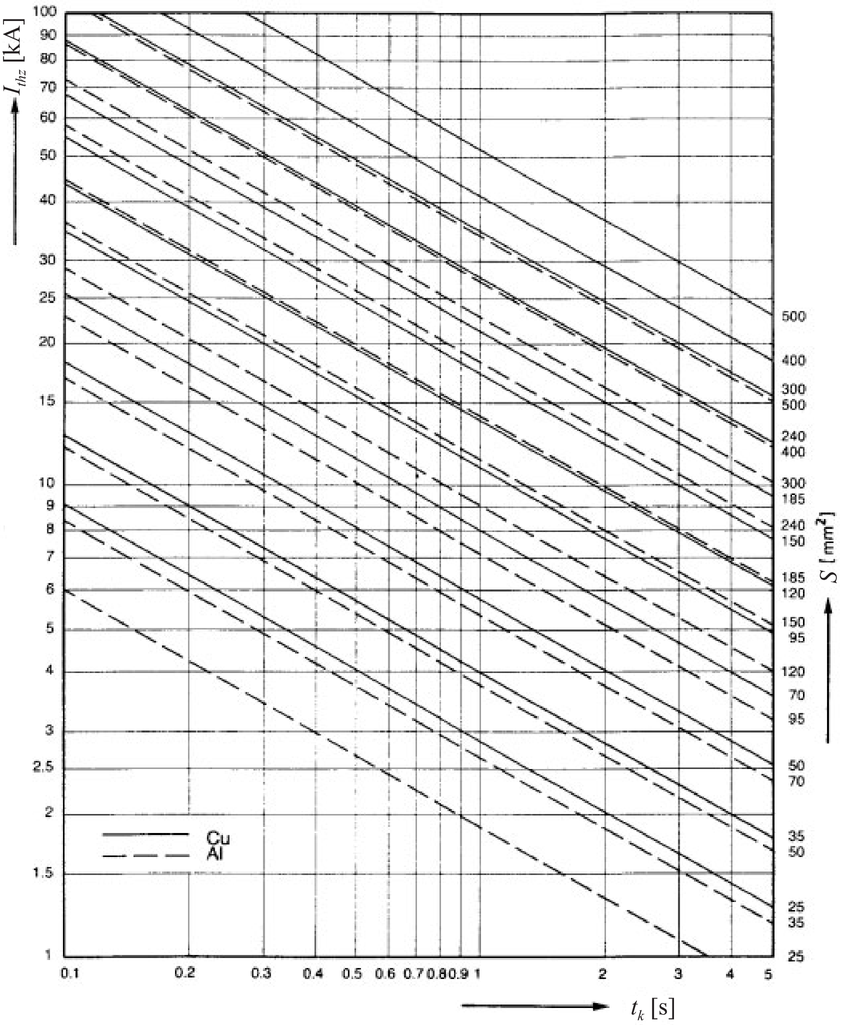


Figure 11.5 Thermally permissible rated short circuit current for cables with PVC insulation at 1–10 kV[35]

Table 11.6: Planning information for cables and lines

Construction of line	Type of line, Number of cores	
	Insulation material	
	Rated cross-section in	mm^2
	Form and class of line	
	Rated cross-section of shielding in	mm^2
	Number of wires	
	Diameter of line in	mm
	Thickness of insulation in	mm
	Thickness of sheath in	mm
	Outer diameter of line in	mm
	Weight of cable and line in	kg/km
Voltage	Rated voltage of network in	V
	Operating voltage in	V
	Power frequency in	Hz
Protective line	Protection against dangerous shock currents	
	Dimensioning of PEN and PE in	mm^2
Loading capacity under normal operating conditions	Operating mode e.g.	LTO or STO
	Installation conditions in	A
	Minimum time in	s
	Number of cores under load	
	Ambient conditions	
Loading capacity under fault conditions	Initial symmetrical short circuit current in	A or kA
	Single-pole and three-pole short circuit currents in	A or kA
	Duration of short circuit in	s
	Cut-off times in	s
Mechanical properties	Minimum bending radius in	mm
	Permissible tensile force during installation in	N
Electrical properties	DC resistance per unit length at 70 °C in	Ω/km
	DC resistance per unit length at 20 °C in	Ω/km
	Working capacitance per unit length in	μF/km
	Charging current in	A/km
	Ground fault current in	A/km
Voltage drop	Losses in	W
	Power factor	
	Maximum length in	m or km
	Preselected voltage drop in	%
Protection against overloading and short circuit	Matching of overload protection equipment	
Maximum length	IEC 60 364, Supplementary Page 5	
	IEC 60 364, Part 52	
Underground installation	Current carrying capacity in	A
	Resistance per unit length at 20 °C in	Ω/km
	Resistance per unit length at 90 °C in	Ω/km
	Effective resistance per unit length in zero-sequence system in	Ω/km
	Reactance per unit length in zero-sequence system in	Ω/km
	Permissible transfer power in	MVA

11.4.3
Installation Types and Load Values for Lines and Cables

Recommended values for the current carrying capacity of cables and insulated lines for permanent installation in buildings and of flexible lines are described in IEC 523.

For the selection of cables and insulated lines for heavy current systems, the following conditions are essential for all tables and calculations:

Loading capacity under normal operating conditions:

1. Operating conditions and loading capacity
   - The mode of operation is continuous operation
   - The loading capacity (rated value) determined in designated I_r in all tables
   - For cables and lines there are new types of installation
   - The loading capacity values in the tables are specified for 30 °C
   - The maximum operating temperature is 70 °C.
2. **Loading capacity under fault conditions**
   - IEC 865 is the reference for the calculation of the thermal short circuit strength
   - The permissible short circuit temperature for PVC lines in 160 °C for a maximum short circuit duration of 5 seconds.

Overhead cables and lines:

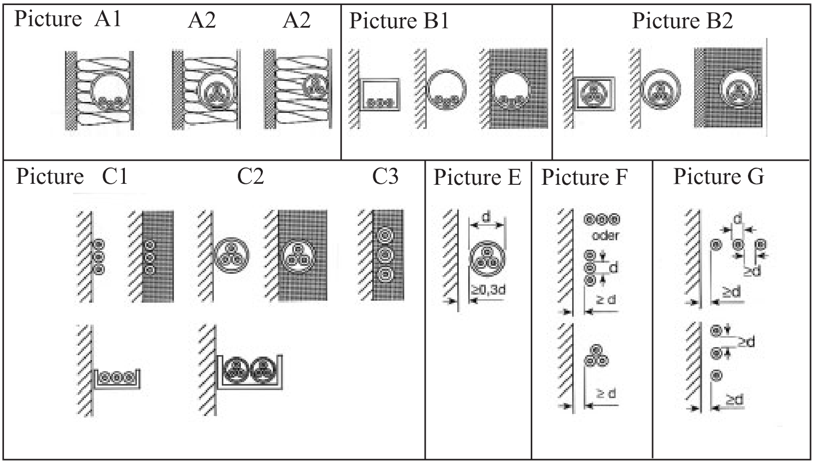
- Load factor of 1.0
- Continuous operation, power supply company load
- Ambient temperature 30 °C
- Operating temperature 70 °C

Frequently occurring terms for the loading capacity of lines and cables as well as correction factors will be briefly explained here (Table 11.7).

- Cable tray: Continuous carrier plate with raised side parts, but with no cover. A cable tray is regarded as perforated when the punched holes cover at least 30 % of the total surface.
- Cable rack: Carrier construction in which the supporting surface is no more than 10 % of the total surface.

The following tables summarize the values for the current carrying capacity of cables and lines for permanent installation in buildings and of flexible lines Current Carrying Capacity, General, Correction Factors.

Table 11.7: Reference installation types A1, A2, B1, B2, C, E, F and G for cables and lines for permanent installation in buildings at 70 °C and 30 °C operating temperature [64]



Installation type	A1	A2		B1	B2
Illustration	(A1)	(A2)	(A2)	(B1)	(B2)
Installation conditions	Installation in thermally insulated walls			Installation in electric wiring conduits or closed electric wiring ducting on or in walls or in ducting for underfloor installation	
	Non-sheathed cables or single- core cables/ sheathed cables in electric wiring conduit or ducting	Multi-core cables or sheathed cables			
		In electric wiring conduit or ducting	Direct installation	Non-sheathed cables or single- core cables/ sheathed cables	Multi-core cables or sheathed cables

Table 11.7: (continued): Reference installation types A1, A2, B1, B2, C, E, F and G for cables and lines for permanent installation in buildings at 70 °C and 30 °C operating temperature [64]

Installation type	**C**			**E**	**F**	**G**
Illustration	**(C1)**	**(C2)**	**(C3)**	**(E)**	**(F)**	**(G)**
Installation conditions	Direct installation or in walls/ceilings or in cable trays		Flat-webbed cable in walls/ ceilings or hollow spaces	Overhead installation, on catenary wires and on cable racks and consoles		
	Single-core cables or sheathed cables	Multi-core cables or sheathed cables		Multi-core cables or sheathed cables	Single-core cables/sheathed cables	
					With contact	Without contact, including non-sheathed cables on insulators

Table 11.8: Loading capacity of cables and lines for permanent installation in buildings at 70 °C and 30 °C operating temperature [64]

Installation type	**A1**		**A2**		**B1**		**B2**		**C**	
Installation	**In thermally insulated walls**				**In electric wiring conduits**				**Direct**	
Number of cores simultaneously under load	**2**	**3**	**2**	**3**	**2**	**3**	**2**	**3**	**2**	**3**
Nominal cross-section in mm^2	**Current carrying capacity I_z in A**									
1.5	15.5	13.5	15.5	13.0	17.5	15.5	16.5	15.0	19.5	17.5
2.5	19.5	18.0	18.5	17.5	24	21	23	20	27	24
4	26	24	25	23	32	28	30	27	36	32
6	34	31	32	29	41	36	38	34	46	41
10	48	42	43	39	57	50	52	46	63	57
16	61	56	57	52	76	68	69	62	85	76
25	80	73	75	68	101	89	90	80	112	96
35	99	89	92	83	125	110	111	99	138	119
50	119	108	110	99	151	134	133	118	168	144
70	151	136	139	125	192	171	168	149	213	184
95	182	164	167	150	232	207	201	179	258	223
120	210	188	192	172	269	239	232	206	299	259

Table 11.8: (continued): Loading capacity of cables and lines for permanent installation in buildings at 70 °C and 30 °C operating temperature [64]

Installation type	**E**		**F**			**G**	
Installation	**Overhead**						
Number of cores simultaneously under load	**2**	**3**	**2**	**3**	**3**	**horizontal 3**	**vertical 3**
Nominal cross-section in mm^2	**Current carrying capacity I_z in A**						
1.5	22	18.5	–	–	–	–	–
2.5	30	25	–	–	–	–	–
4	40	34	–	–	–	–	–
6	51	43	–	–	–	–	–
10	70	60	–	–	–	–	–
16	94	80	–	–	–	–	–
25	119	101	131	114	110	146	130
35	148	126	162	143	137	181	162
50	180	153	196	174	167	219	197
70	232	196	251	225	216	281	254
95	282	238	304	275	264	341	311
120	328	276	352	321	308	396	362

Table 11.9: Recommended values for the current carrying capacity of cables and lines with copper conductor and PVC insulation for permanent installation in buildings, continuous operation, operating temperature 70 °C, ambient temperature 25 °C and matching of rated current of overload protection equipment to conventional tripping current [64]

Installation type		**A1**		**A2**		**B1**		**B2**		**C**		**E**	
Number of cores simultaneously under load		**2**	**3**	**2**	**3**	**2**	**3**	**2**	**3**	**2**	**3**	**2**	**3**
Nominal cross-section in mm^2		**Current carrying capacity I_z in A** **Nominal current I_n in A**											
1.5	I_z	16.5	14.5	16.5	14.0	18.5	16.5	17.5	16.0	21	18.5	23	19.5
	I_n	16	13	16	13	16	16	16	16	20	16	20	16
2.5	I_z	21	19	19.5	18.5	25	22	24	21	29	25	32	27
	I_n	20	16	16	16	25	20	20	20	25	25	32	25
4	I_z	28	25	27	24	34	30	32	29	38	34	42	36
	I_n	25	25	25	20	32	25	32	25	35	35	40	35
6	I_z	36	33	34	31	43	38	40	38	49	43	54	46
	I_n	35	32	32	25	40	35	40	35	40	40	50	40
10	I_z	49	45	46	41	60	53	55	49	67	60	74	64
	I_n	40	40	40	40	50	50	50	40	63	50	63	63
16	I_z	65	59	60	55	81	72	73	66	90	81	100	85
	I_n	63	50	50	50	80	63	63	63	80	80	100	80
25	I_z	85	77	80	72	107	94	95	85	119	102	126	107
	I_n	80	63	80	63	100	80	80	80	100	100	125	100
35	I_z	105	94	98	88	133	117	118	105	146	126	157	134
	I_n	100	80	80	80	125	100	100	100	125	125	125	125
50	I_z	126	114	117	105	160	142	141	125	178	153	191	162
	I_n	125	100	100	100	160	125	125	125	160	125	160	160

Table 11.10: Recommended values for the current carrying capacity of cables and lines with copper conductor and PVC insulation for permanent installation in buildings, continuous operation, operating temperature 70 °C, ambient temperature 40 °C and matching of rated current of overload protection equipment to conventional tripping current in accordance with EN 60204, Part 1: 1993-06 [64]

Installation type		**B1**	**B2**	**C**	**E**
Nominal cross-section in mm^2		**Current carrying capacity I_z in A** **Nominal current I_n in A**			
0.75	I_z	7.6	–	–	–
	I_n	6	–	–	–
1.0	I_z	10.4	9.6	11.7	11.5
	I_n	10	8	10	10
1.5	I_z	13.5	12.2	15.2	16.1
	I_n	13	10	13	16
2.5	I_z	18.3	16.5	21	22
	I_n	16	16	20	20
4	I_z	25	23	28	30
	I_n	25	20	25	25
6	I_z	32	29	36	37
	I_n	32	25	35	35
10	I_z	44	40	50	52
	I_n	40	40	50	50
16	I_z	60	53	66	70
	I_n	50	50	63	63
25	I_z	77	67	84	88
	I_n	63	63	80	80
35	I_z	97	83	104	114
	I_n	80	80	100	100
50	I_z	–	–	123	123
	I_n	–	–	100	100

Table 11.11: Correction factors for grouping of cables and lines with rated load for continuous operation [64]

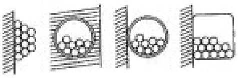
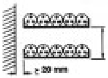
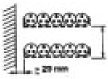
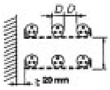
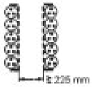
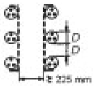
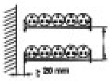
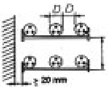
Picture 11a		Picture 12a	
Picture 11b		Picture 12b	
Picture 11c		Picture 12c	
Picture 11d		Picture 12d	
Picture 11e		Picture 12e	
		Picture 12f	
		Picture 12g	

Table 11.11: Correction factors for grouping of cables and lines with rated load for continuous operation [64]

Layout of installation	**Number of multi-core cables or lines or number of AC or three-phase circuits with single-conductor cables or lines (2 or 3 current-carrying conductors)**														
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**12**	**14**	**16**	**18**	**20**
Grouped directly on the wall, on the floor, in electric wiring conduit or ducting, on or in the wall (Picture 11a)	1.00	0.80	0.70	0.65	0.60	0.57	0.54	0.52	0.50	0.48	0.45	0.43	0.41	0.39	0.38
Single-layer on the wall or on the floor, with contact (Picture 11b)	1.00	0.85	0.79	0.75	0.73	0.72	0.72	0.71	0.70	0.70	0.70	0.70	0.70	0.70	0.70
Single-layer on the wall or on the floor, with spacing equal to outer diameter *d* (Picture 11c)	1.00	0.94	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Single-layer under ceiling, with contact (Picture 11d)	0.95	0.81	0.72	0.68	0.66	0.64	0.63	0.62	0.61	0.61	0.61	0.61	0.61	0.61	0.61
Single-layer under ceiling, with spacing equal to outer diameter *d* (Picture 11e)	0.95	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85

Table 11.12: Correction factors for grouping of multi-core cables and lines on cable trays and racks [64]

Layout of installation		Number of trays or racks	Number of multi-core cables or lines					
			1	2	3	4	6	9
Unperforated cable trays (1)	(Picture 12a)	1	0.97	0.84	0.78	0.75	0.71	0.68
		2	0.97	0.83	0.76	0.72	0.68	0.63
		3	0.97	0.82	0.75	0.71	0.66	0.61
		6	0.97	0.81	0.73	0.69	0.63	0.58
Perforated cable trays	(Picture 12b)	1	1.00	0.88	0.82	0.79	0.76	0.73
		2	1.00	0.87	0.80	0.77	0.73	0.68
		3	1.00	0.86	0.79	0.76	0.71	0.66
		6	1.00	0.84	0.77	0.73	0.68	0.64
	(Picture 12c)	1	1.00	1.00	0.98	0.95	0.91	–
		2	1.00	0.99	0.96	0.92	0.87	–
		3	1.00	0.98	0.95	0.91	0.85	–
	(Picture 12d)	1	1.00	0.88	0.82	0.78	0.73	0.72
		2	1.00	0.88	0.81	0.76	0.71	0.70
	(Picture 12e)	1	1.00	0.91	0.89	0.88	0.87	–
		2	1.00	0.91	0.88	0.87	0.85	–
Cable racks	(Picture 12f)	1	1.00	0.87	0.82	0.80	0.79	0.78
		2	1.00	0.86	0.81	0.78	0.76	0.73
		3	1.00	0.85	0.79	0.76	0.73	0.70
		6	1.00	0.83	0.76	0.73	0.69	0.66
	(Picture 12g)	1	1.00	1.00	1.00	1.00	1.00	–
		2	1.00	0.99	0.98	0.97	0.96	–
		3	1.00	0.98	0.97	0.96	0.93	–

[1] perforations cover less than 30 % of total surface

Table 11.13: Correction factors for spooled lines

Number of layers	Correction factors
1	0.80
2	0.61
3	0.49
4	0.42
5	0.38
For spiral-shaped spooling the correction factor 0.80 is used.	

Table 11.14: Correction factors for multi-core cables and lines with $S \leq 10\ \text{mm}^2$

Number of cores under load	Correction factors
5	0.75
7	0.65
10	0.55
14	0.50
19	0.45
24	0.40
40	0.35
61	0.30

Table 11.15: Correction factors for deviating ambient temperatures

Permissible operating temperature	40 °C	60 °C	70 °C	80 °C	85 °C	90 °C
Ambient temperature in °C	Correction factors					
10	1.73	1.29	1.22	1.18	1.17	1.15
15	1.58	1.22	1.17	1.14	1.13	1.12
20	1.41	1.15	1.12	1.10	1.09	1.08
25	1.22	1.08	1.06	1.05	1.04	1.04
30	1.00	1.00	1.00	1.10	1.00	1.00
35	0.71	0.91	0.94	0.95	0.95	0.96
40	–	0.82	0.87	0.89	0.90	0.91
45	–	0.71	0.79	0.84	0.85	0.87
50	–	0.58	0.71	0.77	–	0.82
55	–	0.41	0.61	0.71	–	0.76
60	–	–	0.50	0.63	–	0.71
65	–	–	0.35	0.55	–	0.65
70	–	–	–	0.45	–	0.58
75	–	–	–	0.32	–	0.50
80	–	–	–	–	–	0.41
85	–	–	–	–	–	0.29

11.4.4
Current Carrying Capacity of Heavy Current Cables and Correction Factors for Underground and Overhead Installation

Current carrying capacity in accordance with DIN VDE 0276, Part 603, Correction factors in accordance with DIN VDE 0276, Part 1000
The following conditions are essential for the selection of cables based on all line cross-section tables and calculations for the current carrying capacity of underground cables and overhead cables:

Underground cables:

- Power supply company load with a load factor of 0.7
- Installation depth 0.7 to 1.2 m
- Ground temperature 20 °C
- Thermal resistivity of soil 1.0 K · m/W
- Number of cables/Systems 1

Overhead cables and lines:

- Load factor of 1.0
- Continuous operation, power supply company load
- Ambient temperature 30 °C
- Operating temperature 70 °C

The following tables list recommended values for the current carrying capacity of heavy current cables.

Table 11.16: Loading capacity, underground overhead installation, Layout of installation for the table 11.16 and 11.17 [64]

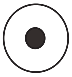
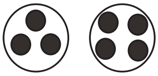
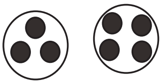
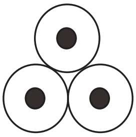
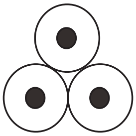
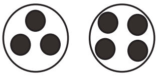
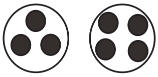
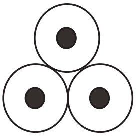
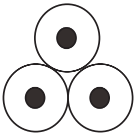
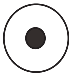
Picture 16a		Picture 16g	
Picture 16b		Picture 16h	
Picture 16c		Picture 16i	
Picture 16d		Picture 16 k	
Picture 16e			
Picture 16f			

Table 11.16: Loading capacity, underground installation, cable with $U_0/U = 0.6/1$ kV

Insulation material	**PVC**									
Permissible operating temperature	**70 °C**									
Construction type symbol	**NYY**			**NYCWY**		**NAYY**			**NAYCWY}**	
Layout	**(a)**[1]	**(b)**	**(c)**	**(d)**	**(e)**	**(f)**[1]	**(g)**	**(h)**	**(i)**	**(k)**
Number of cores under load	**1**	**3**	**3**	**3**	**3**	**1**	**3**	**3**	**3**	**3**
Cross-section in mm^2	Cu-Conductor					Alu-Conductor				
	Rated current in A					Rated current in A				
1.5	41	27	30	27	31	–	–	–	–	–
2.5	55	36	39	36	40	–	–	–	–	–
4	71	47	50	47	51	–	–	–	–	–
6	90	59	62	59	63	–	–	–	–	–
10	124	79	83	79	84	–	–	–	–	–
16	160	102	107	102	108	–	–	–	–	–
25	208	133	138	133	139	160	102	106	103	108
35	250	159	164	160	166	193	123	127	123	129
50	296	188	195	190	196	230	144	151	145	153
70	365	232	238	234	238	283	179	185	180	187
95	438	280	286	280	281	340	215	222	216	223
120	501	318	325	319	315	389	245	253	246	252
150	563	359	365	357	347	436	275	284	276	280
185	639	406	413	402	385	496	313	322	313	314
240	746	473	479	463	432	578	364	375	362	358
300	848	535	541	518	473	656	419	425	415	397
400	975	613	614	579	521	756	484	487	474	441
500	1125	687	693	624	574	873	553	558	528	489
630	1304	–	777	–	636	1011	–	635	–	539
800	1507	–	859	–	–	1166	–	716	–	–
1000	1715	–	936	–	–	1332	–	796	–	–

[1] Rated current in DC systems with return line far away

Table 11.17: Loading capacity, overhead installation, cable with $U_0/U = 0.6/1$ kV

Insulation material	**PVC**									
Permissible operating temperature	**70 °C**									
Construction type symbol	**NYY**			**NYCWY**		**NAYY**			**NAYCWY}**	
Layout	**(a)**[1]	**(b)**	**(c)**	**(d)**	**(e)**	**(f)**[1]	**(g)**	**(h)**	**(i)**	**(k)**
Number of cores under load	**1**	**3**	**3**	**3**	**3**	**1**	**3**	**3**	**3**	**3**
Cross-section in mm^2	Cu-Conductor Rated current in A					Alu-Conductor Rated current in A				
1.5	27	19.5	21	19.5	22	–	–	–	–	–
2.5	35	25	28	26	29	–	–	–	–	–
4	47	34	37	34	39	–	–	–	–	–
6	59	43	47	44	49	–	–	–	–	–
10	81	59	64	60	67	–	–	–	–	–
16	107	79	84	80	89	–	–	–	–	–
25	144	106	114	108	119	110	82	87	83	91
35	176	129	139	132	146	135	100	107	101	112
50	214	157	169	160	177	166	119	131	121	137
70	270	199	213	202	221	210	152	166	155	173
95	334	246	264	249	270	259	186	205	189	212
120	389	285	307	289	310	302	216	239	220	247
150	446	326	352	329	350	345	246	273	249	280
185	516	374	406	377	399	401	285	317	287	321
240	618	445	483	443	462	479	338	378	339	374
300	717	511	557	504	519	555	400	437	401	426
400	843	597	646	577	583	653	472	513	468	488
500	994	669	747	626	657	772	539	600	524	556
630	1180	–	858	–	744	915	–	701	–	628
800	1396	–	971	–	–	1080	–	809	–	–
1000	1620	–	1078	–	–	1258	–	916	–	–

[1] Rated current in DC systems with return line far away

Table 11.18: Correction factors for grouping of overhead lines, single-core cables in three-phase systems, Layout of installation for the table 11.19

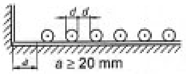
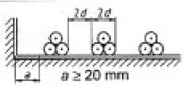
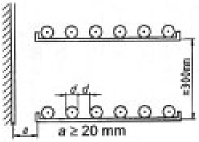
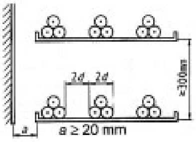
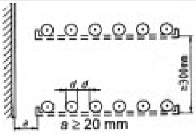
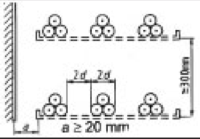
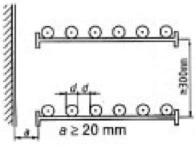
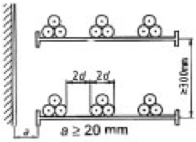
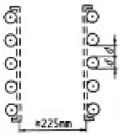
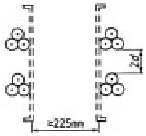
Picture 19a		Picture 19f	
Picture 19b		Picture 19g	
Picture 19c		Picture 19h	
Picture 19d		Picture 19i	
Picture 19e		Picture 19k	

Table 11.19: Correction factors for grouping of overhead lines, single-core cables in three-phase systems

Layout of installation **Level installation** **Spacing = cable diameter *d***		**Number of trays/racks over one another**	**Number of systems[2] next to one another**		
			1	**2**	**3**
On the ground	(Picture 19a)	1	0.92	0.89	0.88
Unperforated cable trays[3]	(Picture 19b)	1	0.92	0.89	0.88
		2	0.87	0.84	0.83
		3	0.84	0.82	0.81
		6	0.82	0.80	0.79
Perforated cable trays[3]	(Picture 19c)	1	1.0	0.93	0.90
		2	0.97	0.89	0.85
		3	0.96	0.88	0.82
		6	0.94	0.85	0.80
Cable racks[4] (cable gratings)	(Picture 19d)	1	1.00	0.97	0.96
		2	0.97	0.94	0.93
		3	0.96	0.93	0.92
		6	0.94	0.91	0.90
On supporting frames or on the wall or laid out vertically on perforated cable trays	(Picture 19f)	Number of trays/racks over one another	Number of systems over one another		
			1	2	3
		1	0.94	0.91	0.89
		2	0.94	0.90	0.86

1) In confined spaces or for the grouping of large number of cables if the heat loss from the cables causes a temperature rise in the air, the correction factors for deviating air temperatures in Table 12 must also be used (see 5.3.2.3).
2) Factors in accordance with CENELEX report R064.001 for HD 384.5.523:1991.
3) A cable tray is s continuous carrier plate with raised side parts, but with no cover. A cable tray is regarded as perforated when the punched holes cover at least 30% of the total surface.
4) A cable rack is a carrier construction in which the supporting surface is no more than 10% of the total surface.

For grouped installation no load reduction is necessary if the spacing between neighboring systems is at least four times the cable diameter, provided that there is no rise in the ambient temperature as a result of heat losses.

Table 11.19: (continued): Correction factors for grouping of overhead lines, single-core cables in three-phase systems

Layout of installation Level installation Spacing = 2*d*		**Number of trays/racks over one another**	**Number of systems[2] next to one another**		
			1	**2**	**3**
On the ground	(Picture 19g)	1	0.98	0.96	0.94
Unperforated cable trays[3]	(Picture 19h)	1	0.98	0.96	0.94
		2	0.95	0.91	0.87
		3	0.94	0.90	0.85
		6	0.93	0.88	0.82
Perforated cable trays[3]	(Picture 19i)	1	1.0	0.98	0.96
		2	0.97	0.93	0.89
		3	0.96	0.92	0.85
		6	0.95	0.90	0.83
Cable racks[4] (cable gratings)	(Picture 19j)	1	1.00	1.00	1.00
		2	0.97	0.95	0.93
		3	0.96	0.94	0.90
		6	0.95	0.93	0.87
On supporting frames or on the wall or laid out vertically on perforated cable trays	(Picture 19k)	Number of trays/racks over one another	Number of systems over one another		
			1	2	3
		1	1.0	0.91	0.89
		2	1.0	0.90	0.86

Table 11.20: Correction factors for grouping of overhead lines, multiple-core cables and single-core DC cables

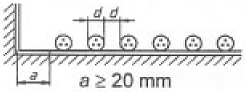
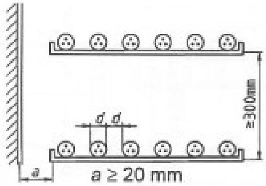
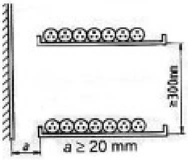
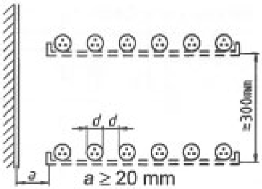
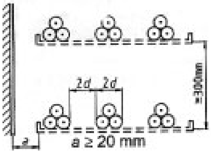
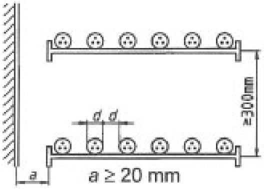
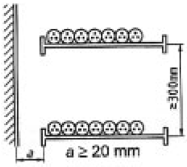
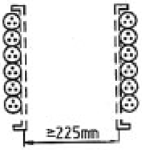
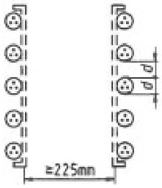
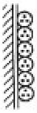
Picture 20a		Picture 20f	
Picture 20b		Picture 20g	
Picture 20c		Picture 20h	
Picture 20d		Picture 20i	
		Picture 20j	
Picture 20e		Picture 20k	

Table 11.20: Correction factors for grouping of overhead lines, multiple-core cables and single-core DC cables, Layout of installation for the table 11.20

Layout of installation Spacing = cable diameter *d*		**Number of trays/racks over one another**	**Number of cables[4] next to one another**				
			1	**2**	**3**	**4**	**6**
On the ground	(Picture 20a)	1	0.97	0.96	0.94	0.93	0.90
Unperforated cable trays[2]	(Picture 20b)	1	0.97	0.96	0.94	0.93	0.90
		2	0.97	0.95	0.92	0.90	0.86
		3	0.97	0.94	0.91	0.89	0.84
		6	0.97	0.93	0.90	0.88	0.83
Perforated cable trays[2]	(Picture 20c)	1	1.0	1.0	0.98	0.95	0.91
		2	1.0	0.99	0.96	0.92	0.87
		3	1.0	0.98	0.95	0.91	0.85
		6	1.0	0.97	0.94	0.90	0.84
Cable racks[3]	(Picture 20d)	1	1.0	1.0	1.0	1.0	1.0
(cable gratings)		2	1.0	0.99	0.98	0.97	0.96
		3	1.0	0.98	0.97	0.96	0.93
		6	1.0	0.97	0.96	0.94	0.91
On supporting frames	(Picture 20e)		Number of cables over one another				
or on the wall or laid out			1	2	3	4	
vertically on perforated		1	1.0	0.91	0.89	0.88	0.87
trays		2	1.0	0.91	0.88	0.87	0.85

1) In confined spaces or for the grouping of large number of cables if the heat loss from the cables causes a temperature rise in the air, the correction factors for deviating air temperatures in Table 12 must also be used (see 5.3.2.3).
2) A cable tray is s continuous carrier plate with raised side parts, but with no cover. A cable tray is regarded as perforated when the punched holes cover at least 30% of the total surface.
3) A cable rack is a carrier construction in which the supporting surface is no more than 10% of the total surface.
4) Factors in accordance with CENELEC report R064.001 for HD 384.5.523:1991.

No load reduction is necessary if the horizontal or vertical spacing between neighboring systems is at least twice the cable diameter, provided that there is no rise in the ambient temperature as a result of heat losses.

Table 11.20: (continued): Correction factors for grouping of overhead lines, multiple-core cables and single-core DC cables

Layout of installation In contact with one another		**Number of trays/racks over one another**	**Number of cables[4] next to one another**					
			1	**2**	**3**	**4**	**6**	**9**
On the ground	(Picture 20f)	1	0.97	0.96	0.94	0.93	0.90	0.90
Unperforated cable trays[2]	(Picture 20g)	1	0.97	0.96	0.94	0.93	0.90	0.90
		2	0.97	0.95	0.92	0.90	0.86	0.90
		3	0.97	0.94	0.91	0.89	0.84	0.90
		6	0.97	0.93	0.90	0.88	0.83	0.90
Perforated cable trays[2]	(Picture 20h)	1	1.0	1.0	0.98	0.95	0.91	0.90
		2	1.0	0.99	0.96	0.92	0.87	0.90
		3	1.0	0.98	0.95	0.91	0.85	0.90
		6	1.0	0.97	0.94	0.90	0.84	0.90
Cable racks[3] (cable gratings)	(Picture 20i)	1	1.0	1.0	1.0	1.0	1.0	0.90
		2	1.0	0.99	0.98	0.97	0.96	0.90
		3	1.0	0.98	0.97	0.96	0.93	0.90
		6	1.0	0.97	0.96	0.94	0.91	0.90
Laid out vertically on perforated cable trays	(Picture 20j)		Number of cables over one another					
			1	2	3	4	6	9
		1	1.0	0.91	0.89	0.88	0.87	0.87
		2	1.0	0.91	0.88	0.87	0.85	0.87
Laid out on supporting frames or on the wall	(Picture 20k)		1.0	0.91	0.89	0.88	0.87	0.87

Table 11.21: Correction factors for deviating ambient temperatures

Permissible operating temperature in °C	**Air temperature in °C**								
	10	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
90	1.15	1.12	1.08	1.04	1.00	0.96	0.91	0.87	0.82
80	1.18	1.14	1.10	1.05	1.00	0.95	0.89	0.84	0.77
70	1.22	1.17	1.12	1.06	1.00	0.94	0.87	0.79	0.71
65	1.12	1.20	1.13	1.07	1.00	0.93	0.85	0.76	0.65
60	1.29	1.22	1.15	1.08	1.00	0.91	0.82	0.71	0.58

11.22: Correction factors for multi-core cables with conductor cross-sections from 1.5 mm^2 to 10 mm^2; underground or overhead installation

Number of cores under load	Underground installation	Overhead installation}
5	0.70	0.75
7	0.60	0.65
10	0.50	0.55
14	0.45	0.50
19	0.40	0.45
24	0.35	0.40
40	0.30	0.35
61	0.25	0.30

The permissible continuous current carrying capacity for overhead lines (Tables 65 and 66) applies for DC and AC up to 60, for a wind speed of 0.6 m/s and a temperature of 35 °C.

Table 11.23: Continuous current carrying capacity of overhead lines

S_r mm^2	S_s mm^2	Number × d mm	d_s	Continuous current carrying capacity A		
				Copper	Aluminum	AAAC
16	15.89	7 × 1.7	5.1	125	110	105
25	24.25	7 × 2.1	6.3	160	145	135
35	34.36	7 × 2.5	7.5	200	180	170
50	48.35	19 × 1.8	9.0	250	225	210
70	65.81	19 × 2.1	10.5	310	270	255
95	93.27	19 × 2.5	12.5	380	340	320
120	117.00	19 × 2.8	14.0	440	390	365

Table 11.24: Continuous current carrying capacity of overhead lines

S_r mm^2	S_s mm^2	Al/St ratio	Continuous current carrying capacity A
16/2.5	17.8	5.4	105
25/4	27.8	6.8	140
35/6	40.1	8.1	170
50/8	56.3	9.6	210
70/12	81.3	11.7	290
95/15	109.7	13.6	350
120/20	141.4	15.5	410

The continuous current carrying capacity of busbars (Table 11.25) applies for an ambient temperature of 35 °C and takes a temperature rise of 30 K, resulting from the current heating losses, into account.

Table 11.25: Continuous current carrying capacity of busbars

Width × Thickness	Cross-section	Loading capacity of busbars in A	
mm	mm^2	enamelled	without enamel
12 × 2	23.5	202	182
15 × 2	29.5	240	212
20 × 2	39.5	302	264
20 × 3	59.5	394	348
25 × 3	74.5	470	412
30 × 3	89.5	544	476
40 × 3	119	692	600
50 × 5	249	1140	994
60 × 5	299	1330	1150
80 × 5	399	1680	1450
100 × 5	499	2010	1730
120 × 10	1200	3280	2860
200 × 10	2000	4970	4310

The meanings of the symbols are:

S_r	Rated cross-section
S_s	Specified cross-section
d	Diameter
d_s	Line diameter

11.5
Examples of Current Carrying Capacity

11.5.1
Example 1: Checking Current Carrying Capacity

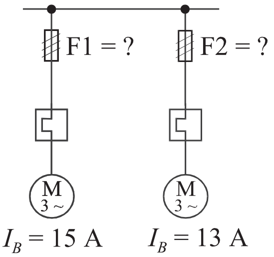


Figure 11.6 Checking the current carrying capacity

Given Figure 11.6.

- 8 NYM-J 5 × 1.5^2 Cu-conductor sheathed lines, grouped directly on the wall, in contact with each other (installation type C)
- Applicable standards: IEC 60 364, Part 43,

Find:

1. The required protective equipment
2. The line cross-sections, taking account of all reduction and correction factors.

Protective equipment: Both motors have 16 A fuses. Using the rule of nominal currents

$$I_b \leq In \leq Iz = 15\,\mathrm{A} \leq 16\,\mathrm{A} \leq Iz$$

Calculation of the line cross-sections:

The reduction factor for a different temperature: from 25 °C to 30 °C, from Table 11.15, is 1.06

The reduction factor for grouping, from Table 11.11,is 0.52

The required loading of the line is given by:

$$I_z' = \frac{I_n}{f_1 f_2} = \frac{16\,\mathrm{A}}{1.06 \cdot 0.52} = 29.03\,\mathrm{A}$$

Selection of lines: NYM-J $5 \times 4\,\mathrm{mm}^2$, from Table 11.8; $I_{z\,Tab.} = 32$ A actual current carrying capacity:

$$I_z = I_{z\,Tab.} f_1 f_2 = 32\,\mathrm{A} \cdot 0.52 \cdot 1.06 = 17.3\,\mathrm{A}$$

It then follows that:

$$I_b \leq I_n \leq I_z = 15\,\mathrm{A} \leq 16\,\mathrm{A} \leq 17.3\,\mathrm{A}$$

The requirement is therefore satisfied.

11.5.2
Example 2: Checking Current Carrying Capacity

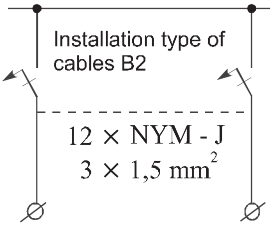


Figure 11.7 Checking the current carrying capacity

Check the current carrying capacity of 12 NYM-J $3 \times 1.5\,\mathrm{mm}^2$ lines in a conduit, surface mounted (Figure 11.7). The coincidence factor, according to information from the manufacturer, is 0.8, the ambient temperature is 25 °C, the installation type B2 and $I_b = 6$ A.

Find the current carrying capacity and the fusing.

Correction factors:
Reduction factor for temperature, from Table 11.15: $f_1 = 1.06$
Reduction factor for grouping, from Table 11.11: $f_2 = 0.45$
Coincidence: 12 lines · 0.8 = 9.6 lines

$I_{z\,Tab.} = 16.5\,\text{A}$, so that:

$$I_z' = I_{z\,Tab.} f_1 f_2 = 16.5\,\text{A} \cdot 1.06 \cdot 0.45 = 7.87\,\text{A}$$

With a 6 A fuse:

$$I_b \leq I_n \leq I_z = 6\,\text{A} \leq 6\,\text{A} \leq 7.87\,\text{A}$$

11.5.3
Example 3: Protection of Cables in Parallel

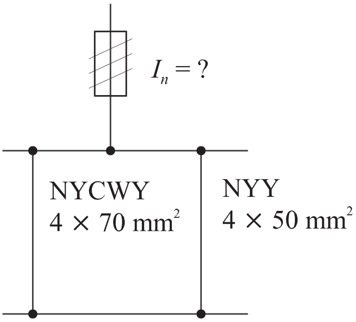


Figure 11.8 Protection of cables in parallel

An additional NYY-J 4 × 50 mm² cable (Figure 11.8) was laid in parallel with the existing NYCWY 4 × 70 mm² cable. Find the fuse required for the cables in parallel.

Conditions: Ambient temperature 25 °C, overhead installation, two trays each with one cable. The current carrying capacity I_z for NYCWY 4 × 70 mm², from Table 11.17, is 202 A.

Correction factor for the ambient temperature, from Table 11.21: $f_1 = 1.06$, correction factor for grouping, from Table 11.20: $f_2 = 0.97$

$$I_z = 202 \times 1.06 \times 0.97 = 207.7\,\text{A}$$

$$I_{zTotal} = I_z \left(1 + \frac{S_1}{S_{max}}\right)$$

$$I_{zTotal} = 207.7\,\text{A} \left(\frac{1{+}50\,\text{mm}^2}{70\,\text{mm}^2}\right) = 356.06\,\text{A}$$

$I_n(\text{gG}) = 315\,\text{A}\,(\text{NH2})$ selected

11.5.4
Example 4: Connection of a Three-Phase Cable

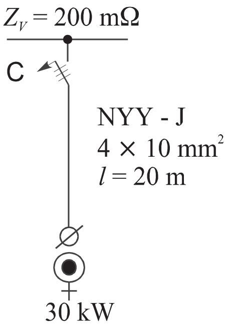


Figure 11.9 Determination of line length for a boiler

Given the connection of a three-phase NYY-J 4×10 mm^2 cable 20 m in length (Figure 11.9) to a boiler with 30 kW, protection by circuit breaker, C characteristic. The loop resistance is $Z_S = 200$ mΩ, $U = 400$ V. Find the permissible length in accordance with IEC 60 364, Supplementary Page 5.

Solution:

- Operating current $I_b = \dfrac{P}{\sqrt{3}\,U} = \dfrac{30\,\text{kW}}{\sqrt{3}\cdot 400} = 43.3\,\text{A}$
- Rated current of overload protection device $I_n = 50\,\text{A}$

From Supplementary Page 5 of IEC 60 364, Table 6, the following values are found: Maximum line length = 55 m, minimum short circuit current = 500 A.

From Table 25: Line length for the given voltage drop $\Delta U = 3\,\%$.

$$l_{max} = 9.56\,\text{m}\,\frac{400\,\text{V}}{43.3\,\text{A}} = 88.3\,\text{m}$$

11.5.5
Example 5: Apartment Building Without Electrical Water Heating

An apartment building without electrical water heating, with a central meter mounting board is to be planned according to Figure 11.10. Answer the following questions:

A **Determination of power requirement:**

1. Central meter mounting board, 15 apartment units on a main line, 100 A fuse, $P_1 \approx 64$ kVA, NH00 100 A fuse
2. Total requirement $P_2 = 11$ kVA $\cdot$ 0.7 = 7.7 kVA
3. Office $P_3 = 80$ kVA $\cdot$ 0.7 = 56 kVA
4. $\Sigma\, P_T = P_1 + P_2 + P_3 = 127.7$ kVA

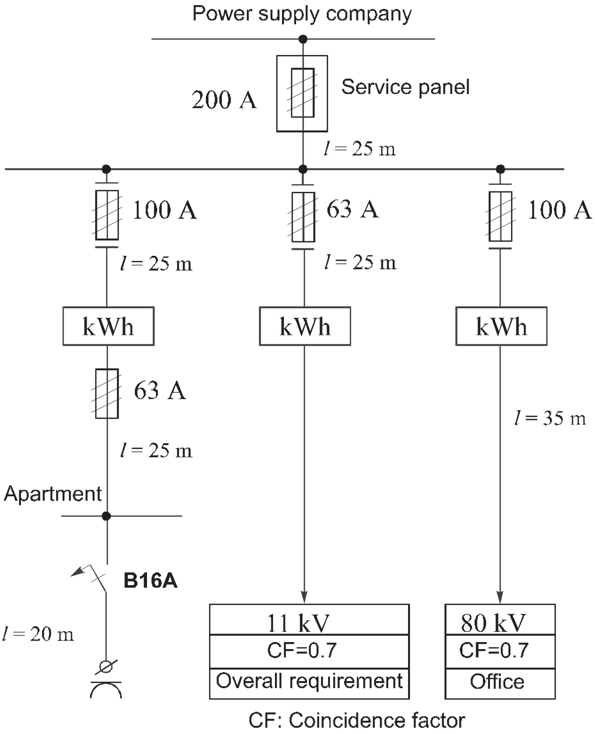


Figure 11.10 Apartment building with a central meter mounting board

B **Calculation of the rated currents, selection of lines and overcurrent protection devices:**

a **Operating current with cos $\varphi = 0.95$:**

$$I_b = \frac{P}{\sqrt{3}\,U\cos\varphi} = \frac{127.7\,\text{kVA}}{\sqrt{3}\cdot 400\cdot 0.95} = 194\,\text{A}$$

b **Protective equipment in service panel: NH1-200** A

c **Selection of line:**

Wall-mounted installation, 25 °C, no grouping. Correction factor for temperature: $f_1 = 1.06$, correction factor for wall-mounted installation: $f_2 = 0.95$.

$$I_z = \frac{I_n}{f_1 f_2} = \frac{200\,\text{A}}{1.06\cdot 0.95} = 198.6\,\text{A}$$

From Table 11.17, I_z' is 202 A with NYCWY 4 × 70 mm^2.

1. **Feeder to meter mounting board for overall requirement:**
Given: $I_n = 63$ A with NYM-J 5 × 16 mm^2 (TN-S system):

Type C installation, no grouping. From Table 11.9, the current carrying capacity I_z is then 81 A and

$$I_n \leq I_z = 63\,\text{A} \leq 81\,\text{A}$$

2. Feeder to office:

Type B2 installation, with 25 °C

$$I_b = \frac{P}{\sqrt{3}\,U\cos\varphi} = \frac{56\,\text{kW}}{\sqrt{3}\cdot 400{\cdot}0.95} = 85.08\,\text{A}$$

Rated current of overcurrent protection device selected: 100 A
Current carrying capacity from Table 11.9: 101 A

$$I_n \leq I_z = 100\,\text{A} \leq 101\,\text{A}$$

Cross-section of line: NYM-J 5 × 35 mm^2

3. Feeder to meter distribution system:

Type B2 installation, with 25 °C, no grouping

$$I_b = \frac{P}{\sqrt{3}\,U\cos\varphi} = \frac{64\,\text{kW}}{\sqrt{3}\cdot 400\cdot 0.95} = 97.2\,\text{A}$$

Rated current of overcurrent protection device selected: 100 A
Current carrying capacity from Table 11.9: 101 A

$$I_n \leq I_z = 100\,\text{A} \leq 101\,\text{A}$$

Cross-section of line: NYM-J 5 × 35 mm^2

4. Feeders to apartment units:

Type B1 installation, $I_n = 63\,\text{A}$, current carrying capacity I_z from Table 11.6 $= 72\,\text{A}$

$$I_n \leq I_z = 63\,\text{A} \leq 72\,\text{A}$$

Cross-section of line: NYM-J 5 × 16 mm^2

5. Electric circuits for apartment installation:

Type B1 installation, $I_n = 16\,\text{A}$, current carrying capacity I_z from Table 11.6 $= 18.5\,\text{A}$

$$I_n \leq I_z = 16\,\text{A} \leq 18.5\,\text{A}$$

Cross-section of line: NYM-J 3 × 1.5 mm^2

C **Voltage drops:**

The calculation is for an operating temperature of 50 °C, with the correction factor 1.12.

1. Feeder for main line:

$I_n = 200\,\text{A}$, $S = 4 \times 70\,\text{mm}^2$, $l = 25$ m, $\cos\varphi = 0.95$

$$\Delta u = \frac{1.12\,\sqrt{3}\,l\,100\,\%\,I_n\cos\varphi}{\kappa\,S\,U_n}$$

$$\Delta u = \frac{1.12\cdot\sqrt{3}\cdot 25\cdot 100\,\%\cdot 200\,\text{A}\cdot 0.95}{56\,\frac{\text{m}}{\Omega\text{mm}^2}\cdot 70^2\cdot 400} = 0.59\,\%$$

According to the technical conditions for connections the voltage drop for 100-250 kVA systems is 1 % maximum. The requirement is therefore satisfied.

2. Main meter - individual meter feeder:

$I_n = 63$ A, $S = 5 \times 16\,\text{mm}^2$, $l = 25$ m, $\cos\varphi = 1$

$$\Delta u = \frac{1.12\cdot\sqrt{3}\cdot 25\cdot 100\,\%\cdot 63\,\text{A}\cdot 1}{56\,\frac{\text{m}}{\Omega\text{mm}^2}\cdot 16^2\cdot 400} = 0.85\,\%$$

Remaining voltage drops for end circuits (maximum 4 %)

Δu for the main line + Δu for the meters 0.59 % +0.85 % = 1.44 %

$4\,\% - 1.44\,\% = 2.56\,\%$

3. Feeder to office:

$I_n = 100$ A, $S = 5 \times 35\,\text{mm}^2$, $l = 35$ m, $\cos\varphi = 0.95$

$$\Delta u = \frac{1.12\cdot\sqrt{3}\cdot 35\,\text{m}\cdot 100\,\%\cdot 100\,\text{A}\cdot 0.95}{56\frac{\text{m}}{\Omega\text{mm}^2}\cdot 35^2\cdot 400} = 0.823\,\%$$

Remaining voltage drops for the end circuits (maximum 4%)

Δu for the main line + Δu for the meters = 0.59 % + 0.823 % = 1.413 %

$4\,\% - 1.413\,\% = 2.58\,\%$

4. Feeder to meter distribution system:

$I_n = 100$ A, $S = 5 \times 35\,\text{mm}^2$, $l = 25$ m, $\cos\varphi = 0.95$

$$\Delta u = \frac{1.12\cdot\sqrt{3}\cdot 25\,\text{m}\cdot 100\,\%\cdot 100\,\text{A}\cdot 1}{56\frac{\text{m}}{\Omega\text{mm}^2}\cdot 35^2\cdot 400\,\text{V}} = 0.619\,\%$$

5. Apartment areas:

$I_n = 63\,\text{A},\ S = 5 \times 16\,\text{mm}^2, l = 25\,\text{m},\ \cos\varphi = 1$

$$\Delta u = 0.85\,\%$$

3 % is permitted from the meter mounting board to the end circuits, so that 2.15 % remain for the end circuits.

6. Electrical outlet circuits:

$I_n = 16\,\text{A},\ S = 3 \times 1.5\,\text{mm}^2, l = 20\,\text{m},\ \cos\varphi = 1,\ U_n = 230,\ T_U = 20\,°\text{C}$

$$\Delta u = \frac{2\,l \cdot I_n \cdot 100\,\%}{\kappa\, S\, U_n} = \frac{2 \cdot 20\,\text{m} \cdot 16\,\text{A} \cdot 100\,\%}{56\frac{\text{m}}{\Omega\text{mm}^2} \cdot 1.5^2 \cdot 230} = 3.31\,\%$$

The voltage drops are too high. A maximum of 2.15% is permissible.
Measures:

1. Increase the cross-section by one step
2. Reduce the circuit breaker to 10 A.

D **Selectivity control:**

For the selectivity condition the rule applies:

The rated current of the upstream fuse must be at least 1.6 times the rated current of the downstream fuse. This drop is ensured except for the circuit between the apartment and the meter distribution system.

E **Cut-off conditions:**

Main feeder

The factor 1.24 is the temperature increase from 20 °C to 80 °C, and the reactance for the cable is $x' = 0.08\,\frac{m\Omega}{m}$, see Table 11.11.

$$R_L = 1.24\,\frac{2\,l\,1000}{\kappa\, S} = 1.24 \cdot \frac{2 \cdot 25\,\text{m} \cdot 1000}{56\frac{\text{m}}{\Omega\text{mm}^2} \cdot 70\,\text{mm}^2} = 15.8\,\text{m}\Omega$$

$$X_L = 2\,l\,x'_L = 2 \cdot 25\,\text{m} \cdot 0.08\,\frac{\text{m}\Omega}{\text{m}} = 4\,\text{m}\Omega$$

$$Z_S = \sqrt{R_L^2 + X_L^2} = \sqrt{15.8^2 + 4^2}\,\text{m}\Omega = 16.3\,\text{m}\Omega$$

Meter distribution – apartment:

$$Z_S = 1.24 \cdot \frac{2 \cdot 25\,\text{m} \cdot 1000}{56\frac{\text{m}}{\Omega\text{mm}^2} \cdot 35\,\text{mm}^2} = 31.6\,\text{m}\Omega$$

Sub-distribution for apartments:

$$Z_S = 1.24 \cdot \frac{2 \cdot 25\,\text{m} \cdot 1000}{56\frac{\text{m}}{\Omega\text{mm}^2} \cdot 16\,\text{mm}^2} = 69.2\,\text{m}\Omega$$

Electrical outlet:

$$Z_S = 1.24 \cdot \frac{2 \cdot 20\,\text{m} \cdot 1000}{56\frac{\text{m}}{\Omega\text{mm}^2} \cdot 1.5\,\text{mm}^2} = 590.5\,\text{m}\Omega$$

The total short circuit impedance is:

$$Z_K = Z_V + Z_{System} = 300\,\text{m}\Omega + 707.6\,\text{m}\Omega \approx 1\Omega$$

Single-pole short circuit current at the electrical outlet:

$$I''_{k1} = \frac{c\,U_n}{\sqrt{3}\,Z_K} = \frac{0.95 \cdot 400}{\sqrt{3} \cdot 1\Omega} = 219.4\,\text{A}$$

Breaking current of circuit breaker $I_a = 5 \cdot 16\,\text{A} = 80\,\text{A}$,

$$I''_{k1} \geq I_a$$

219.5 A > 80 A, so that the requirement is satisfied.

11.6
Examples for the Calculation of Overcurrents

11.6.1
Example 1: Determination of Overcurrents and Short Circuit Currents

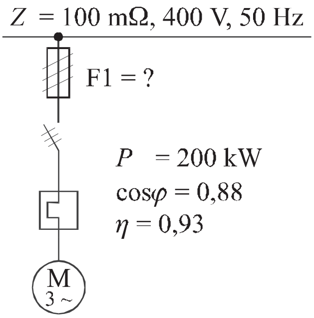


Figure 11.11 Determination of overload and short circuit currents

In a heating system a motor-driven pump with a power of 200 kW, $\cos\varphi = 0.88$, $\eta = 0.93$ is connected through an overhead cable with $l = 45$ m (Figure 11.11). Calculate the:

1. Operating current

$$I_b = \frac{P}{\sqrt{3}\,U_n \cos\varphi\,\eta} = \frac{200\,\text{kW}}{\sqrt{3}\cdot 400\cdot 0.88\cdot 0.93}$$

$$I_b = 353\,\text{A}$$

2. Overload protection, $I_n = 400$ A selected.
From Table 11.17 we find a current carrying capacity of 445 A for an NYY cable with a cross-section of 240 mm^2.

$$I_b \le I_n \le I_z$$

$$353\,\text{A} \le 400\,\text{A} \le 445\,\text{A}$$

3. 2 % voltage drop is permissible (20 °C)

$$\Delta U = \frac{\sqrt{3}\,l\,I\cos\varphi}{\kappa\,S}$$

$$\Delta U = \frac{\sqrt{3}\cdot 45\,\text{m}\cdot 353\,\text{A}\cdot 0.88}{56\frac{\text{m}}{\Omega\,\text{mm}^2}\cdot 240^2} = 1.8\,\text{V}$$

$$\Delta u = \frac{100\,\%\,\Delta U}{U_n} = \frac{100\cdot 1.8}{400} = 0.45\,\%$$

4. Protection by cut-off
Requirement: $I''_{k1} > I_a$ must always hold true:
The cut-off current of the 400 A gL fuse in 5 seconds is (Figure 7.26):

$$I_a = 2800\,\text{A}$$

$$I''_{k1} = \frac{c\,U_n}{\sqrt{3}Z_k}$$

$$R_l = 1.24\,\frac{2\,l\cdot 1000}{\kappa\,S} = 1.24\,\cdot\,\frac{2\cdot 45\,\text{m}\cdot 1000}{56\,\frac{\text{m}}{\Omega\text{mm}^2}\cdot 240^2} = 8.30\,\text{m}\Omega$$

$$X_l = 2\,l\,x'_l = 2\,\cdot\,45\,\text{m}\,\cdot\,0.08\,\frac{\text{m}\Omega}{m} = 7.2\,\text{m}\Omega$$

$$Z_k = \sqrt{R_l^2 + X_l^2} = \sqrt{8.30^2 + 7.2^2}\,\text{m}\Omega = 10.99\,\text{m}\Omega$$

$$Z_k = Z_v + Z_l = 100\,\text{m}\Omega + 10.99\,\text{m}\Omega \approx 111\,\text{m}\Omega$$

$$I''_{k1} = \frac{0.95 \cdot 400}{\sqrt{3} \cdot 0.111\Omega} = 1976.5\,\text{A}$$

The condition:

$$I''_{k1} > I_a$$

must always hold true.
Since in this example $I''_{k1} < I_a$, i.e. 1976.5 A < 2800, the condition is not satisfied.
Measure:
a) Increase the cross-section of the cable, if possible
b) Use a smaller value fuse.

5. Calculational proof of short circuit protection

$$t = \left(\frac{k\,S}{I''_{k1}}\right)^2 = \left(\frac{115\,\frac{\text{A}\sqrt{\text{s}}}{2} \cdot 240\,\text{mm}^2}{1976.5\,\text{A}}\right)^2$$

$$t = 195\,\text{s}$$

6. Overcurrent relay
Current setting for a power circuit breaker of 240–400 A to I_{rM} = 353 A:
Protection: 400 A–AC3
7. Direct starting
With $I_{an}/I_{rM} = 7$ and a start time of max. 10 s: $I_n = 500$ A. An NH fuse is required.

11.6.2
Example 2: Overload Protection

1. Overload protection

In accordance with IEC 60 364, Part 43 determine the overload and short circuit protection with an operating current of 170 A (Figure 11.12).

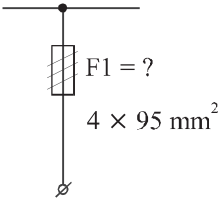


Figure 11.12 Example of overload protection

For a load factor of 0.7 and one cable, we obtain a current carrying capacity of:

$I_z = 280\,\text{A}$ (Table 11.16)

$I_n = 200\,\text{A}$, $I_b = 170\,\text{A}$

From the rule of nominal currents:

$$\begin{aligned} I_b &\leq I_n \leq I_z \\ 170\,\text{A} &\leq 200\,\text{A} \leq 280\,\text{A} \end{aligned}$$

With the tripping rule:

Fuse

$$\begin{aligned} I_2 &\leq 1.45 \cdot I_z \\ 1.6 \cdot I_n &\leq 1.45 \cdot I_z \\ 1.6 \cdot 200\,\text{A} &\leq 1.45 \cdot 280\,\text{A} \\ 320\,\text{A} &\leq 406\,\text{A} \end{aligned}$$

Overload protection is therefore ensured.

2. Short circuit protection

   The let-through energy of the protective device and the cable is found for $t_a <$ 0.1 s from:

   $$I^2\,t \leq k^2\,S^2$$

   where t is read from the characteristic

   $$\begin{aligned} &\text{at 5 s: } I''_{k1} = 1.3\,\text{kA} \\ &(1.3\,\text{kA})^2 \cdot 5\,\text{s} \leq (115\,\text{A}\sqrt{\text{s}}/\text{mm}^2)^2 \cdot (95\,\text{mm})^2 \\ &> 8450000\ \text{A}^2\,\text{s} \leq 119355625\,\text{A}^2\,\text{s} \end{aligned}$$

Short circuit protection is therefore ensured as well.

11.6.3
Example 3: Short Circuit Strength of a Conductor

At the end of a 16-mm^2 Cu line (Figure 11.13) a short circuit current of 3 kA was measured. Prove that this line has sufficient short circuit strength.

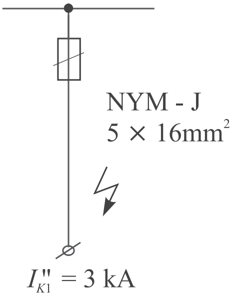


Figure 11.13 Short circuit strength of a line

$$I''_{k1} = 3\,\text{kA} \Rightarrow S = 16\,\text{mm}^2$$

$$t_{zul} = \left(\frac{k\,S}{I''_{k1}}\right) = \left(\frac{115\,\text{A}\,\sqrt{\text{s}}}{\text{mm}^2}\frac{16\,\text{mm}^2}{3\,\text{kA}}\right)^2 = 0.3765\,\text{s}$$

A comparison of the let through energies at $t_a < 0.1$s is necessary:

$$\begin{aligned} I^2\,t &\leq k^2\,S^2 \\ (3\,\text{kA})^2 \cdot 0.1\,\text{s} &\leq (115\,\text{A}\sqrt{\text{s}}/\text{mm}^2)^2 \cdot (16\,\text{mm}^2)^2 \\ 900000\,\text{A}^2\,\text{s} &\leq 3385600\,\text{A}^2\,\text{s} \end{aligned}$$

How large is the short-time current density for a short circuit lasting 1 second with $\vartheta_e = 160\,°\text{C}$ and $\vartheta_a = 30\,°\text{C}$?

Using the constants from Table 11.2 we obtain the rated short-time current density J_{thr}:

$$J_{thr} = \sqrt{\frac{\kappa_{20}\,c\,\rho}{\alpha_{20}\,T_{kr}} \ln \frac{1+\alpha_{20}\,(\vartheta_e - 20\,°\text{C})}{1+\alpha_{20}\,(\vartheta_b - 20\,°\text{C})}}$$

$$I_{thr} = \sqrt{\frac{56 \cdot 10^3 \cdot 8.9 \cdot 10^{-3}\,\text{g} \cdot \text{K} \cdot 0.39\,\text{W}s}{\Omega \cdot \text{mm}^2 \cdot \text{mm}^3 \cdot \text{g} \cdot \text{K} \cdot 0.0039 \cdot 1} \ln \frac{1 + 0.0039 \cdot 1/\text{K} \cdot (160 - 20)\text{K}}{1 + 0.0039 \cdot 1/\text{K} \cdot (30 - 20)\text{K}}} \tag{11.20}$$

$$J_{thr} = 140 \approx 143\,\frac{\text{A}}{\text{mm}^2}$$

rated short-time current:

$$I_{thr} = J_{thr}\,S = 143\,\frac{\text{A}}{\text{mm}^2} \cdot 16\,\text{mm}^2 = 2.288\,\text{kA}$$

Permissible short-time current for another short-time period:

$$I_{thz} = I_{thr}\sqrt{\frac{t_{kr}}{t_k}} = 2.288\,\text{kA} \cdot \sqrt{\frac{1}{2.3\,\text{s}}} = 1.508\,\text{kA}$$

11.6.4
Example 4: Checking Protective Measures for Circuit Breakers

Given the system (Figure 11.14) with different circuit breakers, which are to be compared with each other.

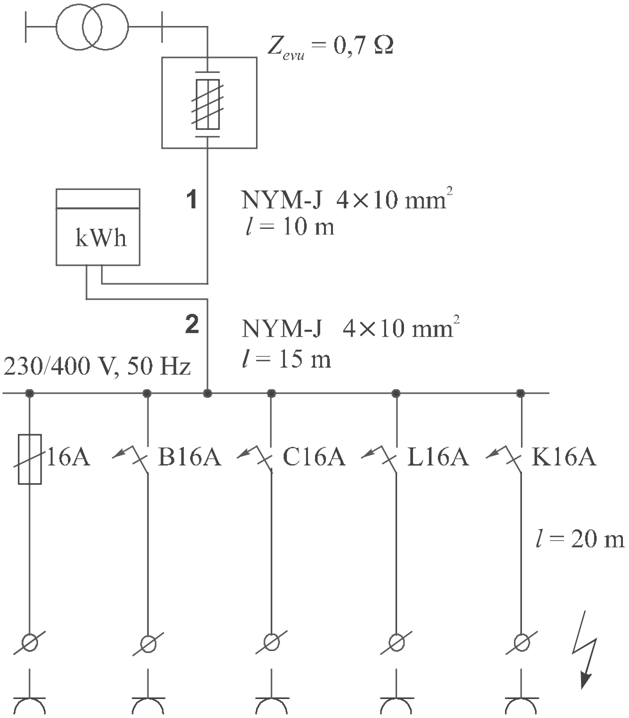


Figure 11.14 Terminal diagram for protective equipment

All exit cables: NYM-J 3 × 1.5 mm ^{2}, $P = 3$ kW
T =70 °C, $l = 20$ m, type B2 installation, $\cos\varphi = 1$

Operating current:

$$I_b = \frac{3\,\text{kW}}{230} = 13\,\text{A}$$

Check the:

1. **Single-pole short circuit current**
   For NYM-J 4 × 10 mm^2 the impedance is: $Z_L^{'} = 0.00449\,\text{m}\Omega/\text{m}$ (outward and return line):

$$Z_G = \sum Z_L = \sum (Z_L' \, l)$$
$$Z_G = Z_{Network} + Z_{L1}' \, l + Z_{L2}' \, l + Z_{L3}' \, l$$

$$
\begin{aligned}
Z_G &= 0.7\,\Omega + 0.00449\,\frac{\Omega}{\mathrm{m}} \cdot 10\,\mathrm{m} + 0.00449\,\frac{\Omega}{\mathrm{m}} \cdot 15\,\mathrm{m} \\
&+ 0.03001\,\frac{\Omega}{\mathrm{m}} \cdot 20\,\mathrm{m} \\
Z_G &= 1.41245\Omega \\
I''_{k1} &= \frac{c\,U_n}{\sqrt{3}\,Z_G} = \frac{0.95 \cdot 400}{\sqrt{3} \cdot 1.41245\Omega} = 155.3\,\mathrm{A}
\end{aligned}
$$

2. **Current carrying capacity**
   NYM-J 3 × 1.5 mm², for type B2 installation Table 11.9; gives a current carrying capacity of $I_z = 16.5$ A at 25 °C.
3. **Overload protection**
   From the rule of nominal currents:

   $$I_b \leq I_n \leq I_z$$

   $$13\,\mathrm{A} < 16\,\mathrm{A} < 16.5\,\mathrm{A}$$

   Conventional tripping current: $I_2 = k \cdot I_n$
   Tripping rule: $I_2 \leq 1.45 \cdot Iz$

   $$
   \begin{aligned}
   I_2 &\leq 1.45 \cdot I_z \\
   k \cdot I_n &\leq 1.45 \cdot I_z \\
   &\leq 1.45 \cdot 16.5\,\mathrm{A} \\
   &\leq 23.9\,\mathrm{A} \\
   \mathrm{gG} : I_2 &= 1.75\,I_n = 1.75 \cdot 16\,\mathrm{A} = 28\,\mathrm{A} \\
   \mathrm{B} : I_2 &= 1.45\,I_n = 1.45 \cdot 16\,\mathrm{A} = 23.2\mathrm{A} \\
   \mathrm{C} : I_2 &= 1.45\,I_n = 1.45 \cdot 16\,\mathrm{A} = 23.2\,\mathrm{A} \\
   \mathrm{L} : I_2 &= 1.9\,I_n = 1.9 \cdot 16\,\mathrm{A} = 30.4\,\mathrm{A} \\
   \mathrm{K} : I_2 &= 1.2\,I_n = 1.2 \cdot 16\,\mathrm{A} = 19.2\,\mathrm{A} \\
   \mathrm{G} : I_2 &= 1.35\,I_n = 1.35 \cdot 16\,\mathrm{A} = 21.6\,\mathrm{A}
   \end{aligned}
   $$

   For gG and L overload protection is not ensured.
4. **Cut-off currents for the overcurrent protection equipment**

   $$
   \begin{aligned}
   \mathrm{B} : I_a &= 5\,I_n = 5 \cdot 16\,\mathrm{A} = 80\,\mathrm{A} \\
   \mathrm{C} : Ia &= 10\,In = 10 \cdot 16\,\mathrm{A} = 160\,\mathrm{A} \\
   \mathrm{gG} : Ia &= \mathrm{bei}\,0.2s\ \mathrm{mit}\ In = 16\,\mathrm{A} = 148\,\mathrm{A} \\
   \mathrm{K} : Ia &= 14\,In = 14 \cdot 16\,\mathrm{A} = 224\,\mathrm{A} \\
   \mathrm{L} : Ia &= 4.9\,In = 4.9 \cdot 16\,\mathrm{A} = 78.4\,\mathrm{A}
   \end{aligned}
   $$

For the cut-off condition:

$$\begin{aligned} I''_{k1} &> I_a \\ 155.3\,\text{A} &> I_a \end{aligned}$$

For the C and K characteristics the cut-off conditions are not satisfied.

5. **Utilization factor**

   The utilization factor N should be as large as possible, so that the 100% capability of the line is used.

$$\begin{aligned} N &= \frac{I_n}{Iz}\,100\,\% \\ N &= \frac{16\,\text{A}}{15\,\text{A}} \cdot 100\,\% = 106\,\%\,\text{mit}\,1.5\,\text{mm}^2 \\ N &= \frac{16\,\text{A}}{20\,\text{A}} \cdot 100\,\% = 80\,\%\,\text{mit}\,2.5\,\text{mm}^2 \end{aligned}$$

6. **Degree of protection**

   The degree of protection S should be as small as possible. The loading capacity of the line and the overtemperature are then kept low and the life of the line increases.

$$\begin{aligned} S &= \frac{I_2}{Iz} \\ S &= \frac{k\,I_n}{Iz} \\ S &= \frac{1.75 \cdot 16\,\text{A}}{16.5\,\text{A}} = 1.69\,\text{with the fuse} \\ S &= \frac{1.9 \cdot 16\,\text{A}}{16.5\,\text{A}} = 1.84\,\text{with the circuit breaker} \end{aligned}$$

   The factor above is the ratio of the tripping current to the nominal current for the overcurrent protection device and can serve for the calculation of the tripping current, e.g. $I_2 = x \cdot I_n$.

   Both examples show that the degree of protection of $S \leq 1.45$ is not satisfied. It is therefore necessary to choose a smaller I_n.

7. **Selection of fuse or circuit breaker**

$$\begin{aligned} I_n &\leq \frac{1.45}{k}\,I_z \\ \text{gG}: I_n &\leq \frac{1.45}{1.75} \cdot 16.5\,\text{A} = 13.6\,\text{A} \\ \text{B}: I_n &\leq \frac{1.45}{1.45} \cdot 16.5\,\text{A} = 16.5\,\text{A} \\ \text{C}: I_n &\leq \frac{1.45}{1.45} \cdot 16.5\,\text{A} = 16.5\,\text{A} \end{aligned}$$

$$\begin{aligned}
\mathrm{L}: I_n &\leq \frac{1.45}{1.9} \cdot 16.5\,\mathrm{A} = 12.6\,\mathrm{A}\\
\mathrm{K}: I_n &\leq \frac{1.45}{1.2} \cdot 16.5\,\mathrm{A} = 19.94\,\mathrm{A}\\
\mathrm{G}: I_n &\leq \frac{1.45}{1.35} \cdot 16.5\,\mathrm{A} = 17.72\,\mathrm{A}
\end{aligned}$$

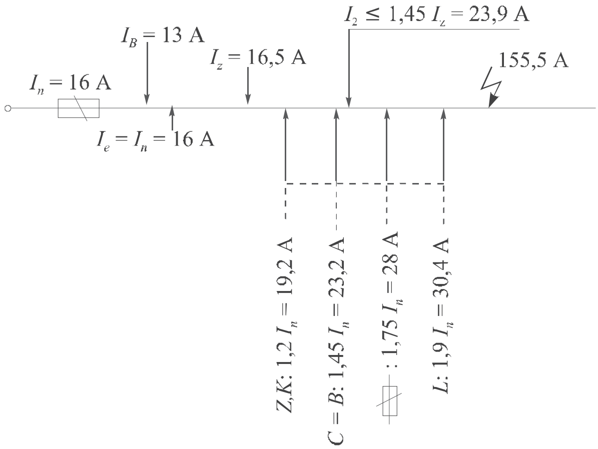


Figure 11.15 Coordination of overcurrent protection equipment characteristics

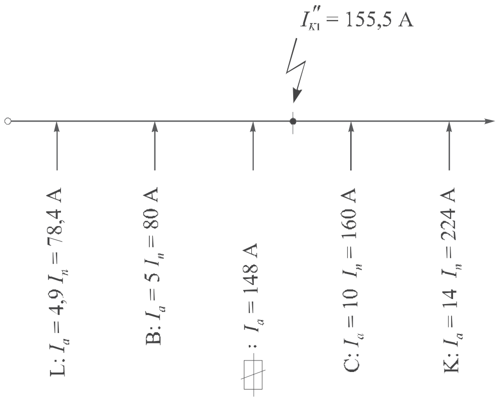


Figure 11.16 Cut-off currents of protective equipment

8 Factors for grouping and temperature
Lines in conduit

$$\begin{aligned}
f_1 &= 0.8\\
T &= 25\,^\circ\mathrm{C}
\end{aligned}$$

$$f_2 = 1.06$$

$$I_{z\text{Tab}} = \frac{I_n}{f_1 f_2} = \frac{16\,\text{A}}{0.8 \cdot 1.06} = 18.86\,\text{A}$$

NYM-J 3 × 2.5 mm^2 selected.

9. **Voltage drop calculation at 20 °C and cos $\varphi = 1$**

a) Service panel meter distribution system (Figure 11.14):

$$\Delta u = \frac{\sqrt{3} \cdot 10\,\text{m} \cdot 100\,\% \cdot 63\,\text{A}}{56 \frac{\text{m}}{\Omega\text{mm}^2} \cdot 10\,mm^2 \cdot 400\,\text{V}} = 0\,.49\,\%$$

According to the technical conditions for connections only 0.5% is permissible.

b) Service panel meter distribution - sub-distribution:

$$\Delta u = \frac{\sqrt{3} \cdot 15\,\text{m} \cdot 100\,\% \cdot 63\,\text{A}}{56 \frac{\text{m}}{\Omega\text{mm}^2} \cdot 10\,\text{mm}^2 \cdot 400\,\text{V}} = 0.73\,\%$$

c) Sub-distribution – end circuits:

$$\Delta u = \frac{2 \cdot 10\,\text{m} \cdot 100\,\% \cdot 16\,\text{A}}{56 \frac{\text{m}}{\Omega\text{mm}^2} \cdot 2.5\,\text{mm}^2 \cdot 230\,\text{V}} = 1\,\%$$

The sum of all voltage drops is:

$$0.49\,\% + 0.73\,\% + 1\,\% = 2.22\,\%$$

(maximum permissible is 4 %).

12
Calculation of Short Circuit Currents in Three-Phase Networks

IEC 60 909

For the dimensioning of electrical systems to withstand thermal and mechanical stresses under fault conditions the three-pole initial symmetrical short circuit current I''_k is of great importance. The fundamentals of the short circuit calculation with the equivalent voltage source method at the fault location are found in IEC 60 909. This method represents a simplification, since the calculation is independent of the current operating state and future load flows. The electrical operational equipment parameters are taken into account in the calculation, and all network feeders, generators and motors are short circuited behind their internal reactances. The equivalent voltage source $c\,U_n/\sqrt{3}$ is then the only driving voltage in the network. The largest possible short circuit current I''_{k3} is the value which determines the dimensioning of the operational equipment, and the smallest short circuit current I''_{k1} is the value which determines the protective measure "protection by cut-off" and the setting for the network protection.

Except for the three-pole short circuit current, all short circuit types are calculated with the use of symmetrical components.

IEC 60 909 is comprised of four main sections (HA):

HA 1: General
HA 2: Properties of short circuit currents. Method of calculation.
HA 3: Short circuit impedances for electrical operational equipment
HA 4: Calculation of short circuit currents

The following points have been added to this standard:

- New classification into low-voltage and high-voltage networks
- Supplementary sheets with examples and correction factors, supplementing the theoretical part
- Low-voltage and high-voltage networks are treated in the same way. They differ only in the information listed in IEC 60 364.
- The information regarding the calculation of three-pole and single-pole short circuits applies equally to low-voltage and high-voltage networks.
- Voltage factors (c_{max} and c_{min}) are given.

Analysis and Design of Low-Voltage Power Systems. Ismail Kasikci

ISBN: 3-527-30483-5

- Impedance corrections, independent of the behavior of the short circuit over time, have been introduced for generators and power stations
- μ and q curves have been newly included for $t_{min} = 0.02$ s in order to take account of the decay of the AC component of the short circuit current for asynchronous machines or motor groups.
- Equations for the calculation of μ and q factors have been newly included.
- In low-voltage networks a temperature rise from 20 °C to 80 °C (in Future 160 °C for PVC-Cable) is used for the single-pole short circuit.
- Indices for symmetrical components (0,1,2) are internationally recognized.

The behavior of the initial symmetrical short circuit current over time, from the beginning of the short circuit to the end, is shown in Figure 12.1 beginning with the momentary value of the voltage at the onset of the short circuit. For a complete calculation of the short circuit it is necessary to consider this behavior. In most cases, the initial symmetrical short circuit current and the peak short circuit current must be calculated.

The following pages will now deal with the fundamentals of calculating short circuit currents on the basis of this standard.

In addition, the KUBSplus and NEPLAN program on the CD-ROM accompanying this book are intended for the calculation of short circuits in low-voltage networks.

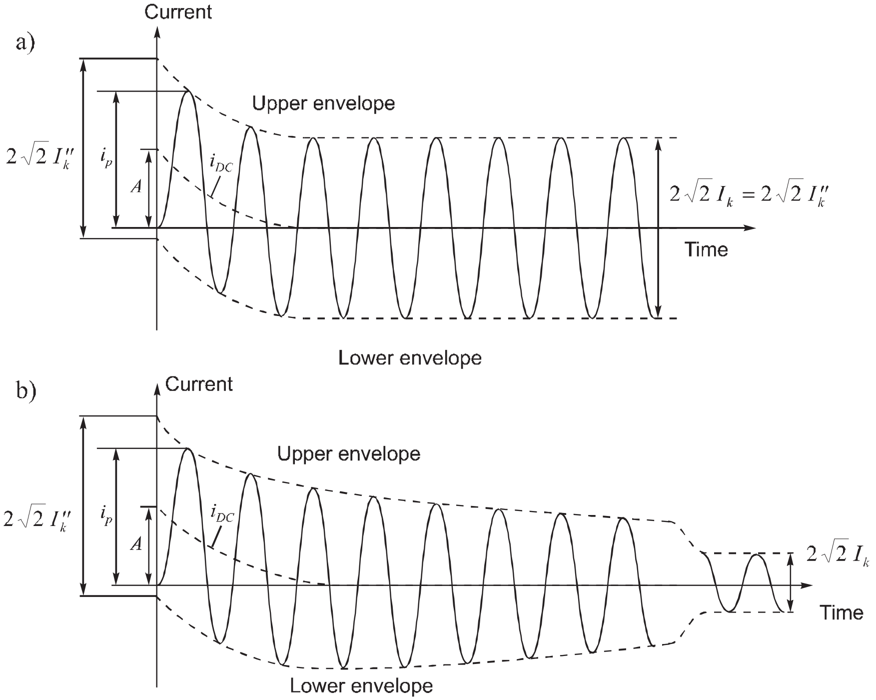


Figure 12.1 Behavior of the short circuit current over time

Here the meanings of the symbols are (Figure 12.1):

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_k	Steady state short circuit current
i_{DC}	Decaying DC current component
A	Initial value of DC current component i_{DC}

Different types of short circuits (Figure 12.2) are calculated with the method of symmetrical components.

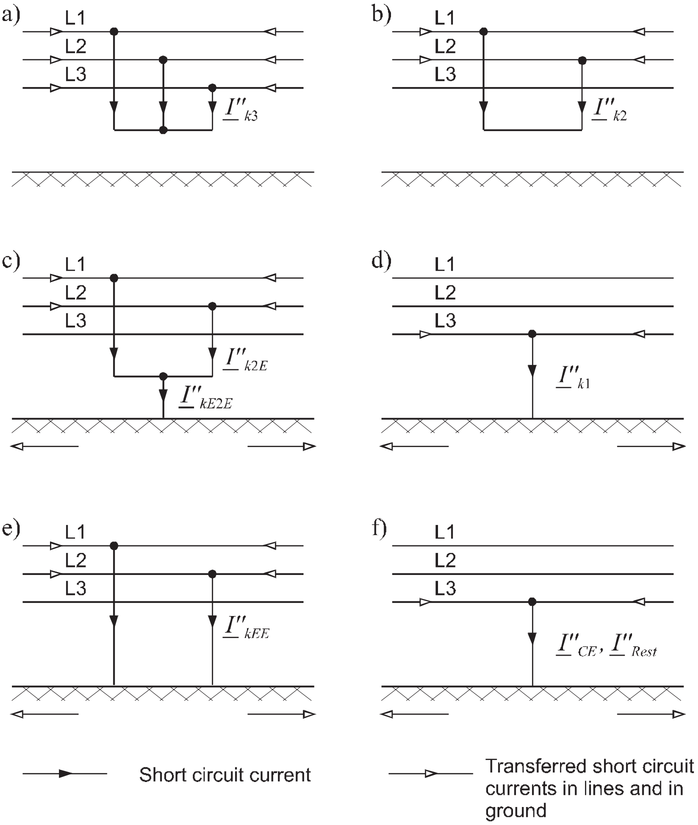


Figure 12.2 Types of faults
a) Three-pole short circuit
b) Two-pole short circuit without contact to ground
c) Two-pole short circuit with contact to ground
d) Single-pole ground fault
e) Double line-to-ground fault
f) Capacitive ground fault current I_{CE}, residual ground fault current I_{Rest}

12.1
The Equivalent Voltage Source Method

The short circuit current at the fault location F is calculated using the equivalent voltage source (Figure 12.3). This is the only voltage acting in the network at the fault location F. All other voltages for the operational equipment are short circuited behind their internal impedances [24]. The voltage factor *c* is defined exactly in IEC 60 909 and can be taken from Table 12.1.

Table 12.1: Voltage factor c in accordance with IEC 60 909

Rated voltage U_n	Voltage factor c for calculation of the largest short circuit current c_{max}	the smallest short circuit current c_{min}
Low voltage		
100 V to 1000 V (IEC 60038, Table I)		
a) 230 V/400 V	1.00	0.95
b) Other voltages	1,05	1.00
Medium voltage		
> 1 kV to 35 kV (IEC 60038, Table III)	1.10	1.00
High voltage		
> 35 kV to 230 kV (IEC 60038, Table IV)	1.10	1.00
380 kV (see explanations)	1.10	1.00

Note: cU_n must not exceed the highest voltage U_m for operational equipment

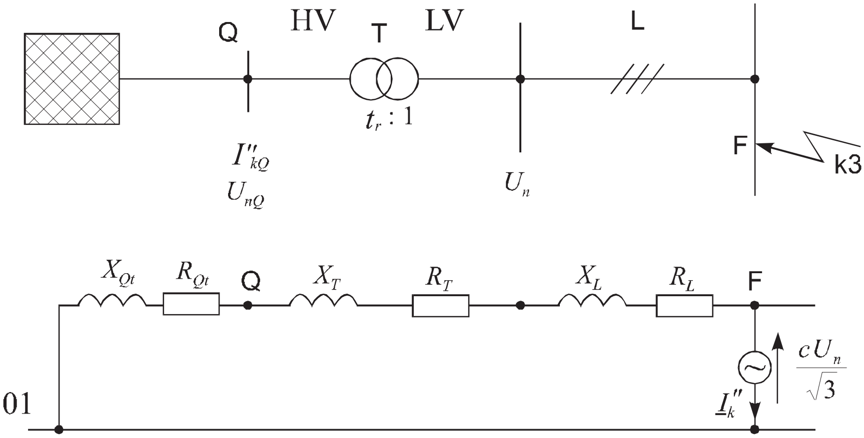


Figure 12.3 Equivalent voltage source

The introduction of the voltage factor c is necessary for the following reasons:

- Different voltages within the network
- Subtransient behavior of generators, power stations and motors
- Neglecting of loads and line capacitances
- Neglecting of the stationary operating state.

12.1.1
Single-Pole Short Circuits to Ground

The Single-Pole Short Circuits to Ground is an asymmetrical fault, which is calculated on the basis of symmetrical components. This type of fault involves an external conductor (PEN) or a protective ground conductor (PE). In practice, however, a simpler approach is used, which entails an error of up to 20 %. Since the OPE and the cross-section of the conductor are matched to each other, tripping takes place within 0.2 seconds, 0.4 seconds or 5 seconds. The initial symmetrical short circuit current for a single-pole short circuit to ground as in Figure 4 is calculated from $\underline{Z}_{(1)} + \underline{Z}_{(0)}$

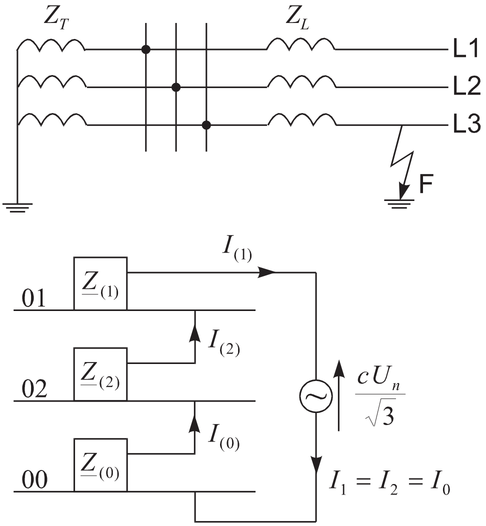


Figure 12.4 Network and equivalent circuit for a single-pole short circuit current I''_{k1}

$$I''_{k1} = \frac{\sqrt{3}\, c\, U_n}{|2\,\underline{Z}_{(1)} + \underline{Z}_{(0)}|} \tag{12.1}$$

Here the symbols have the meanings:
$Z_{(1)}$ Positive-sequence impedance
$Z_{(0)}$ Negative-sequence impedance
c voltage factor

12.1.2
Calculation of Loop Impedance

In low-voltage networks the loop impedance, which accounts for the effective resistances and for the reactances from the transformer to the fault location in the outwards and return directions, is required in order to determine the cut-off conditions in accordance with IEC 60 364, Parts 41 and 61. According to the installation of the system, this value can be determined very easily for the circuit assumed using measuring instruments. This value must not be greater than the values listed in Tables F.1 and F.2 in IEC 60 364, Part 61. Figure 12.5 depicts the network, the equivalent circuit and the related loop impedance.

For the calculation of the single-pole short circuit current the method of symmetrical components [24] is used. This method requires the determination of three independent component systems (positive-sequence, zero-sequence and negative-sequence systems). For the impedances of the operational equipment from Figure 12.5, it follows for the fault location that:

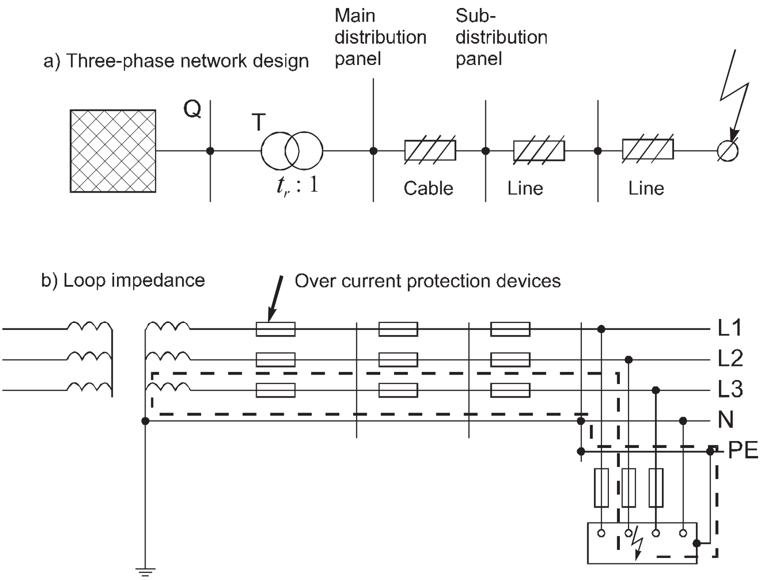


Figure 12.5 Loop impedance

$$\sum R = (2R_Q + 2R_T + 2R_K + 2R_{L1} + 2R_{L2} + R_{0T} + R_{0K} + R_{0L1} + R_{0L2})$$

$$\sum X = (2X_Q + 2X_T + 2X_K + 2X_{L1} + 2X_{L2} + X_{0T} + X_{0K} + X_{0L1} + X_{0L2})$$

$$Z_k = \sqrt{\sum R^2 + \sum X^2} \tag{12.2}$$

$$I''_{k1} = \frac{c_{min} U_n}{\sqrt{3} Z_k} \tag{12.3}$$

The short circuit impedance Z_k (loop impedance) includes the impedances of the supply network, the transformer, the external conductor, the PEN conductor and the PE conductor. The result is on the safe side, since the short circuit current which actually flows is greater than the value calculated. The source impedance or the single-pole short circuit current is often known at the connection to the line, so that the maximum permissible circuit lengths and the cut-off conditions can then be determined.

Here, the meanings of the symbols are:

R_Q, X_Q	Resistance and inductive reactance of network feeder
R_T, X_T	Resistance and inductive reactance of transformer
R_K, X_K	Resistance and inductive reactance of cable
R_{L1}, X_{L1}	Resistance and inductive reactance of line 1
R_{L2}, X_{L2}	Resistance and inductive reactance of line 2
R_{0T}, X_{0T}	Zero-sequence resistance and inductive reactance of transformer
R_{0K}, X_{0K}	Zero-sequence resistance and inductive reactance of cable
R_{0L1}, X_{0L1}	Zero-sequence resistance and inductive reactance of line 1
R_{0L2}, X_{0L2}	Zero-sequence resistance and inductive reactance of line 2

12.1.3
Three-Pole Short Circuits

By contrast with a single-pole short circuit, a three-pole short circuit is a symmetrical fault, which is used for the evaluation of the rated breaking capacity of the overcurrent protective equipment (Figure 12.6).

$$I''_{k3} = \frac{c\, U_n}{\sqrt{3}\, Z_k} \tag{12.4}$$

$$Z_k = \sqrt{R_k^2 + X_k^2} \tag{12.5}$$

$$R_k = R_{Qt} + R_T + R_L \tag{12.6}$$

$$X_k = X_{Qt} + X_T + X_L \tag{12.7}$$

Here, the meanings of the symbols are:

R_k	Sum of resistances in series
X_k	Sum of reactances in series
Z_k	Short circuit impedance
c	Voltage factor

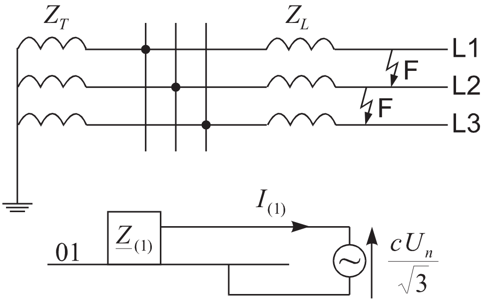


Figure 12.6 Network and equivalent circuit for a three-pole short circuit current I''_{k3}

12.2
Calculation of Resistance Values for Operational Equipment

Power always begins with the external network. In general, the short circuit power of the network is known and is given in MVA. Equipment found in the network includes generators, transformers, lines and cables, motors and other loads. For the determination of short circuit currents, we will discuss impedances and equivalent circuit diagrams for three-phase equipment in this section.

12.2.1
Network Feeders

The internal impedance of the network Z_Q at the terminal Q is calculated from the initial symmetrical short circuit current power S''_{kQ} or the initial symmetrical short circuit current I''_{kQ} (Figure 12.7).

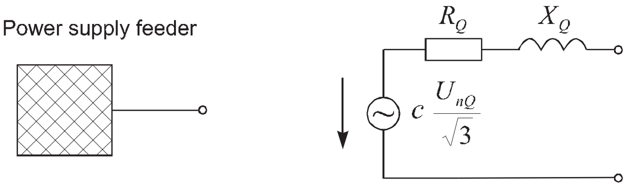


Figure 12.7 Power supply feeder

$$S''_{kQ} = \sqrt{3}\,U_{nQ}\,I''_{kQ} \tag{12.8}$$

$$Z_Q = \frac{cU_{nQ}}{\sqrt{3}\,I''_{kQ}} = \frac{c\,U^2_{nQ}}{S''_{kQ}} \tag{12.9}$$

The conversion of the internal impedance of the network to the lower voltage side of the transformer is given by:

$$Z_{Qt} = \frac{c\,U_{nQ}^2}{S_{kQ}''}\,\frac{1}{t_r^2} \tag{12.10}$$

When the resistance of the power supply feeder R_Q is not known, we can introduce in its place:

$$X_Q = 0.995\,Z_Q \tag{12.13}$$

$$R_Q = 0.1\,X_Q \tag{12.14}$$

Here the symbols have the meanings:

U_{nQ}	Nominal voltage of the network at the terminal Q
S_{kQ}''	Initial symmetrical short circuit apparent power
I_{kQ}''	Initial symmetrical short circuit current
t_r	rated transformation ratio at which the tap-changer in the main position
c	Voltage factor

12.2.2
Synchronous Machines

In general, for the calculation of the initial symmetrical short circuit current I_{kG}'' at the generator terminals we first find the subtransient part of the equivalent circuit E'' (Figure 12.8).

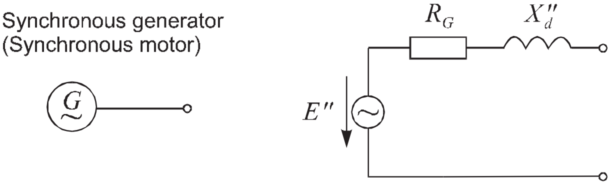


Figure 12.8 Synchronous machine

For low-voltage generators:

$$Z_G = R_G + \mathrm{j}\,X_d'' \tag{12.13}$$

$$R_G = 0.15\,X_d'' \tag{12.14}$$

For high-voltage generators $U_{rG} > 1\text{kV}$ and $S_G \geq 100\,\text{MVA}$:

$$R_G = 0.05\,X_d'' \tag{12.15}$$

and with $S_G < 100\ \text{MVA}$:

$$R_G = 0.07\,X''_d \tag{12.16}$$

$$X''_d = \frac{x''_d\,U_{rG}}{100\,\%\,S_{rG}} \tag{12.17}$$

Here the symbols have the meanings:

X''_d	Subtransient reactance
x''_d	Initial reactance in %
R_G	Resistance of generator
Z_G	Impedance of generator

12.2.3
Consideration of Motors

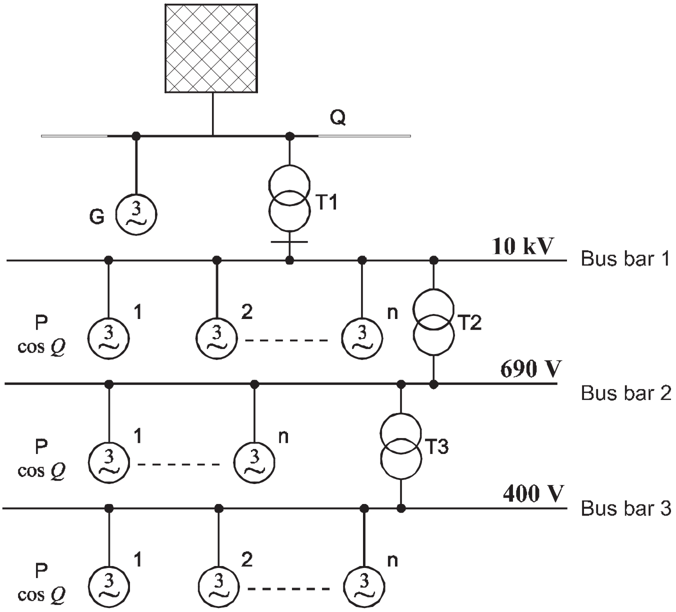


Figure 12.9 Example for the connection of different motors in industrial networks

In industry mostly asynchronous motors are used (Figure 12.9). With the occurrence of a fault these contribute to the initial symmetrical short circuit current, the peak short circuit current, the symmetrical breaking current and for a two-pole short circuit also to the steady state short circuit current, depending on the location of the motors and the fault [24], [59]. The peak short circuit component of the asynchronous motors must be taken into account. There is no difference in the calculations for squirrel cage rotor and slip-ring rotor motors, since the starting resistors of slip-ring rotor motors are short circuited during operation.

The impedance $\underline{Z}_M$ of an asynchronous machine in the positive-sequence and negative-sequence systems is calculated from:

$$Z_M = \frac{1}{I_{LR}/I_{rM}} \frac{U_{rM}}{\sqrt{3}\, I_{rM}} = \frac{1}{I_{LR}/I_{rM}} \frac{U_{rM}^2}{S_{rM}} \tag{12.18}$$

$$I''_{kM} = \frac{c\, U_n}{\sqrt{3}\, Z_M} \tag{12.19}$$

Motors or groups of motors on a busbar following a three-pole short circuit can be neglected, provided that:

$$\sum I_{rM} \le 0.01\, I''_{kQ} \tag{12.20}$$

$$\frac{R_M}{X_M} = 0.42 \qquad \text{and} \qquad X_M = 0.922\, Z_M \tag{12.21}$$

High-voltage and low-voltage motors fed from a short circuit at the terminal Q by way of transformers with two windings can also be neglected under the conditions $u_{kr} = 6\,\%$, $\cos\varphi_{rM} = 0.8$ and $I_{LR}/I_{rM} = 5$, so that

$$\frac{P_{rM}}{S_{rT}} \le \frac{0.8}{\left| \frac{c\, 100\, S_{rT}}{S''_{kQ}} - 0.3 \right|} \tag{12.22}$$

Motor groups fed through transformers with different rated voltages can be calculated as follows:

$$\frac{\sum P_{rM}}{\sum S_{rT}} \le \frac{\cos\varphi\, \eta_r}{\frac{I_{LR}}{I_{rM}}} \left(\frac{c \sum S_{rT}}{0.05\, S''_{kQ}} - u_{kr} \right) \tag{12.23}$$

Here, the symbols have the meanings:

I_{LR}	Breakaway starting current
I_{rM}	Rated current of motors in a group
U_{rM}	Rated voltage of motor
I_{LR}/I_{rM}	Ratio of breakaway starting current to rated current for motor (lies between 4 and 8)
$\sum P_{rM}$	Sum of rated effective powers
$\sum S_{rT}$	Sum of rated apparent powers
S''_{kQ}	Initial symmetrical short circuit apparent power
Z_M	Short circuit impedance

Conclusion

Under the following conditions asynchronous motors can be neglected for the short circuit calculation:

- Motors in public low-voltage networks
- Contributions from motors or groups of motors which represent less than 5 % of the initial symmetrical short circuit current without motors
- Motors which due to interlocking or the type of process execution do not run at the same time
- Motors fed from a short circuit by way of transformers with two windings.

12.2.4
Overland Lines, Cables and Lines

The short circuit impedance in the positive-sequence system can be calculated from the line data, the tables, the cross-sections and the minimum spacing between the lines.

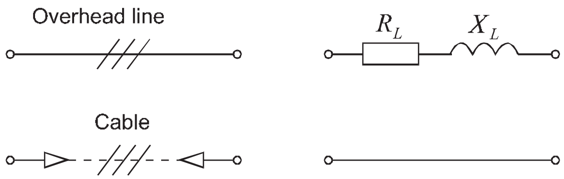


Figure 12.10 Cables and lines

From Figure 12.10, the short circuit impedance is:

$$Z = R_L + \mathrm{j}X_L \tag{12.24}$$

Ohmic resistance:

$$R_L = R'_L\, l \tag{12.25}$$

Inductive reactance:

$$X_L = X'_L\, l \tag{12.26}$$

For the calculation of the single-pole short circuit current in accordance with IEC 60 909 a temperature rise of 80 °C and 160 °C is assumed:

$$R_{80\,^\circ\mathrm{C}} = 1.24\, \frac{l}{\kappa\, S} \tag{12.27}$$

$$R_{160\,^\circ\mathrm{C}} = 1.56\, \frac{l}{\kappa\, S} \tag{12.28}$$

Zero-sequence resistances of lines:

$$R_{0L} = \text{Table value } R_L \tag{12.28}$$

$$X_{0L} = \text{Table value } X_L \tag{12.29}$$

The effective resistance R'_L for overhead lines can be calculated for a line temperature of 20 °C from:

$$R'_L = \frac{1}{\kappa\, S} \tag{12.30}$$

The reactance per unit length X'_L for overhead lines can be calculated from:

$$X'_L = 2\,\pi\,10^{-2}\left(0.25 + \ln\frac{d}{r}\right) \tag{12.31}$$

with

$$d = \sqrt[3]{d_{L1L2}\cdot d_{L2L3}\cdot d_{L3L1}}$$

The symbols have the meanings:

d	Average spacing between lines in mm
r	Radius of lines in mm
κ	Conductivity in m/Ω mm²
R'_L	Line resistance at 20 °C

12.2.5
Transformers

The short circuit voltage is the primary voltage at which the transformer with short circuited output winding takes up its primary current. It is a measure of the voltage change occurring under load. The positive-sequence impedance of the transformer is as shown in Figure 12.11:

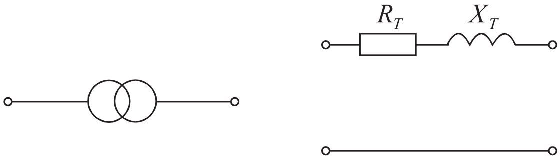


Figure 12.11: Transformer and its equivalent circuit

$$\underline{Z}_1 = \underline{Z}_T = R_T + \mathrm{j}X_T \tag{12.32}$$

The positive-sequence impedance is:

$$Z_T = \frac{u_{kr}\,U_{rT}^2}{100\,\%\,S_{rT}} \tag{12.33}$$

$$R_T = \frac{u_{Rr}\, U_{rT}^2}{100\,\%\, S_{rT}} = \frac{P_{krT}}{3\, I_{rT}^2} \tag{12.34}$$

$$X_T = \sqrt{Z_T^2 - R_T^2} \tag{12.35}$$

The characteristic values of three-phase distribution transformers can be found in DIN 42500, 42503 and 42511. For the calculation of the zero-sequence resistances, we can use Table 12.2.

Zero-sequence resistances of transformers

Zero-sequence resistances	Dy	Dz, Yy
R_{0T}	R_T	$0.4\ R_T$
X_{0T}	$0.95\ X_T$	$0.1\ X_T$

12.2.6

Impedance Corrections

For the calculation of the three-pole initial symmetrical short circuit current in networks with generators, with or without generator transformers, impedance corrections must be performed once (Figures 12.12 and 12.13). The correction factor K accounts for a voltage higher than E''.

Figure 12.12: Impedance correction for generators

1. Generators For generators in industrial networks or in low-voltage networks with direct connection, we can use the following equation in the positive-sequence system:

$$\underline{Z}_G = R_G + \mathrm{j}''_d \tag{12.36}$$

$$\underline{Z}_{(GK)} = K_G\, \underline{Z}_G = K_G\, (R_G + \mathrm{j}''_d) \tag{12.37}$$

with the correction factor

$$K_G = \frac{U_n}{U_{rG}} \frac{c_{max}}{(1 + x''_d\, \sin\varphi_{rG})} \tag{12.38}$$

Here the symbols have the meanings:

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}

2. Impedance correction for two-winding transformer

Impedance correction for two-winding transformer can be calculated with and without tap-changer as follows:

Short circuit impedance of the transformer:

$$\underline{Z}_T = R_T + jX_T \tag{12.39}$$

With the correction factor K_T:

$$\underline{Z}_{TK} = K_T \cdot \underline{Z}_T \tag{12.40}$$

$$K_T = 0,95 \frac{c_{max}}{1+0,6\, x_T} \tag{12.41}$$

$$x_T = \frac{X_T}{(U_{rT}^2/S_{rT})} \tag{12.42}$$

Here the symbols have the meanings:

U_{rT}	rated voltage of the transformer
	rated current of the transformer
S_{rT}	rated apparent power of the transformer
P_{krT}	total loss of the transformer in the windings at rated current
u_{kr}	rated short-circuit voltage in %
x_T	related reactance of the transformer
u_{Rr}	rated ohmique voltage in %.

3. Power station blocks with tap-changer

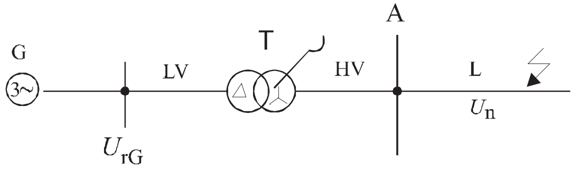


Figure 12.13: Impedance correction for power station transformer

$$\underline{Z}_S = K_S(t_r^2\underline{Z}_G + \underline{Z}_{THV}) \tag{12.43}$$

with the correction factor

$$K_S = \frac{U_{nQ}^2}{U_{rG}^2}\frac{U_{rTLV}^2}{U_{rTHV}^2}\;\frac{c_{max}}{(|1+x_d - x_T|\,\sin\varphi_{\rho\Gamma})} \tag{12.44}$$

4. Power station blocks without tap-changer
   The short circuit impedance of power supply blocks on the higher voltage side of the block transformer is:

$$\underline{Z}_{SO} = K_S(t_r^2\underline{Z}_G + \underline{Z}_{THV}) \tag{12.45}$$

with the correction factor

$$K_{SO} = \frac{U_{nQ}}{U_{rG}\,(1+p_G)} \cdot \frac{U_{rTLV}}{U_{rTHV}} \cdot (1 \pm p_T) \cdot \frac{c_{max}}{(1+x_d''\ \sin_{rG})} \tag{12.46}$$

Here the symbols have the meanings:

$\underline{Z}_S, \underline{Z}_{SO},$	Corrected impedance with and without tap-changer
$\underline{Z}_G$	Impedance of generator
t_r	rated transformation ratio at which the tap-changer at main position
$\underline{Z}_{TLV}$	Impedance of transformer (lower voltage side)
$\underline{Z}_{THV}$	Impedance of transformer (upper voltage side)
U_{nQ}	Nominal voltage of network
U_{rG}	Rated voltage of generator
x_d''	Subtransient reactance of generator
φ_{rG}	Phase angle between $U_{rG}/\sqrt{3}$ and I_{rG}

12.3
Short Circuit Currents for Three-Pole Short Circuits

12.3.1
Peak Short Circuit Current

The calculation of the peak short circuit current is important for:

- the dynamic stressing of electrical systems
- the making capacity of switchgear.

The following relationships apply:

$$i_p = \kappa\sqrt{2}\,I_k'' \tag{12.47}$$

$$\kappa = f\left(\frac{R_k}{X_k}\right) \tag{12.48}$$

The factor κ is taken from Figure 12.14.

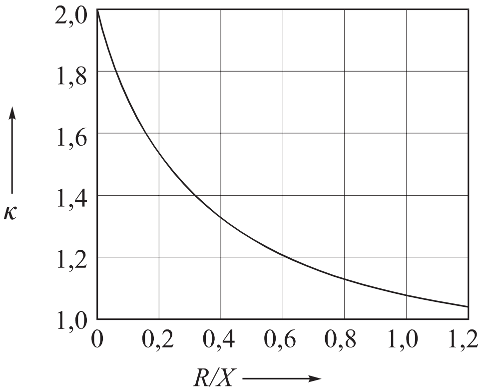


Figure 12.14: Factor κ for calculation of the peak short circuit current i_p

12.3.2
Symmetrical Breaking Current

The symmetrical breaking current is the effective value of the symmetrical AC component of the expected short circuit current at the moment of contact separation of the first pole which quenches in the overcurrent protective device.

1. For synchronous machines:

$$I_a = \mu \, I''_{kG} \tag{12.49}$$

If $I_a = I''_k$, then $\mu = 1$, i.e. a far-from-generator short circuit. For synchronous machines:

$$\frac{I''_{k3}}{I_{rG}} \leq 2 \tag{12.50}$$

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

$$\frac{I''_{k3}}{I_{rG}} \geq 2 \tag{12.51}$$

In practice: The minimum switching delay (for tripping an overcurrent protection device) is 0.1 seconds.

2. For asynchronous machines:

$$I_a = \mu\, q\, I''_{kM} \tag{12.52}$$

μ depends on the ratio I''_k / I_{rG} for the individual short circuit sources and the minimum switching delay t_{min}, and q depends on the effective power of the pole pair (Figure 12.15).

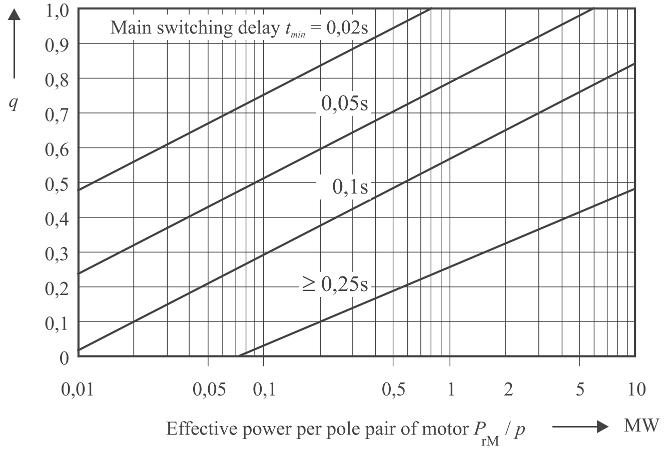


Figure 12.15: Factor q for calculation of the symmetrical breaking current of asynchronous machines

3. For power supply feeders:

$$I_{aQ} = I''_{kQ} \tag{12.53}$$

The μ factor can be taken from Figure 12.16.

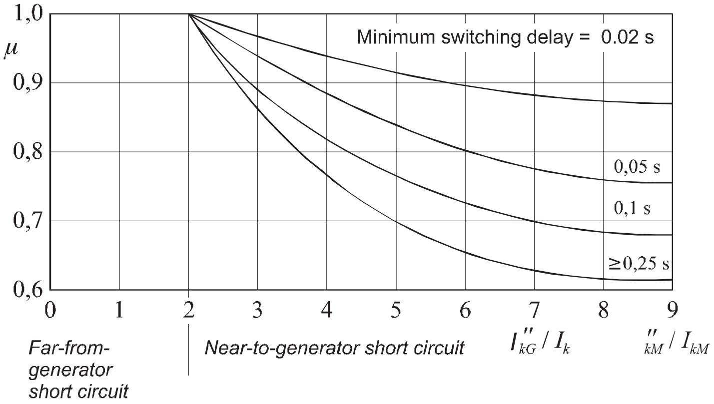


Figure 12.16: Factor μ for calculation of the symmetrical breaking current of asynchronous machines

12.3.3
Steady State Short Circuit Current

We distinguish between the maximum steady state short circuit current I_{kmax} and the minimum current I_{kmin}, which applies for the maximum excitation voltage of the synchronous machine and arises for a constant unregulated no-load voltage. The factor λ depends on the ratio l''_{kG}/I_{rG}, the excitation and the type of synchronous machine (Figure 12.17). λ can be taken from the figures for the upper and lower limit values. Furthermore, it is also necessary to consider the λ curves of the two generators for the excitation voltage in rated operation.

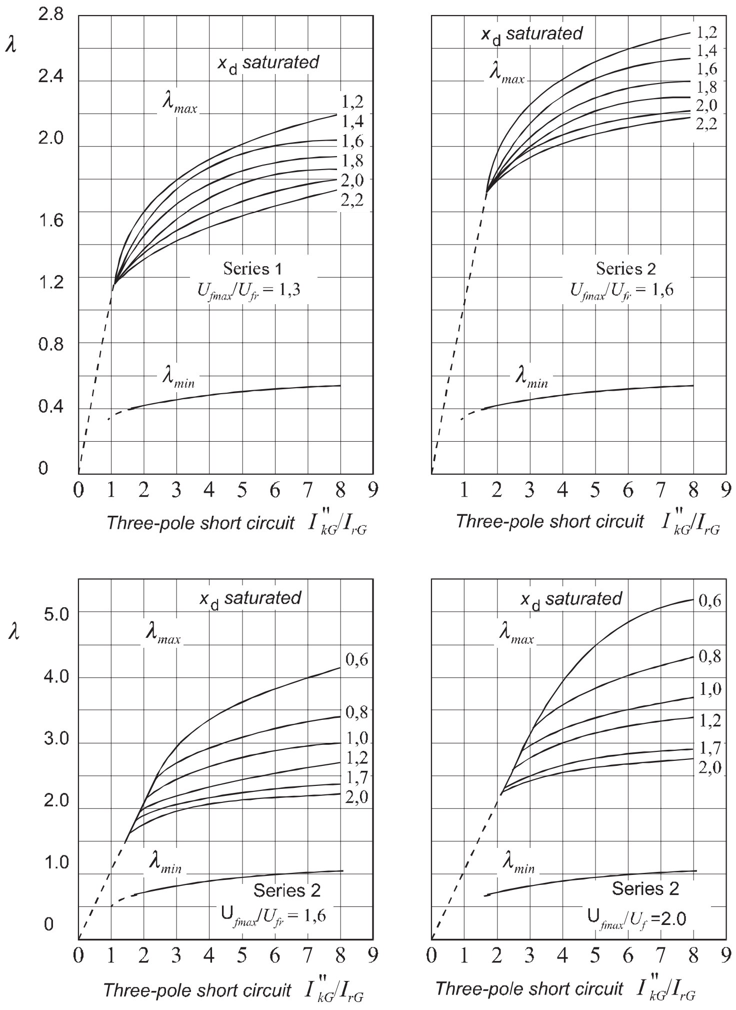


Figure 12.17: Factors λ_{max} and λ_{min} for calculation of the steady state short circuit current I_k

The following relationships hold true:

$$I_{kmax} = \lambda_{max}\, I_{rG} \tag{12.54}$$

$$I_{kmin} = \lambda_{min}\, I_{rG} \tag{12.55}$$

12.4
Thermal and Dynamic Short Circuit Strength

Electrical operational equipment such as busbars, overcurrent protection devices, cables and lines are thermally and mechanically very strongly stressed in the event of a fault (IEC 893). For a short circuit of duration T_K the short circuit current I_{th} results, with the factor m for the temperature rise resulting from the DC aperiodic component and the factor n for the temperature rise resulting from the AC component:

$$I_{th} = I_k'' \sqrt{m + n} \tag{12.56}$$

The factors m and n can be taken from Figure 12.18. The dynamic stressing of the systems through the short circuit currents gives rise to forces which can destroy

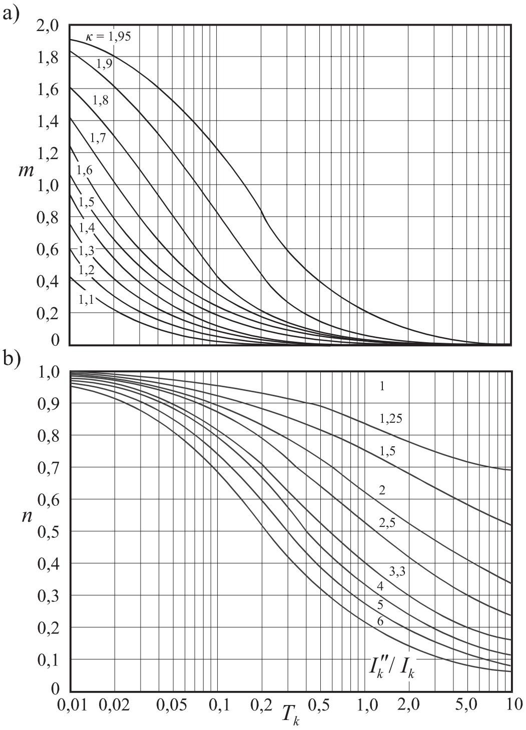


Figure 12.18: Factors m and n for calculation of the short-time current

the systems and endanger the operating staff. The greatest possible force between the main supply lines with length l and spacing $a$is:

$$F = 0.2\, i_p^2\, \frac{l}{a} \tag{12.57}$$

Here the symbols have the meanings:

m	Thermal effect of the DC aperiodic component for three-phase and single-phase AC current
n	Thermal effect of the AC component for a three-pole short circuit
F	Electrodynamic force between lines
i_p	Peak short circuit current
I_{th}	Short-time current
I_k''	Initial symmetrical short circuit current
l	Length of line
a	Spacing between lines

12.5
Examples for the Calculation of Short Circuit Currents

12.5.1
Example 1: Calculation of the Short Circuit Current in a DC System

With the occurrence of a fault, the operational equipment connected is not thermally protected. The sensitive components connected to the line (e.g. initiators or printed circuit boards) are subjected to high Joule heat values. Given the system in Figure 12.19 with the following data:

Installation: $l_1 = 20\,\text{m}$, $S_1 = 1.5\,\text{mm}^2$ Cu
Initiator: $l_2 = 2\,\text{m}$, $S_2 = 0.14\,\text{mm}^2$ Cu

Check the thermal strength of the insulation for the 0.14-mm^2 Cu line in the event of a fault.

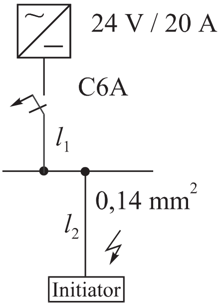


Figure 12.19: Wiring diagram

Calculation of the loop resistance with the use of a C 6 A (the internal resistances of the power supply (ca. 50 mΩ) and overcurrent protective device (55 mΩ) can be neglected) overcurrent protection device:

$$
\begin{aligned}
R_{Total(20\,°C)} &= 2(R_1 + R_2) = 2\left(\frac{l_1}{\kappa\, S_1} + \frac{l_2}{\kappa\, S_2}\right) \\
&= 2\left(\frac{20\,\mathrm{m}}{56\frac{\mathrm{m}}{\Omega\,\mathrm{mm}^2}\cdot 1.5\,\mathrm{mm}^2} + \frac{2\,\mathrm{m}}{56\frac{\mathrm{m}}{\Omega\,\mathrm{mm}^2}\cdot 0.14\,\mathrm{mm}^2}\right) \\
&= 0.986\Omega \approx 1\Omega
\end{aligned}
$$

For a line temperature of 80 °C (as required by IEC 60 909):

$$R_{Total(80\,°C)} = 1.24\, R_{Total(20\,°C)} = 1.24 \cdot 1\Omega = 1.24\Omega$$

This results in a short circuit current of

$$I''_{k1} = \frac{U_n}{R_{Total}} = \frac{24\,\mathrm{V}}{1.24\Omega} = 19.35\,\mathrm{A}$$

$$t_{k_{acceptable}} = \left(\frac{k\cdot S}{I''_{k_1}}\right)^2 \text{ and } t_{k_{acceptable}} > t_a$$

$$t_{k_{acceptable}} = \left(\frac{115\cdot \mathrm{A}\cdot\sqrt{\mathrm{s}}\cdot 0.14\,\mathrm{mm}^2}{\mathrm{mm}^2\cdot 19.35\,\mathrm{A}}\right)^2 = 0.69s$$

$$\text{Faktor } k = \frac{I''_{k_1}}{I_n} = \frac{19.35\,\mathrm{A}}{6\,\mathrm{A}} = 3.2$$

According to Figure 7.12, $t_a = 18$ seconds. Since $t_{k_{acceptable}} < t_a$, the insulation strength is inadequate. Solution: Replace C6A by Z6A.

12.5.2
Example 2: Calculation of Short Circuit Currents in a Building Electrical System

In the electrical installation of a building the following data are known (Figure 12.20). Calculate all required short circuit currents and check the cut-off conditions.

1. Calculation of the single-pole short circuit current

$$I''_{k1} = \frac{c\,U_n}{\sqrt{3}\,Z_k} \Rightarrow Z_k = \frac{c\,U_n}{\sqrt{3}I''_{k1}} = \frac{0.95\cdot 400\,\mathrm{V}}{\sqrt{3}\cdot 250\,\mathrm{A}} = 0.8775\Omega$$

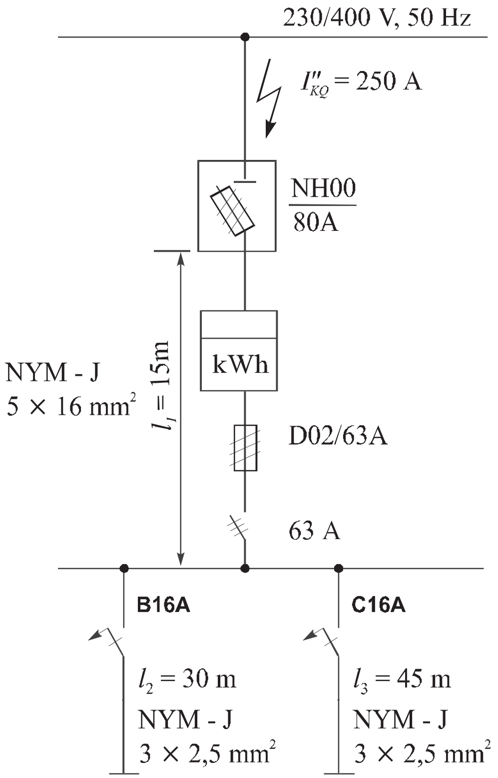


Figure 12.20: Building installation

$$Z_{L1} = 1.24\,\frac{2\cdot l_1}{\kappa\, S} = 1.24\cdot\frac{2\cdot 15\,\mathrm{m}}{56\frac{\mathrm{m}}{\Omega\,\mathrm{mm}^2}\cdot 16\,\mathrm{mm}^2} = 0.0415\Omega$$

$$Z_G = Z_k + Z_{L1} = 0.91907\Omega$$

$$I''_{k1} = \frac{c\,U_n}{\sqrt{3}\,Z_G}$$

$$I''_{k1} = \frac{0.95\cdot 400\,\mathrm{V}}{\sqrt{3}\cdot 0.91907\Omega} = 238.71\,\mathrm{A}$$

$$Z_{L2} = Z_G + 1.24\,\frac{2\,l_2}{\kappa\, S}$$

$$Z_{L2} = 0.91907\Omega + 1.24\cdot\frac{2\cdot 30\,\mathrm{m}}{56\frac{\mathrm{m}}{\Omega\,\mathrm{mm}^2}\cdot 2.5\,\mathrm{mm}^2} = 1.451\Omega$$

$$I''_{k1} = \frac{c\,U_n}{\sqrt{3}\,Z_{L2}} = \frac{0.95 \cdot 400\,\text{V}}{\sqrt{3} \cdot 1.451\Omega} = 151.2\,\text{A}$$

$$Z_{L3} = Z_{L2} + 1.24\,\frac{2\,l_3}{\kappa\,S}$$

$$Z_{L3} = 1.451\Omega + 1.24\,\frac{2 \cdot 45\,\text{m}}{56\,\frac{\text{m}}{\Omega\,\text{mm}^2} \cdot 2.5\,\text{mm}^2} = 2.248\Omega$$

$$I''_{k1} = \frac{c\,U_n}{\sqrt{3}\,Z_{L3}} = \frac{0.95 \cdot 400\,\text{V}}{\sqrt{3} \cdot 2.248\Omega} = 97.59\,\text{A}$$

2. Evaluation of the cut-off conditions
   a) Connection with B characteristic
      $I_a = 5\,I_n = 5 \cdot 16\,\text{A} = 80\,\text{A}$
      $I''_{k1} = 151.2\,\text{A}$
      $I''_{k1} > I_a$ satisfied
   b) Connection with C characteristic
      $I_a = 10\,I_n = 10 \cdot 16\,\text{A} = 160\,\text{A}$
      $I''_{k1} = 97.59\,\text{A}$
      Cut-off does not take place, since $I''_{k1} < I_a$.

   The following measures are possible:
   a) Increasing the cross-section
   b) Installing an RCD
   c) Limiting the line length.

12.5.3
Example 3: Dimensioning of an Exit Cable

A load is connected through an overhead line having the following data to a transformer:

Network data:

$S_{rT} = 400\,\text{kVA}$
$u_{kr} = 4\,\%$
$S = 4 \times 50\,\text{mm}^2\,\text{Cu}$
$l = 700\,\text{m}$

1. Calculate the single-pole short circuit current:

$$Z_T = \frac{u_{kr}}{100\,\%}\,\frac{U_n^2}{S_{rT}} = 0.016\Omega,\ Z_l = 0.565\Omega/\text{km}$$

$$Z_G = Z_T + 2\,l\,Z_l = 0.807\,\Omega$$

$$I''_{k1} = \frac{c\,U_n}{\sqrt{3}\,Z_G} = \frac{0.95 \cdot 400\,\text{V}}{\sqrt{3} \cdot 0.807\Omega} = 271.86\,\text{A}$$

2. Select the fuse according to overload conditions:

$$I_n \leq \frac{1.45\,I_z}{1.6} = \frac{1.45\ \cdot\ 250\,\text{A}}{1.6} = 226.5\,\text{A}$$

$I_n = 200$ A is selected.

3. Prove that the cut-off condition is satisfied:
The cut-off current I_a for the 200 A fuse in 0.4 s is: 2.1 kA (Figure 7.26).
The following relationship must always hold true:

$$I''_{k_1} > I_a$$

In this practical case, however, it is found that

$$I''_{k_1} = 271.86 < I_a = 2.1\,\text{kA}$$

The cut-off current is greater than the single-pole short circuit current. The cut-off condition is therefore not satisfied.

12.5.4
Example 4: Calculation of Short Circuit Currents with Zero-Sequence Resistances

The single-pole short circuit current is to be calculated at the end of the line, considering the zero-sequence resistances. The data are given in Figure 12.21.

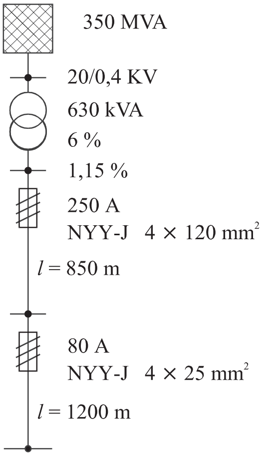


Figure 12.21: Power supply feeder

Power supply feeder:

$$X_{Qt} = \frac{c\,U_{nQ}^2}{\sqrt{3}\,S''_{kQ}} = \frac{1.1 \cdot (400\,\mathrm{V})^2}{\sqrt{3} \cdot 350\,\mathrm{MVA}} = 0.290\,\mathrm{m\Omega}$$

$$R_{Qt} = 0.1 \cdot X_Q = 0.1 \cdot 0.290\,\mathrm{m\Omega} = 0.0290\,\mathrm{m\Omega}$$

Transformer:

$$R_{TLV} = \frac{u_{Rr}}{100\,\%} \cdot \frac{U_{rTLV}^2}{S_{rT}} = \frac{1.15\,\%}{100\,\%}\,\frac{(0.4\,\mathrm{kV})^2}{630\,\mathrm{kVA}} = 2.92\,\mathrm{m\Omega}$$

$$Z_{TLV} = \frac{u_{kr}}{100\,\%} \cdot \frac{U_{rTLV}^2}{S_{rT}} = \frac{6\,\%}{100\,\%}\,\frac{(0.4\,\mathrm{kV})^2}{630\,\mathrm{kVA}} = 15\,\mathrm{m\Omega}$$

$$X_{TLV} = \sqrt{Z_{TLV}^2 - R_{TLV}^2} = \sqrt{15^2 - 2.92^2}\,\mathrm{m\Omega} = 14.71\,\mathrm{m\Omega}$$

$$\frac{R_{THV}}{R_{TLV}} = 1 \Rightarrow R_{THV} = 1 \cdot 2.92\,\mathrm{m\Omega} = 2.92\,\mathrm{m\Omega}$$

$$\frac{X_{THV}}{X_{TLV}} = 0.96 \Rightarrow X_{THV} = 0.96 \cdot 14.71\,\mathrm{m\Omega} = 14.12\,\mathrm{m\Omega}$$

Cable:

$$R_l = R'_l\,l = 0.195\Omega/\,\mathrm{km} \cdot 0.850\,\mathrm{km} = 165.75\,\mathrm{m\Omega}$$

$$X_l = X'_l\,l = 0.080\Omega/\,\mathrm{km} \cdot 0.850\,\mathrm{km} = 68\,\mathrm{m\Omega}$$

$$\frac{R_{OL}}{R_l} = 4 \Rightarrow R_{OL} = 4 \cdot 165.75\,\mathrm{m\Omega} = 663\,\mathrm{m\Omega}$$

$$\frac{X_{OL}}{X_l} = 3.65 \Rightarrow X_{OL} = 3.65 \cdot 68\,\mathrm{m\Omega} = 248.2\,\mathrm{m\Omega}$$

Line:

$$R_l = R'_l\,l = 0.898\Omega/\,\mathrm{km} \cdot 1.2\,\mathrm{km} = 1077.6\,\mathrm{m\Omega}$$

$$X_l = X'_l\,l = 0.086\Omega/\,\mathrm{km} \cdot 1.2\,\mathrm{km} = 103.2\,\mathrm{m\Omega}$$

$$\frac{R_{OL}}{R_l} = 4 \Rightarrow R_{OL} = 4 \cdot 1077.6\,\mathrm{m\Omega} = 4310.4\,\mathrm{m\Omega}$$

$$\frac{X_{OL}}{X_l} = 4.13 \Rightarrow X_{OL} = 4.13 \cdot 103.2\,\text{m}\Omega = 426.21\,\text{m}\Omega \tag{12.}$$

Calculation of the single-pole short circuit current:

$$\sum R = (2R_{Qt} + 2R_T + 2R_K + 2R_l + R_{0T} + R_{0K} + R_{0L})$$

$$\sum X = (2X_{Qt} + 2X_T + 2X_K + 2X_l + X_{0T} + X_{0K} + X_{0L})$$

$$\sum R = (2 \cdot 0.0290 + 2 \cdot 2.92 + 2 \cdot 165.75 + 2 \cdot 1077.6$$

$$+ 2.92 + 663 + 4310.4)\,\text{m}\Omega = 7.46\Omega$$

$$\sum X = (2 \cdot 0.290 + 2 \cdot 14.71 + 2 \cdot 14.12 + 2 \cdot 68$$

$$+ 248.2 + 103.2 + 426.216)\,\text{m}\Omega = 0.971\Omega$$

$$I''_{k1} = \frac{\sqrt{3}\,c\,U_n}{\sqrt{R^2+X^2}} = \frac{\sqrt{3} \cdot 0.95 \cdot 400\,\text{V}}{\sqrt{(7.46\Omega)^2+(0.971\Omega)^2}} = 87.48\,\text{A}$$

12.5.5
Example 5: Complex Calculation of Short Circuit Currents

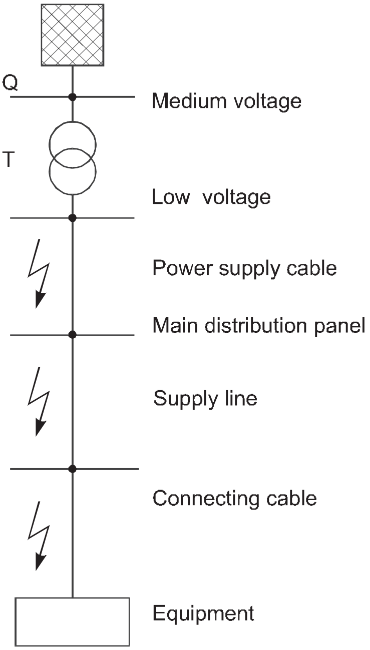


Figure 12.22: Complex calculation

The complex calculation is shown with this example.

a) Calculation of primary distribution voltage

$$
\begin{aligned}
S''_{kQ} &= 500\,\mathrm{MVA}\\
Z_Q &= \frac{c\,U_n^2}{S''_{kQ}} = \frac{1.1\cdot(400\,\mathrm{V})^2}{500\,\mathrm{MVA}} = 0.352\,\mathrm{m\Omega}\\
X_Q &= 0.995\,Z_Q\\
X_Q &= 0.995\,\cdot\,0.352\,\mathrm{m\Omega} = 0.35\,\mathrm{m\Omega}\\
R_Q &= 0.1\,X_Q\\
R_Q &= 0.1\,\cdot\,0.35\,\mathrm{m\Omega} = 0.035\,\mathrm{m\Omega}
\end{aligned}
$$

b) Transformer

$$
\begin{aligned}
U_n &= 400\\
S_{rT} &= 316\,\mathrm{kVA}\\
u_{kr} &= 6\,\%\\
u_{Rr} &= 1\,\%\\
u_{xr} &= \sqrt{u_{kr}^2 - u_{Rr}^2} = \sqrt{6^2 - 1}\,\% = 5.92\,\%\\
X_T &= \frac{u_{xr}}{100\,\%}\cdot\frac{U_{rT}^2}{S_{rT}} = \frac{5.92\,\%}{100\,\%}\cdot\frac{(400\,\mathrm{V})^2}{316\,\mathrm{kVA}} = 29.9\,\mathrm{m\Omega}\\
R_T &= \frac{u_{Rr}}{100\,\%}\cdot\frac{u_{rT}^2}{S_{rT}} = \frac{1\,\%}{100\,\%}\cdot\frac{(400\,\mathrm{V})^2}{316\,\mathrm{kVA}} = 5.06\,\mathrm{m\Omega}
\end{aligned}
$$

c) Supply cable $3 \times 185/95\ \mathrm{mm}^2$

$$
\begin{aligned}
R'_1 &= 0.105\,\mathrm{m\Omega/m}\\
X'_1 &= 0.072\,\mathrm{m\Omega/m}\\
l_1 &= 30\,\mathrm{m}\\
R_{L1} &= R_1\,l = 0.105\,\mathrm{m\Omega/m}\,\cdot\,30\,\mathrm{m} = 3.15\,\mathrm{m\Omega}\\
X_{L1} &= X_1\,l = 0.072\,\mathrm{m\Omega/m}\,\cdot\,30\,\mathrm{m} = 2.16\,\mathrm{m\Omega}
\end{aligned}
$$

d) Main low-voltage distribution
Three-pole short circuit:

$$
\begin{aligned}
Z_G &= |(R_Q + R_T + R_{L1}) + \mathrm{j}(X_Q + X_T + X_{L1})|\\
&= |(0.035 + 5.06 + 3.15)\,\mathrm{m\Omega} + \mathrm{j}(0.35 + 29.9 + 2.16)\,\mathrm{m\Omega}| = 33.44\,\mathrm{m\Omega}
\end{aligned}
$$

$$I''_{k3} = \frac{c\,U_n}{\sqrt{3}\,Z_G} = \frac{1 \cdot 400\,\text{V}}{\sqrt{3} \cdot 33.44\,\text{m}\Omega} = 6.9\,\text{kA}$$

$$i_p = \kappa\,\sqrt{2}\,I''_{k3} = 1.2 \cdot \sqrt{2} \cdot 6.9\,\text{kA} = 11.72\,\text{kA}$$

e) Supply line
Cable or line: 4 × 35 mm^2

$$R_2 = 0.627\,\text{m}\Omega/\text{m}$$

$$X_2 = 0.083\,\text{m}\Omega/\text{m}$$

$$l_2 = 250\,\text{m}$$

$$R_{L2} = R'_2\,l_2 = 0.627\,\text{m}\Omega/\text{m} \cdot 250\,\text{m} = 156.75\,\text{m}\Omega$$

$$X_{L2} = X'_2\,l_2 = 0.089\,\text{m}\Omega/\text{m} \cdot 250\,\text{m} = 22.25\,\text{m}\Omega$$

f) Sub-distribution
Three-pole short circuit:

$$\begin{aligned} Z_G &= |(R_Q + R_T + R_{L1} + R_{L2})\,\text{m}\Omega \\ &+ \text{j}(X_Q + X_T + X_{L1} + X_{L2})\,\text{m}\Omega| \\ Z_G &= |(0.035 + 5.06 + 3.15 + 156.75)\,\text{m}\Omega \\ &+ \text{j}(0.35 + 29.9 + 2.16 + 22.25)\,\text{m}\Omega| \\ Z_G &= 173.81\,\text{m}\Omega \end{aligned}$$

$$I''_{k3} = \frac{U_n}{Z_G\,\sqrt{3}} = \frac{400\,\text{V}}{\sqrt{3} \cdot 173.81\,\text{m}\Omega} = 1.33\,\text{kA}$$

$$i_p = \kappa\,\sqrt{2}\,I''_{k3} = 2.26\,\text{kA}$$

g) Connection cable
Cable or line: 5 × 2.5 mm^2

$$R'_3 = 8.71\,\text{m}\Omega/\text{m}$$

$$X'_3 = 0.11\,\text{m}\Omega/\text{m}$$

$$l_3 = 25\,\text{m}$$

$$R_{L3} = R'_3\,l_3 = 8.71\,\text{m}\Omega/\text{m} \cdot 25\,\text{m} = 217.75\,\text{m}\Omega$$

$$X_{L3} = X'_3\,l_3 = 0.11\,\text{m}\Omega/\text{m} \cdot 25\,\text{m} = 2.75\,\text{m}\Omega$$

h) Equipment
Three-pole short circuit

$$Z_G = |(R_Q + R_T + R_{L1} + R -_{L2} + R_{L3}) + \mathrm{jk}(X_Q + X_T + X_{L1} + X_{L2} + X_{L3})|$$

$$Z_G = (0.035 + 5.06 + 3.15 + 156.75 + 217.75)\,\mathrm{m}\Omega$$

$$+\ \mathrm{jk}\,(0.35 + 29.9 + 2.16 + 22.25 + 2.75)\,\mathrm{m}\Omega$$

$$Z_G = 387.03\,\mathrm{m}\Omega$$

$$I''_{k3} = \frac{c\,U_n}{\sqrt{3}\,Z_G} = \frac{1 \cdot 400\,\mathrm{V}}{\sqrt{3} \cdot 387.03\,\mathrm{m}\Omega} = 0.597\,\mathrm{kA}$$

$$i_p = \kappa\sqrt{2}\,I''_{k3} = 1.41 \cdot \sqrt{2} \cdot 0.597\,\mathrm{kA} = 1.19\,\mathrm{kA}$$

12.5.6
Example 6: Calculation With Effective Power and Reactive Power

Find the following for the electrical system shown in Figure 12.23:

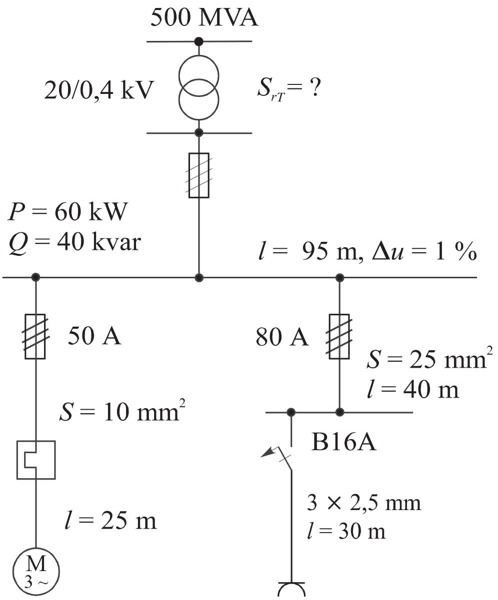


Figure 12.23 Calculation with effective and reactive power

1. Calculate the value cos φ for the system.
2. Select the overcurrent protection devices.
3. Calculate the voltage drops.
4. Dimension the transformer.
5. Design the reactive current compensation for a value cos $\varphi = 0.95$.

6. Calculate the single-pole and three-pole short circuit currents.
7. Calculate the single-pole and three-pole short circuit currents with the simplified method.
8. Determine the permissible lengths.

1. **cos φ for the system**

$$\tan\varphi = \frac{Q}{P} = \frac{40}{60\,\text{kW}} = 0.66 \Rightarrow \ \cos\varphi = 0.83$$

2. **Selection of the overcurrent protective equipment**

$$\begin{aligned}
I_b &= \frac{P}{\sqrt{3}\,U_n\cos\varphi} = \frac{60\,\text{kW}}{\sqrt{3}\cdot 400\cdot 0.83} = 104.46\,\text{A}\\
&\quad I_b \le In \le I_z\\
&\quad 104.4\,\text{A} \le 125\,\text{A} \le 128\,\text{A}\\
I_n &= 125\,\text{A} \qquad \text{for } 25\,\text{mm}^2\\
&\quad \text{NYY} - \text{J}\,4\times 25\,\text{mm}^2 \text{ underground installation,}\\
&\quad \text{from Table 11.16 we obtain } I_z = 133\,\text{A}\\
Ir &= \frac{104.46\,\text{A}}{0.91} = 115\,\text{A},\\
&\quad f_1 = 0.91\\
I_z' &= I_z f_1 = 133\,\text{A}\cdot 0.91 = 121.03\,\text{A}\\
S &= 35\,\text{mm}^2 \Rightarrow I_z = 159\,\text{A}\cdot 0.91 = 144.69\,\text{A}\\
&\quad I_b \le I_n \le I_z\\
&\quad 104.5\,\text{A} \le 125\,\text{A} \le 144.69\,\text{A}\\
S &= \frac{\sqrt{3}\cdot 125\,\text{A}\cdot 95\,\text{m}\cdot 0.83}{56\frac{\text{m}}{\Omega\,\text{mm}^2}\cdot 4\,\text{V}} = 76\,\text{mm}^2\\
&\quad \text{Selected : } 4\times 95\,\text{mm}^2\\
I_z' &= 280\,\text{A}\cdot 0.91 = 254.8\,\text{A} \Rightarrow In = 160\,\text{A}
\end{aligned}$$

3. **Actual voltage drop**

$$\Delta U = \frac{\sqrt{3}\,l\,I_n\cos\varphi}{\kappa\,S} = \frac{\sqrt{3}\cdot 95\,\text{m}\cdot 160\,\text{A}\cdot 0.83}{56\frac{\text{m}}{\Omega\,\text{mm}^2}\cdot 95\,\text{mm}^2} = 4.1\,\text{V}$$

$$\Delta u = \frac{\Delta U}{U_n}\cdot 100\,\% = \frac{4.1\,\text{V}}{400\,\text{V}}\cdot 100\,\% = 1\,\%$$

Voltage drop calculation for the main line

$$\Delta U = \frac{\Delta u}{100\,\%}\,U_n = \frac{1\,\%}{100\,\%}\cdot 400\,\text{V} = 4\,\text{V}$$

$$R_L'\cos\varphi + X_L'\sin\varphi = \frac{\Delta U}{\sqrt{3}\,l\,I_b}$$

$$R_L'\cos\varphi + X_L'\sin\varphi = \frac{4\,\text{V}}{\sqrt{3}\cdot 0.095\,\text{km}\cdot 104.46\,\text{A}} = 0.233\Omega/\,\text{km}$$

From Table 13.4, the effective resistance per unit length for 4 × 95 mm^2 0.232 Ω/km}. The actual voltage drop is therefore:

$$\Delta U = \sqrt{3}\,l\,I\,(R_l'\cos\varphi + X_L'\sin\varphi)$$

$$\Delta U = \sqrt{3}\cdot 0.095\,\text{km}\cdot 104.46\,\text{A}\cdot 0.232\Omega/\,\text{km} = 4\,\text{V}$$

This corresponds to

$$\Delta u = \frac{\Delta U}{U_n}\cdot 100\,\% = \frac{4\,\text{V}}{400\,\text{V}}\cdot 100\,\% = 1\,\%$$

Motor $$\Delta u = \frac{\sqrt{3}\,l\,I_r\cos\varphi\cdot 100\,\%}{\kappa\,S\,U_n}$$

$$\Delta u = \frac{\sqrt{3}\cdot 25\,\text{m}\cdot 50\,\text{A}\cdot 0.8\cdot 100\,\%}{56\,\frac{\text{m}}{\Omega\,\text{mm}^2}\cdot 10\,\text{mm}^2\cdot 400\,\text{V}} = 0.77\,\%$$

Sub-distribution: $$\Delta U = \frac{\sqrt{3}\cdot 40\,\text{m}\cdot 80\,\text{A}\cdot 0.8\cdot 100\,\%}{56\,\frac{\text{m}}{\Omega\,\text{mm}^2}\cdot 25\,\text{mm}^2\cdot 400\,\text{V}} = 0.79\,\%$$

Electrical outlet: $$\Delta U = \frac{2\cdot 30\,\text{m}\cdot 16\,\text{A}\cdot 1\cdot 100\,\%}{56\,\frac{\text{m}}{\Omega\,\text{mm}^2}\cdot 2.5\,\text{mm}^2\cdot 230\,\text{V}} = 2.98\,\%$$

4. **Dimensioning of transformer:**

$$S_{rT} = \frac{P_{Total}}{\cos\varphi} = \frac{60\,\text{kW}}{0.83} = 72.28\,\text{kVA} \quad \text{or}$$

$$S_{rT} = \sqrt{3}\,U_n\,I_n = \sqrt{3}\cdot 400\,\text{V}\cdot 160\,\text{A} = 110.89\,\text{kVA}$$

Selected: 100 kVA with $I_{rT} = 144\,\text{A}$, $u_{Rr} = 1.75\,\%$, $u_{kr} = 3.6\,\%\,(4\,\%)$

$$R_T = \frac{u_{Rr}\,U_n^2}{100\,\%\,S_{rT}} = \frac{1.75\,\%\cdot(400\,\text{V})^2}{100\,\%\cdot 100\,\text{kVA}} = 28\,\text{m}\Omega$$

$$Z_T = \frac{u_{kr}\,U_n^2}{100\,\%\,S_{rT}} = \frac{4\,\%\cdot(400\,\text{V})^2}{100\,\%\cdot 100\,\text{kVA}} = 64\,\text{m}\Omega$$

$$X_T = \sqrt{Z_T^2 - R_T^2} = 57.55\,\text{m}\Omega$$

5. Reactive current compensation

$$Q_G = P_{Total}\,(\tan\varphi_1 - \tan\varphi_2)$$

$$Q_G = 60\,\text{kW} \cdot (0.672 - 0.2029) = 28.146$$

$$C_{Total} = \frac{Q_G}{w\,U_n^2} = \frac{28.146\ \text{kvar}}{314 s^{-1} \cdot (400\,\text{V})^2} = 560.23\,\mu\text{F}$$

6. Calculation of the single-pole short circuit current

Impedance in the main distribution system

$$Z_{MDP} = 64\,\text{m}\Omega + \frac{1.24 \cdot 2 \cdot 95\,\text{m}}{56 \frac{\text{m}}{\Omega\,\text{mm}^2} \cdot 95\,\text{mm}^2} = 108.28\,\text{m}\Omega$$

$$I''_{k1} = \frac{c\,U_n}{\sqrt{3}\,Z_{MDP}} = \frac{0.95 \cdot 400\,\text{V}}{\sqrt{3} \cdot 108.28\,\text{m}\Omega} = 2\,\text{kA}$$

With $I_n = 160\,\text{A}$, $I_a = 1\,\text{kA}$, read at 5 s

$I''_{k1} > I_a$, so that the cut-off condition is satisfied.

Main distribution: $$I''_{k1} = \frac{c\,U_n}{\sqrt{3}\,Z_T} = \frac{0.95 \cdot 400\,\text{V}}{\sqrt{3} \cdot 64\,\text{m}\Omega} = 3.43\,\text{kA}$$

Motor: $$Z_L = \frac{1.24 \cdot 2 \cdot l}{\kappa\,S} = \frac{1.24 \cdot 2 \cdot 25\text{m}}{56 \frac{\text{m}}{\Omega\,\text{mm}^2} \cdot 10\,\text{mm}^2} = 0.11\Omega$$

$$Z_G = Z_{MDP} + Z_L = 108.28 + 110\,\text{m}\Omega = 218.28\,\text{m}\Omega$$

$$I''_{k1} = \frac{0.95 \cdot 400\,\text{V}}{\sqrt{3} \cdot 218.28\,\text{m}\Omega} = 1005.1\,\text{A}$$

Sub-distribution: $$Z_l = \frac{1.24 \cdot 2 \cdot l}{\kappa\,S} = \frac{1.24 \cdot 2 \cdot 40\,\text{m}}{56 \frac{\text{m}}{\Omega\,\text{mm}^2} \cdot 25\,\text{mm}^2} = 70.85\,\text{m}\Omega$$

$$Z_G = Z_{MDP} + Z_l = 108.28\,\text{m}\Omega + 70.85\,\text{m}\Omega$$

$$= 179.13\,\text{m}\Omega$$

$$I''_{k1} = \frac{0.95 \cdot 400\,\text{V}}{\sqrt{3} \cdot 179.13\,\text{m}\Omega} = 1.22\,\text{kA}$$

Electrical outlet: $$Z_L = \frac{1.24 \cdot 2 \cdot l}{\kappa\,S} = \frac{1.24 \cdot 2 \cdot 30\,\text{m}}{56 \frac{\text{m}}{\Omega\,\text{mm}^2} \cdot 2.5\,\text{mm}^2} = 531.42\,\text{m}\Omega$$

$$Z_G = Z_{MDP} + Z_L = 108.28\,\text{m}\Omega + 531.42\,\text{m}\Omega$$

$$= 639.7\,\text{m}\Omega$$

$$I''_{k1} = \frac{0.95 \cdot 400\,\text{V}}{\sqrt{3} \cdot 639.7\,\text{m}\Omega} = 342.96\,\text{A}$$

7. **Simplified method with the specified impedance values**

Transformer $$Z_T = \frac{u_{kr}}{100\,\%}\frac{(U_n)^2}{S_{rT}} = \frac{4\,\%}{100\,\%} \cdot \frac{(400\,\mathrm{V})^2}{100\,\mathrm{kVA}} = 64\,\mathrm{m\Omega}$$

Main distribution feeder

$$Z_l = 2\,z\,l = 2 \cdot 0.257\Omega/\,\mathrm{km} \cdot 0.095\,\mathrm{km} = 48.83\,\mathrm{m\Omega}$$

$$I''_{k1} = \frac{c\,U_n}{\sqrt{3}\,Z_G} = \frac{0.95 \cdot 400\,\mathrm{V}}{\sqrt{3} \cdot (64 + 48.83)\,\mathrm{m\Omega}} = 1.944\,\mathrm{kA}$$

Motor feeder

$$Z_{LM} = 2\,z\,l = 2 \cdot 2.246\Omega/\,\mathrm{km} \cdot 0.025\,\mathrm{km} = 112.3\,\mathrm{m\Omega}$$

$$Z_G = Z_T + Z_l + Z_{LM} = 225.13\,\mathrm{m\Omega}$$

$$I''_{k1} = \frac{0.95 \cdot 400\,\mathrm{V}}{\sqrt{3}\,Z_G} = \frac{0.95 \cdot 400\,\mathrm{V}}{\sqrt{3} \cdot 225.13\,\mathrm{m\Omega}} = 974\,\mathrm{A}$$

Sub-distribution feeder

$$Z_{UV} = 2\,z\,l = 2 \cdot 0.902\Omega/\,\mathrm{km} \cdot 0.040\,\mathrm{km} = 72.16\,\mathrm{m\Omega}$$

$$Z_G = Z_T + Z_l + Z_{UV} = 184.99\,\mathrm{m\Omega}$$

$$I''_{k1} = \frac{0.95 \cdot 400\,\mathrm{V}}{\sqrt{3} \cdot 184.99\,\mathrm{m\Omega}} = 1.185\,\mathrm{kA}$$

Electrical outlet

$$Z_{SD} = 2\,z\,l = 2 \cdot 8.77\,\mathrm{m\Omega}/\,\mathrm{m} \cdot 0.030\,\mathrm{km} = 526.2\,\mathrm{m\Omega}$$

$$Z_G = Z_T + Z_l + Z_{UV} + Z_{LM} + Z_{SD} = 823.49\,\mathrm{m\Omega}$$

$$I''_{k1} = 266.42\,\mathrm{A}$$

8. **Calculation of the three-pole short circuit currents**
Impedances for I''_{k3}
($S_{rT} = 100\,\mathrm{kVA}$, $R_T = 28\,\mathrm{m\Omega}$, $X_T = 57.55\,\mathrm{m\Omega}$)

1. Main distribution feeder

$$R_L = \frac{l}{\kappa\,S} = \frac{95\,\mathrm{m}}{56\frac{\mathrm{m}}{\Omega\,\mathrm{mm}^2} \cdot 95\,\mathrm{mm}^2} = 17.85\,\mathrm{m\Omega}$$

$$X_L = X'_l\,l = 0.082\Omega/\,\mathrm{km} \cdot 0.095\,\mathrm{km} = 7.79\,\mathrm{m\Omega}$$

2. Motor feeder

$$R_L = R'_l\,l = \frac{25\,\mathrm{m}}{56\frac{\mathrm{m}}{\Omega\,\mathrm{mm}^2} \cdot 10\,\mathrm{mm}^2} = 44.64\,\mathrm{m\Omega}$$

$$X_L = X_l' \, l = 0.094 \Omega/\,\text{km} \cdot 0.025\,\text{km} = 2.35\,\text{m}\Omega$$

3. Sub-distribution feeder

$$R_L = R_l' \, l = \frac{40\,\text{m}}{56 \frac{\text{m}}{\Omega\,\text{mm}^2} \cdot 25\,\text{mm}^2} = 28.57\,\text{m}\Omega$$

$$X_L = X_l' \, l = 0.086 \Omega/\,\text{km} \cdot 0.04\,\text{km} = 3.44\,\text{m}\Omega$$

1. Main distribution

$$\begin{aligned} Z_{MDP} &= \sqrt{(R_T + R_L)^2 + (X_T + X_L)^2} \\ &= \sqrt{(28\,\text{m}\Omega + 17.85\,\text{m}\Omega)^2 + (57.55\,\text{m}\Omega + 7.79\,\text{m}\Omega)^2} \\ &= 79.822\,\text{m}\Omega \\ I_{k3}'' &= \frac{c\,U_n}{\sqrt{3}\,Z_{MDP}} = \frac{1 \cdot 400\,\text{V}}{\sqrt{3} \cdot 79.82\,\text{m}\Omega} \\ &= 2.893\,\text{kA} \end{aligned}$$

2. Motor

$$\begin{aligned} Z_M &= \sqrt{(90.49^2 + 67.69^2)}\,\text{m}\Omega = 113\,\text{m}\Omega \\ I_{k3}'' &= \frac{400\,\text{V}}{\sqrt{3} \cdot 113\,\text{m}\Omega} = 2.043\,\text{kA} \end{aligned}$$

3. Sub-distribution

$$\begin{aligned} Z_{SD} &= \sqrt{(74.42^2 + 68.78^2)}\,\text{m}\Omega = 101.34\,\text{m}\Omega \\ I_{k3}'' &= 2.28\,\text{kA} \end{aligned}$$

9. Determination of the maximum length

The permissible lengths are [23]:

$$l = \frac{\frac{c\,U_n}{\sqrt{3}\,I_a} - Z_V}{2\,z}$$

Main distribution $l = \dfrac{\frac{0.95 \cdot 400\,\text{V}}{\sqrt{3} \cdot 950\,\text{A}} - 64\,\text{m}\Omega}{2 \cdot 0.257\,\Omega/\,\text{km}} = 324\,\text{m}$ $> 95\,\text{m}$

Motor $l = \dfrac{\frac{0.95 \cdot 400\,\text{V}}{\sqrt{3} \cdot 250\,\text{A}} - 79.82\,\text{m}\Omega}{2 \cdot 2.246\,\Omega/\,\text{km}} = 177.6\,\text{m}$ $> 25\,\text{m}$

Sub-distribution $l = \dfrac{\frac{0.95 \cdot 400\,\text{V}}{\sqrt{3} \cdot 450\,\text{A}} - 79.82\,\text{m}\Omega}{2 \cdot 0.902\,\Omega/\,\text{km}} = 226\,\text{m}$ $> 40\,\text{m}$

$$\text{Electrical outlet} \quad l = \frac{\frac{0.95 \cdot 400\,\text{V}}{\sqrt{3} \cdot 80\,\text{A}} - 102.94\,\text{m}\Omega}{2 \cdot 8.770\,\Omega/\,\text{km}} = 150\,\text{m} \qquad > 30\,\text{m}$$

The circuits are now correctly dimensioned.

12.5.7
Example 7: Complete Calculation for a System

The following calculations are for an electrical system as shown in Figure 12.24:

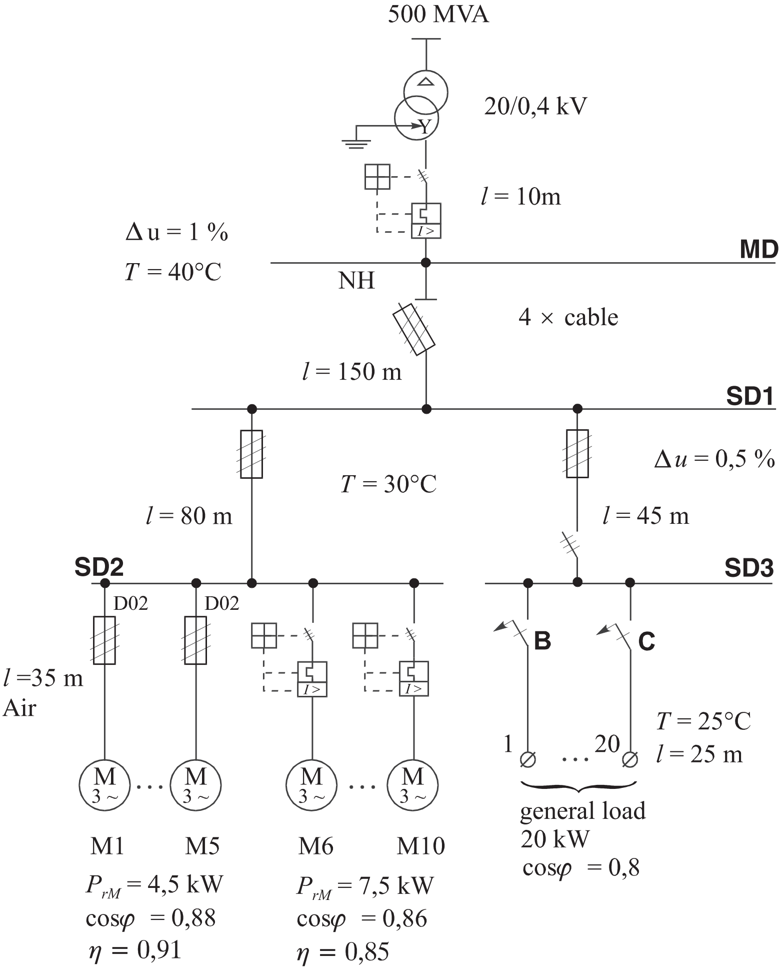


Figure 24 System calculation

1. Determine the feeders, fuses and motor circuit breakers for all motors for:
   a) Direct starting
   b) Y/Δ starting.
2. Determine I''_{k1} and I''_{k3} for:
   a) Main distribution 1
   b) Sub-distribution 1
   c) Sub-distribution 2
   d) Motor 1
   e) Circuit no. 20.
3. Determine the voltage drops for:
   a) Main distribution 1
   b) Sub-distribution 1
   c) Sub-distribution 2
   d) Circuit no. 20, connected to sub-distribution 3, with $I_b = 8\,\text{A}$.
4. Select all circuit breakers and fuses.
5. Demonstrate the selectivity.
6. Determine the transformer data.
7. Determine the compensation power.
8. Determine the cut-off conditions for all circuits.

The network voltage is 400/230 V, 50 Hz. As a protective measure, the TN system is required.

Solution:

1. **Power balance for the system**

   a) Sub-distribution 3

   Given: $P_{SD3} = 20\ \text{kW}$, $\cos\varphi = 0.8$, $U_n = 400\,\text{V}$

$$I_{SD3} = \frac{P_{SD3}}{\sqrt{3}\,U_n\cos\varphi} = \frac{20\,\text{kW}}{\sqrt{3}\cdot 400\,\text{V}\cdot 0.8} = 36.12\,\text{A}$$

$$S_{SD3} = \frac{P_{SD3}}{\cos\varphi} = \frac{20\,\text{kW}}{0.8} = 25\,\text{kVA}$$

   b) Sub-distribution 2
   Given:

Motors 1 to 5	Motors 6 to 10
$P = 4.5\,\text{kW}$	$P = 7.5\,\text{kW}$
$1 = 0.91$	$\eta_6 = 0.85$
$\cos\varphi_1 = 0.88$	$\cos\varphi_6 = 0.86$

$$I_{1-5} = \frac{4500\,\text{W}}{\sqrt{3}\cdot 400\,\text{V}\cdot 0.91\cdot 0.88} = 8.11\,\text{A}$$

$$I_{6-10} = \frac{7500\,\text{W}}{\sqrt{3}\cdot 400\,\text{V}\cdot 0.85\cdot 0.86} = 14.82\,\text{A}$$

$$P_1 = \frac{P_1}{\eta} = \frac{4.5\,\text{kW}}{0.91} = 4.95\,\text{kW}$$

$$S_{1-5} = \frac{5\,P_1}{\cos\varphi_1} = 28.125\,\text{kVA}$$

$$P_6 = \frac{P_6}{\eta} = \frac{7.5\,\text{kW}}{0.85} = 8.82\,\text{kW}$$

$$S_{6-10} = \frac{5\,P_6}{\cos\varphi_6} = 51.28\,\text{kW}$$

$$P_{SD2} = 5\,P_1 + 5\,P_6 = 5\cdot 4.95\,\text{kW} + 5\cdot 8.82\,\text{kW} = 68.85\,\text{kW}$$

$$S_{SD2} = S_{1-5} + S_{6-10} = 79.4\,\text{kVA}$$

$$I_{SD2} = \frac{S_{SD2}}{\sqrt{3}\,U_n} = \frac{79.4\,\text{kVA}}{\sqrt{3}\cdot 400\,\text{V}} = 114.6\,\text{A}$$

$$\cos\varphi = \frac{P_{SD2}}{S_{SD2}} = \frac{68.86\,\text{kW}}{79.4\,\text{kVA}} = 0.867$$

c) Sub-distribution 1

$$P_{SD1} = P_{SD3} + P_{SD2} = 20\,\text{kW} + 68.86\,\text{kW} = 88.86\,\text{kW}$$

$$S_{SD1} = S_{SD3} + S_{SD2} = 25\,\text{kVA} + 79.4\,\text{kVA} = 104.4\,\text{kVA}$$

$$\cos\varphi_{SD1} = \frac{P_{SD1}}{S_{SD1}} = \frac{88.86\,\text{kW}}{104.4\,\text{kVA}} = 0.85$$

$$I_{SD1} = \frac{S_{SD1}}{\sqrt{3}\,U_n} = \frac{104.4\,\text{kVA}}{\sqrt{3}\cdot 400\,\text{V}} = 150.7\,\text{A}$$

For $I_n = 35\,\text{A}$ the cross-section is chosen: NYY $5 \times 4\,\text{mm}^2$.
From Table 11.17, the current carrying capacity is 34 A.
$I_z = f_1\,I_{z\text{Tab.}} = 1.07\cdot 34\,\text{A} = 36.38\,\text{A}$
From the rule for nominal currents:
$14.81\,\text{A} \leq 16\,\text{A} \leq 36.38\,\text{A}$

d) The motor protection is placed before the network protection

$$I_n = 16\,\text{A}, I_r = 18.5\,\text{A}, \text{ from Table 11.17} \rightarrow \text{NYY}5\times 4\,\text{mm}^2$$
$$I_z = Ir f_1 = 19.5\,\text{A}\cdot 1.07 = 20.865\,\text{A}$$
$$I_b \leq I_n \leq Iz \rightarrow 14.81\,\text{A} \leq 16\,\text{A} \leq 20.865\,\text{A}$$

2. **Selection of lines (except for motors)**

   a) Feeder to main distribution 1 ⟶ power circuit breaker in transformer station

   I_b = 150.7 A, I_n =250 A, ambient temperature $T =$ 30 °C, underground installation.

   I_z = 280 A, from Table 11.16

   $$I_b \leq I_n \leq I_z$$

   $$150.7\,\text{A} \leq 250\,\text{A} \leq 280\,\text{A}$$

   Selected: NYCWY $4 \times 95\,\text{mm}^2$

   b) Feeder to sub-distribution 1

   I_b = 150.7 A, I_n = 160 A, ambient temperature T = 40 °C

   free installation, perforated cable rack, grouping f_2 = 4 lines.

   I_z = 202 A from Table 11.17

   f_1 = 0.87 from Table 11.21 at 40 °C

   f_2 = 0.95 from Table 11.20

   $$I_z = I_r f_1 f_2$$

   $$= 202\,\text{A} \cdot 0.87 \cdot 0.95 = 166.9\,\text{A}$$

   $I_b \leq I_n \leq I_z \rightarrow 150.7\,\text{A} \leq 160\,\text{A} \leq 166.9\,\text{A}$ from Table 11.16

   Selected: NYY $4 \times 50\,\text{mm}^2$

3. **Selection of protective equipment (backup fuses for distribution)**

   a) Backup fuse for sub-distribution 3

   I_b = $36.12\,\text{A} \Rightarrow I_n = 50\,\text{A}$ (D02)

   RCD = 63 A/0.5 A(269)

   b) Backup fuse for sub-distribution 2

   I_b = $114.68\,\text{A} \Rightarrow I_n = 125\,\text{A}$/(NH1)

   RCD = 125 A/0.3 A

   c) Backup fuse for sub-distribution 1

   I_b = $150.7\,\text{A} \Rightarrow I_n = 160\,\text{A}$ (NH1)

   Because of the selectivity:

   125 A (*sub-distribution* 2) · 1.6 = 200 A (NH1)

   Feeders, fuses for all motors M1-M10

d) Directly connected
Given: M1-M5 $P = 4.5\,\text{kW}$, $I = 8.11\,\text{A}$
The fuse is chosen with $I_n = 20\,\text{A}$
The line cross-section follows from Table 11.17
$I_r = 25\,\text{A}$, $f_1 = 1.06$ (25 °C) from Table 11.21
$I_z = f_1\,I_r = 1.06 \cdot 25\,\text{A} = 26.5\,\text{A} \Rightarrow$ NYY $4 \times 2.5\,\text{mm}^2$
$I_b \le I_n \le I_z$
$8.11\,\text{A} \le 20\,\text{A} \le 26.5\,\text{A} \Rightarrow$ The requirement is satisfied.

e) in $\text{Y}/\Delta = 10\,\text{A}$
I) Motor protection installed before network protection $I_e = 1 \cdot I_b$
Line cross-section, from Table 11.17:
$I_r = 19.5\,\text{A}, f_1 = 1.06$ (25 °C) from Table 11.21
$I_z = I_r f_1 = 1.06 \cdot 19.5\,\text{A} = 20.67\,\text{A} \Rightarrow$ NYY $4 \times 1.5\,\text{mm}^2$
$I_b \le I_n \le I_z$
$8.11\,\text{A} \le 10\,\text{A} \le 20.67\,\text{A} \Rightarrow$ The requirement is satisfied.
II) Motor protection installed after network protection $I_e = 0.58 \cdot I_b = 4.7\,\text{A} I_r = 19.5\,\text{A}, f_1 = 1.06, f_2 = 0.65$ from Table 11.22
$I_z = f_1 f_2\,I_r = 1.06 \cdot 0.65 \cdot 19.5\,\text{A} = 13.43\,\text{A} \Rightarrow$NYY $7 \times 1.5\,\text{mm}^2$

f) Feeder to sub-distribution 2
$I_b = 114.68\,\text{A}$, $I_n = 125\,\text{A}$,
ambient temperature $T = 30\,°\text{C}$, $\Rightarrow f_1 = 1$, free installation, cable rack, unperforated, no grouping
$I_r = 129\,\text{A}$ from Table 11.17
$f_2 = 0.97$ from Table 11.20
$I_z = f_2\,I_r = 0.97 \cdot 129\,\text{A} = 125.13\,\text{A} \Rightarrow I_z$ value too small, increase cross-section.
$I_r = 157\,\text{A}$ from Table 11.17
$I_2 = f_2\,Ir = 0.97 \cdot 157\,\text{A} = 152.29\,\text{A}$
$I_b \le I_r \le I_z$
$114.6\,\text{A} \le 125\,\text{A} \le 152.29\,\text{A} \Rightarrow$ The requirement is satisfied.
Selected: NYY $4 \times 50\,\text{mm}^2$

g) Feeder to sub-distribution 3
$I_b = 36.12\,\text{A}$, $I_n = 50\,\text{A}$
ambient temperature $T = 25\,°\text{C}$, free installation, cable rack, unperforated, no grouping
$I_r = 59\,\text{A}$ from Table 11.17
$f_1 = 1.06$ from Table 11.21 at 25 °C
$f_2 = 0.97$ from Table 11.20, for one cable tray = 1
$I_z = f_1 f_2\,I_r = 1.06 \cdot 0.97 \cdot 59\,\text{A} = 60.66\,\text{A}$
$I_b \le I_r \le I_2$
$36.1\,\text{A} \le 50\,\text{A} \le 60.66\,\text{A} \Rightarrow$ The requirement is satisfied.
Selected: NYY$4 \times 10\,\text{mm}^2$

h) Feeder to circuit no. 20
$I_b = 8\,\text{A}$, $I_n = 16\,\text{A}$
ambient temperature $T = 25\,°\text{C}$
installation type B2, no grouping
$I_z = 16.5\,\text{A}$ from Table 11.8
$I_b \le I_n \le I_Z$
$8\,\text{A} \le 16\,\text{A} \le 16.5\,\text{A} \Rightarrow$ The requirement is satisfied.
Selected: NYY $3 \times 1.5\,\text{mm}^2$

4. **Determination of the voltage drops in accordance with IEC 60 364, with the operating current I_b**
Determination of cable or line

a) Main distribution 1
Given: $I_b = 150.7\,\text{A}$, $S = 95\,\text{mm}^2$, $l = 10\,\text{m}$, $\Delta u_{max} = 1\,\%$

$$\begin{aligned}\Delta u &= \frac{\sqrt{3}\, I_b\, l\, 100\,\%}{U_n}\left(\frac{1}{\kappa\, S}\cos\varphi + X_1'\sin\varphi\right)\\ &= \frac{\sqrt{3}\cdot 150.7\,\text{A}\cdot 10\,\text{m}\cdot 100\,\%}{400\,\text{V}}\\ &\quad\cdot\left(\frac{1}{56\,\frac{\text{m}}{\Omega\,\text{mm}^2}\cdot 95\,\text{mm}^2}\cdot 0.9787 + 0.08\cdot 10^{-3}\,\frac{\Omega}{\text{m}}\cdot 0.199\right)\end{aligned}$$

$$\Delta u = 0.13\,\%\text{, so that the requirement is satisfied.}$$

Selected: NYCWY $4 \times 95\,\text{mm}^2$

b) Sub-distribution 1
Given: $I_b = 150.7\,\text{A}$, $S = 150\,\text{mm}^2$, $l = 150\,\text{m}$, $\Delta u_{max} = 1\,\%$

$$\Delta u = \frac{\sqrt{3}\; I_b\, l\; 100\,\%}{U_n}\left(\frac{1}{\kappa\, S}\cos\varphi + X_l'\sin\varphi\right)$$

$$\begin{aligned}\Delta u &= \frac{\sqrt{3}\cdot 150.7\,\text{A}\cdot 150\,\text{m}\cdot 100\,\%}{400\,\text{V}}\\ &\quad\cdot\left(\frac{1}{56\,\frac{\text{m}}{\Omega\,\text{mm}^2}\cdot 150\,\text{mm}^2}\cdot 0.98 + 0.08\cdot 10^{-3}\,\frac{\Omega}{\text{m}}\cdot 0.199\right)\end{aligned}$$

$$\Delta u = 1.3\,\%$$

$\Rightarrow$ The value is too high, increase S

$$\begin{aligned}S &= \frac{l\cos\varphi}{\kappa\left(\frac{\Delta U_{max}}{\sqrt{3}\, I_b} - X_l'\; l\sin\varphi\right)}\\ &= \frac{150\,\text{m}\cdot 0.98}{56\,\frac{\text{m}}{\Omega\,\text{mm}^2}\left(\frac{4\,\text{V}}{\sqrt{3}\cdot 150.7\,\text{A}} - 0.08\cdot 10^{-3}\,\frac{\Omega}{\text{m}}\cdot 150\,\text{m}\cdot 0.199\right)}\end{aligned}$$

$$S = 202.9\,\text{mm}^2 \Rightarrow \text{next standard cross section will be taken: } 240\,\text{mm}^2$$

$\Delta u = 0.87\,\%$

Selected: NYY 4 × 240 mm^2

c) Sub-distribution 2
Given: $I_b = 114.6\,\text{A},\ S = 50\,\text{mm}^2,\ l = 80\,\text{m},\ \Delta u_{max} = 0.5\,\%,$
$\cos\varphi = 0.867$

$$\Delta u = \frac{\sqrt{3}\cdot 114.6\,\text{A}\cdot 80\,\text{m}\cdot 100\,\%}{400\,\text{V}} \cdot \left(\frac{1}{56\frac{\Omega}{\text{m}\,\text{mm}^2}\cdot 50\,\text{mm}^2\cdot 0.867 + 0.08\cdot 10^{-3}\frac{\Omega}{\text{m}}\cdot 0.489}\right)$$

$$\Delta u = 1.4\,\%$$

$\Rightarrow$ The value is too high, increase S.

$$S = \frac{80\,\text{m}\cdot 0.867}{56\frac{\text{m}}{\Omega\,\text{mm}^2}\cdot\left(\frac{2\,\text{V}}{\sqrt{3}\cdot 114.6\,\text{A}} - 0.08\cdot 10^{-3}\frac{\Omega}{\text{m}}\cdot 80\,\text{m}\cdot 0.498\right)}$$

$S = 179.8\,\text{mm}^2 \Rightarrow$ next standard cross section will be taken $= 185\,\text{mm}^2$

$\Delta u = 0.42\,\%$

Selected: NYY 4 × 185 mm^2

d) Sub-distribution 3
Given: $I_b = 36.1\,\text{A},\ S = 10\,\text{mm}^2,\ l = 45\,\text{m},\ \Delta u_{max} = 0.5\,\%,\ \cos\varphi = 0.8$

$$\Delta u = \frac{\sqrt{3}\,l\,I_b\cos\varphi\,100\,\%}{\kappa\,S\,U_n} = \frac{\sqrt{3}\cdot 45\,\text{m}\cdot 36.12\,\text{A}\cdot 0.8\cdot 100\,\%}{56\frac{\text{m}}{\Omega\,\text{mm}^2}\cdot 10\,\text{mm}^2\cdot 400\,\text{V}} = 1\,\%$$

The value is too high, increase S.

$$S = \frac{45\,\text{m}\cdot 0.8}{56\frac{\text{m}}{\Omega\,\text{mm}^2}\left(\frac{2\,\text{V}}{\sqrt{3}\cdot 36.1\,\text{A}} - 0.08\cdot 10^{-3}\frac{\Omega}{\text{m}}\cdot 45\,\text{m}\cdot 0.6\right)} = 21.6\,\text{mm}^2$$

The next standard cross-section $S = 25\,\text{mm}^2 \Rightarrow \Delta u = 0.44\,\%$
Selected: NYY 4 × 25 mm^2

e) Circuit no. 20
In accordance with IEC 60 364, Part 52 the maximum permissible voltage drop in the system is 4 %.
Main distribution $= 0.13\,\%$, Sub-distribution 1 $= 0.87\,\%$, Sub-distribution 3 $= 0.44\,\%$
The maximum calculated voltage drop from the main distribution, sub-distribution 1 and sub-distribution 3 is 1.44%.
$\Rightarrow u_{max} = 4\,\% - 1.44\,\% = 2.56\,\%$

$I_b = 8\,\mathrm{A},\ S = 1.5\,\mathrm{mm}^2,\ l = 25\,\mathrm{m},\ \Delta u_{max} = 2.54\,\%,\ \cos\varphi = 0.8,$
$U = 230\,\mathrm{V}$

$$\Delta u = \frac{2\,l\,I_b \cos\varphi\, 100\,\%}{\kappa\, S\, U_n} = \frac{2 \cdot 25\,\mathrm{m} \cdot 8\,\mathrm{A} \cdot 0.8 \cdot 100\,\%}{56\,\frac{\mathrm{m}}{\Omega\,\mathrm{mm}^2} \cdot 1.5\,\mathrm{mm}^2 \cdot 230\,\mathrm{V}} = 1.65\,\%$$

⇒ The requirement is satisfied.
Selected: NYM 3 × 1.5 mm^2

5. **Determination of the transformer data**
   Given: $u_{kr} = 4\,\%,\ U_{THV}/U_{TLV} = 20\,\mathrm{kV}/0.4\,\mathrm{kV},\ S''_{kQ} = 500\,\mathrm{MVA}$
   Power balance of the system: $S_G = 104.4\,\mathrm{kVA}$
   The rated power of the transformer is selected: $S_{rT} \Rightarrow 160\,\mathrm{kVA}$

6. **Short circuit current calculation**

$$Z_{QT} = \frac{c\,U_n{}^2}{S''_k} = \frac{1.1 \cdot (0.4\,\mathrm{kV})^2}{500\,\mathrm{MVA}} = 0.352\,\mathrm{m\Omega}$$

$$X_{QT} = 0.995\,Z_{QT} = 0.35\,\mathrm{m\Omega}$$

$$R_{QT} = 0.1\,X_{QT} = 0.035\,\mathrm{m\Omega}$$

$$R_T = 15\,\mathrm{m\Omega}$$

$$X_T = 37\,\mathrm{m\Omega}$$

$$Z_T = \frac{u_{kr}\,U_{rT}^2}{100\,\%\,S_{rT}} = \frac{4\,\% \cdot (400\,\mathrm{V})^2}{100\,\% \cdot 160\,\mathrm{kVA}} = 40\,\mathrm{m\Omega}$$

a) Main distribution 1 – I''_{k3}

$$R_{LHV} = \frac{l}{\kappa\, S} = \frac{10\,\mathrm{m}}{56\,\frac{\mathrm{m}}{\Omega\,\mathrm{mm}^2} \cdot 95\,\mathrm{mm}^2} = 1.88\,\mathrm{m\Omega}$$

$$X_{LHV} = l\,X'_l = 10\,\mathrm{m} \cdot 0.08\,\frac{\mathrm{m\Omega}}{\mathrm{m}} = 0.8\,\mathrm{m\Omega}$$

Summary of resistances and reactances

	R	X
Network	$0.035\,\mathrm{m\Omega}$	$0.35\,\mathrm{m\Omega}$
Transformer	$15\,\mathrm{m\Omega}$	$37\,\mathrm{m\Omega}$
R_{LHV}	$1.88\,\mathrm{m\Omega}$	$0.80\,\mathrm{m\Omega}$
$R_{MDP} =$	$16.92\,\mathrm{m\Omega}$,	$X_{MDP} = 38.15\,\mathrm{m\Omega}$

$$Z_{MDP} = \sqrt{R_{MDP}^2 + X_{MDP}^2}$$

$$Z_{MDP} = \sqrt{(16.92\,\mathrm{m\Omega})^2 + (38.15\,\mathrm{m\Omega})^2} = 41.73\,\mathrm{m\Omega}$$

$$I''_{k3} = \frac{c\,U_n}{\sqrt{3}\,Z_{MDP}} = \frac{1 \cdot 400\,\mathrm{V}}{\sqrt{3} \cdot 41.73\,\mathrm{m\Omega}} = 5.53\,\mathrm{kA}$$

b) Main distribution 1 – I''_{k1}

$$R_{LHV} = 1.24\frac{2\,l}{\kappa\,S} = 1.24\cdot\frac{2\cdot 10\,\text{m}\cdot 1000}{56\,\frac{\text{m}}{\Omega\,\text{mm}^2}\cdot 95\,\text{mm}^2} = 4.66\,\text{m}\Omega$$

$$X_{LHV} = 2\,l\,X_L = 2\cdot 10\,\text{m}\cdot 0.08\,\frac{\text{m}\Omega}{\text{m}} = 1.6\,\text{m}\Omega$$

Summary of resistances and reactances

	R	X
Network	$0.035\,\text{m}\Omega$	$0.35\,\text{m}\Omega$
Transformer	$15\,\text{m}\Omega$	$37\,\text{m}\Omega$
R_{LHV}	$4.66\,\text{m}\Omega$	$1.6\,\text{m}\Omega$
$R_{MDP} =$	$19.695\,\text{m}\Omega$,	$X_{MDP} = 39.95\,\text{m}\Omega$

$$Z_{MDP} = \sqrt{(19.695\,\text{m}\Omega)^2 + (39.95\,\text{m}\Omega)^2} = 43.64\,\text{m}\Omega$$

$$I''_{k1} = \frac{c\,U_n}{\sqrt{3}\,Z_{MDP}} = \frac{0.95\cdot 400\,\text{V}}{\sqrt{3}\cdot 43.64\,\text{m}\Omega} = 5.02\,\text{kA}$$

c) Main distribution 1 – I''_{k3}

$$R_{LSD1} = \frac{150\,\text{m}\cdot 1000}{56\,\frac{\text{m}}{\Omega\,\text{mm}^2}\cdot 240\,\text{mm}^2} = 11.16\,\text{m}\Omega$$

$$X_{SD1} = 2\cdot 150\,\text{m}\cdot 0.08\,\text{m}\Omega\,\text{m} = 24\,\text{m}\Omega$$

$$R_{SD1} = R_{LSD1} + R_{MDP} = 11.16\,\text{m}\Omega + 16.97\,\text{m}\Omega = 28.13\,\text{m}\Omega$$

$$X_{SD1} = X_{LSD1} + X_{MDP} = 24\,\text{m}\Omega + 38.76\,\text{m}\Omega = 62.76\,\text{m}\Omega$$

$$Z_{SD1} = \sqrt{R_{SD1}2 + X_{SD1}^2} = \sqrt{(28.13\,\text{m}\Omega)^2 + (62.676\,\text{m}\Omega)^2}$$

$$= 68.77\,\text{m}\Omega$$

$$I''_{k3} = \frac{1\cdot 400\,\text{V}}{\sqrt{3}\cdot 68.77\,\text{m}\Omega} = 3.36\,\text{kA}$$

d) Sub-distribution 1 – I''_{k1}

$$R_{LSD1} = 1.24\cdot\frac{2\cdot 150\,\text{m}}{56\,\frac{\text{m}}{\Omega\,\text{mm}^2}\cdot 240\,\text{mm}^2} = 27.68\,\text{m}\Omega$$

$$X_{LSD1} = 2\cdot 150\,\text{m}\cdot 0.08\,\frac{\text{m}\Omega}{\text{m}} = 24\,\text{m}\Omega$$

$$R_{SD1} = R_{LSD1} + R_{LHV} = 27.68\,\text{m}\Omega + 20.54\,\text{m}\Omega = 48.22\,\text{m}\Omega$$

$$X_{SD1} = X_{LSD1} + R_{LHV} = 24\,\text{m}\Omega + 39.476\,\text{m}\Omega = 63.476\,\text{m}\Omega$$

$$Z_{SD1} = \sqrt{(48.22\,\text{m}\Omega)^2 + (63.476\,\text{m}\Omega)^2} = 79.71\,\text{m}\Omega$$

$$I''_{k1} = \frac{0.95\cdot 400\,\text{V}}{\sqrt{3}\cdot 79.71\,\text{m}\Omega} = 2.755\text{kA}$$

e) Sub-distribution 2 – I''_{k3}

$$
\begin{aligned}
R_{LSD2} &= \frac{80\,\mathrm{m}\cdot 1000}{56\,\frac{\mathrm{m}}{\Omega\,\mathrm{mm}^2}\cdot 185\,\mathrm{mm}^2} = 7.72\,\mathrm{m}\Omega \\
X_{LSD2} &= 80\,\mathrm{m}\ \cdot\ 0.08\,\frac{\mathrm{m}\Omega}{\mathrm{m}} = 6.4\,\mathrm{m}\Omega \\
R_{SD2} &= R_{LSD1} + R_{SD1} = 7.72\,\mathrm{m}\Omega + 28.13\,\mathrm{m}\Omega = 35.85\,\mathrm{m}\Omega \\
X_{SD2} &= X_{LSD2} + X_{SD1} = 6.4\,\mathrm{m}\Omega + 62.68\,\mathrm{m}\Omega = 69\,\mathrm{m}\Omega \\
Z_{SD2} &= \sqrt{(35.85\,\mathrm{m}\Omega)^2 + (69\,\mathrm{m}\Omega)^2} = 77.75\,\mathrm{m}\Omega \\
I''_{k3} &= \frac{1\cdot 400\,\mathrm{V}}{\sqrt{3}\cdot 77.75\,\mathrm{m}\Omega} = 2.97\mathrm{kA}
\end{aligned}
$$

f) Sub-distribution 2 – I''_{k1}

$$
\begin{aligned}
R_{LSD2} &= 1.24\ \cdot\ \frac{2\cdot 80\,\mathrm{m}\cdot 1000}{56\,\frac{\mathrm{m}}{\Omega\,\mathrm{mm}^2}\cdot 185\,\mathrm{mm}^2} = 19.15\,\mathrm{m}\Omega \\
X_{LSD2} &= 2\cdot 80\,\mathrm{m}\cdot 0.08\,\frac{\mathrm{m}\Omega}{\mathrm{m}} = 12.8\,\mathrm{m}\Omega \\
R_{LSD2} &= R_{LSD2} + R_{SD1} = 19.15\,\mathrm{m}\Omega + 48.22\,\mathrm{m}\Omega = 67.37\,\mathrm{m}\Omega \\
X_{SD2} &= X_{LSD2} + X_{SD1} = 12.8\,\mathrm{m}\Omega + 63.48\,\mathrm{m}\Omega = 76.28\,\mathrm{m}\Omega \\
Z_{SD2} &= \sqrt{(67.37\,\mathrm{m}\Omega)^2 + (76.28\,\mathrm{m}\Omega)^2} = 101.77\,\mathrm{m}\Omega \\
I''_{k1} &= \frac{1\cdot 400\,\mathrm{V}}{\sqrt{3}\cdot 0.10177\Omega} = 2.27\,\mathrm{kA}
\end{aligned}
$$

g) Motor 1 – I''_{k3}

$$
\begin{aligned}
R_{LM1} &= \frac{35\,\mathrm{m}\cdot 1000}{56\,\frac{\mathrm{m}}{\Omega\,\mathrm{mm}^2}\cdot 1.5\,\mathrm{mm}^2} = 416.7\,\mathrm{m}\Omega \\
R_{M1} &= Z_{M1} = R_{LM1} + R_{SD2} = 416.7\,\mathrm{m}\Omega + 35.85\,\mathrm{m}\Omega \\
&= 452.5\,\mathrm{m}\Omega \\
I''_{k3} &= \frac{1\cdot 400\,\mathrm{V}}{\sqrt{3}\cdot 452.5\,\mathrm{m}\Omega} = 510.4\,\mathrm{A}
\end{aligned}
$$

h) Motor 1 – I''_{k1}

$$
\begin{aligned}
R_{LM1} &= 1.24\ \cdot\ \frac{2\cdot 35\,\mathrm{m}\cdot 1000}{56\,\frac{\mathrm{m}}{\Omega\,\mathrm{mm}^2}\cdot 1.5\,\mathrm{mm}^2} \\
&= 1033\,\mathrm{m}\Omega \\
R_{M1} &= R_{LM1} + R_{SD2} = 1033\,\mathrm{m}\Omega + 67.33\,\mathrm{m}\Omega \\
&= 1100.33\,\mathrm{m}\Omega \\
I''_{k1} &= \frac{1\cdot 400\,\mathrm{V}}{\sqrt{3}\cdot 1100.33\,\mathrm{m}\Omega} = 209.9\,\mathrm{A}
\end{aligned}
$$

i) Circuit no. 20 – I''_{k3}

$$
\begin{aligned}
R_{L20} &= \frac{25\,\mathrm{m}\cdot 1000}{56\,\frac{\mathrm{m}}{\Omega\,\mathrm{mm}^2}\cdot 1.5\,\mathrm{mm}^2} = 297.6\,\mathrm{m}\Omega\\
R_{LSD3} &= \frac{45\,\mathrm{m}\cdot 1000}{56\,\frac{\mathrm{m}}{\Omega\,\mathrm{mm}^2}\cdot 25\,\mathrm{mm}^2} = 32.14\,\mathrm{m}\Omega\\
X_{LSD3} &= 45\,\mathrm{m}\,\cdot\,0.08\frac{\mathrm{m}\Omega}{\mathrm{m}} = 3.6\,\mathrm{m}\Omega\\
R_{20} &= R_{L20} + R_{LSD3} + R_{SD1}\\
&= 297.6\,\mathrm{m}\Omega + 32.14\,\mathrm{m}\Omega + 28.13\,\mathrm{m}\Omega = 357.8\,\mathrm{m}\Omega\\
X_{20} &= X_{LSD3} + X_{SD1} = 3.6\,\mathrm{m}\Omega + 62.68\,\mathrm{m}\Omega = 66.28\,\mathrm{m}\Omega\\
Z_{20} &= \sqrt{(357.87\,\mathrm{m}\Omega)^2 + (66.28\,\mathrm{m}\Omega)^2} = 364\,\mathrm{m}\Omega\\
I''_{k3} &= \frac{1\cdot 400\,\mathrm{V}}{\sqrt{3}\cdot 0.364\Omega} = 635\,\mathrm{A}
\end{aligned}
$$

j) Circuit no. 20 – I''_{k1}

$$
\begin{aligned}
R_{L20} &= 1.24\frac{2\cdot 25\,\mathrm{m}\cdot 1000}{56\,\frac{\mathrm{m}}{\Omega\,\mathrm{mm}^2}\cdot 1.5\,\mathrm{mm}^2} = 738.1\,\mathrm{m}\Omega\\
R_{LSD3} &= 1.24\cdot 2\cdot R_{LSD3} = 1.24\,\cdot 2\cdot 32.14\,\mathrm{m}\Omega = 79.71\,\mathrm{m}\Omega\\
X_{LSD3} &= 2\cdot 45\,\mathrm{m}\cdot 0.08\frac{\mathrm{m}\Omega}{\mathrm{m}} = 7.2\,\mathrm{m}\Omega\\
R_{20} &= R_{L20} + R_{LSD3} + R_{SD1}\\
&= 738.1\,\mathrm{m}\Omega + 79.71\,\mathrm{m}\Omega + 48.22\,\mathrm{m}\Omega = 866.03\,\mathrm{m}\Omega\\
X_{20} &= X_{SD3} + X_{SD1} = 7.2\,\mathrm{m}\Omega + 63.48\,\mathrm{m}\Omega = 70.68\,\mathrm{m}\Omega\\
Z_{20} &= \sqrt{(866.03\,\mathrm{m}\Omega)^2 + (70.68\,\mathrm{m}\Omega)^2} = 869\,\mathrm{m}\Omega\\
I''_{k1} &= \frac{0.95\cdot 400\,\mathrm{V}}{\sqrt{3}\cdot 0.869\Omega} = 252.5\,\mathrm{A}
\end{aligned}
$$

7. **Calculation of the compensation system:**
Given: $\cos\varphi_1 = 0.85$, $\cos\varphi_2 = 0.95$, $P = 88.86\,\mathrm{kW}$

$$Q_C = P(\tan\varphi_1 - \tan\varphi_2) = 88.86\,\mathrm{kW}\cdot(0.62 - 0.32) = 26.65\,\mathrm{kvar}$$

$$C = \frac{Q_C}{U_n^2\,2\,\pi f} = \frac{26.65\,\mathrm{kvar}}{(400\,\mathrm{V})^2\cdot 2\cdot\pi\cdot 50\,s^{-1}} = 530.34\,\mu\mathrm{F}$$

$$I_{new} = \frac{P}{\sqrt{3}\,U\cos\varphi^2} = \frac{88.86\,\mathrm{kW}}{\sqrt{3}\cdot 400\,\mathrm{V}\cdot 0.95} = 135\,\mathrm{A}$$

8. **Proof: Protection by cut-off**
   a) Main distribution 1 ⇒ $I_r = 250\,\text{A}$, $I''_{k1} = 5\,\text{A}$, $t_a = 0.015\,\text{s}$
   b) Sub-distribution 1 ⇒ $I_r = 200\,\text{A}$, $I''_{k1} = 2.75\,\text{kA}$, $t_a = 0.3\,\text{s}$ (this satisfies the requirement of maximum 5 seconds)
   c) Sub-distribution 2 ⇒ $I_r = 125\,\text{A}$, $I''_{k1} = 2.25\,\text{kA}$, $t_a = 0.06\,\text{s}$
   d) Circuit no. 20 ⇒ $I_r = 16\,\text{A}$, $I''_{K1} = 252.5\,\text{A}$, $t_a = 0.01\,\text{s}$ (maximum 0.2 seconds)

9. **Selectivity considerations**
   a) No selectivity between power circuit breaker and NH1
   b) No selectivity between main distribution 1 and sub-distribution 2
   c) Selectivity between main distribution 1 and sub-distribution 3
   d) Selectivity between sub-distribution 1 and sub-distribution 2
   e) Selectivity between sub-distribution 1 and sub-distribution 3

Possibilities for optimizing the system:

- Use of power circuit breakers with graded time selectivity
- Star-shaped cabling of main distribution 1

12.5.8
Example 8: Calculation of Short Circuit Currents With Impedance Corrections

Given a 220 kV network with the operating data in Figure 12.25 calculate the short circuit currents in Q and A with impedance corrections:

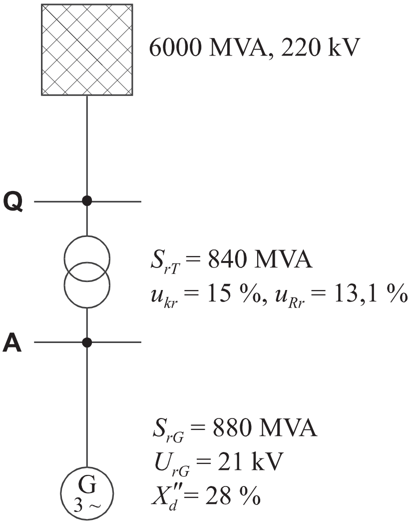


Figure 25 Short circuit currents with impedance corrections

Network:

$$Z_Q = \frac{c\,U_{nQ}^2}{S''_{kQ}} = \frac{1.1 \cdot (220\,\mathrm{kV})^2}{6000\,\mathrm{MVA}} = 8.873\,\Omega$$

Generator:

$$Z_G = \frac{x''_d\,U_{rG}^2}{100\,\%\,S_{rG}} = \frac{28\,\% \cdot (21\,\mathrm{kV})^2}{100\,\% \cdot 880\,\mathrm{MVA}} = 0.14\,\Omega$$

Correction factor:

$$K_{G,KW} = \frac{c}{1+x''_d\,\sin\varphi_{rG}} = \frac{1.1}{1+0.28 \cdot 0.557} = 0.951$$

Corrected generator impedance:

$$Z_{G,KW} = K_{G,KW}\,Z_G = 0.951 \cdot 0.14\,\Omega = 0.133\,\Omega$$

Block transformer:

$$Z_{THV} = \frac{u_{kr}}{100\,\%} \cdot \frac{U_{rTHV}^2}{S_{rT}} = \frac{15\,\%}{100\,\%} \cdot \frac{(220\,\mathrm{kV})^2}{840\,\mathrm{MVA}} = 8.64\,\Omega$$

$$Z_{TLV} = \frac{u_{kr}}{100\,\%} \cdot \frac{U_{rTLV}^2}{S_{rT}} = \frac{13.1\,\%}{100\,\%} \cdot \frac{(21\,\mathrm{kV})^2}{840\,\mathrm{MVA}} = 0.06877\,\Omega$$

$$Z_{T,KW} = c\,Z_{TLV} = 1.1 \cdot 0.06877\,\Omega = 0.0756\,\Omega$$

Calculation of the short circuit currents at the network power supply feeder Q:

$$I''_k = I''_{kQ} + I''_{kKW}$$

$$I''_{kQ} = \frac{c\,U_{nQ}}{\sqrt{3}\,Z_Q} = \frac{1.1 \cdot 220\,\mathrm{kV}}{\sqrt{3} \cdot 8.873\,\Omega} = 15.76\,\mathrm{kA}$$

$$\begin{aligned} K_{KW} &= \left(\frac{\ddot{u}_f}{\ddot{u}_r}\right)^2 \cdot \frac{c}{1+(x_d - x_T)\sin\varphi_{rG}} \\ &= \left(\frac{220\,\mathrm{kV}}{21\,\mathrm{kV}}\right)^2 \cdot \left(\frac{21\,\mathrm{kV}}{233\,\mathrm{kV}}\right)^2 \cdot \frac{1.1}{1+(0.28-0.131) \cdot 0.63} \\ &= 0.8965 \end{aligned}$$

$$\begin{aligned} Z_{KW} &= K_{KW}\,(\ddot{u}_r^2\,Z_G + Z_{TOS}) \\ &= 0.8965 \left[\left(\frac{220\,\mathrm{kV}}{21\,\mathrm{kV}}\right)^2 \cdot 0.14 + 8.64\,\Omega\right] = 21.52\,\Omega \end{aligned}$$

$$I''_{kKW} = \frac{1.1 \cdot 220\,\mathrm{kV}}{\sqrt{3} \cdot 21.52\,\Omega} = 6.49\,\mathrm{kA}$$

$$I''_k = 15.76\,\mathrm{kA} + 6.49\,\mathrm{kA} = 22.25\,\mathrm{kA}$$

Calculation of the short circuit currents in A:

$$
\begin{aligned}
I_k'' &= I_{kG}'' + I_{kT}'' \\
I_{kG}'' &= \frac{c\,U_{rG}}{\sqrt{3}\,Z_{G,KW}} = \frac{1.1\cdot 21\,\mathrm{kV}}{\sqrt{3}\cdot 0.133\Omega} = 100.4\,\mathrm{kA} \\
I_{kT}'' &= \frac{1.1\,U_{rG}}{\sqrt{3}\,(Z_{T,KW}+\frac{1}{\ddot{u}_r^2}\,Z_Q)} \\
I_{kT}'' &= \frac{1.1\cdot 21\,\mathrm{kV}}{\sqrt{3}\cdot(0.0756\Omega+(\frac{21\,\mathrm{kV}}{220\,\mathrm{kV}})^2\cdot 8.873\Omega)} = 85.24\,\mathrm{kA} \\
I_k'' &= 100.4\,\mathrm{kA} + 85.24\,\mathrm{kA} = 185.64\,\mathrm{kA}
\end{aligned}
$$

13
Voltage Drop Calculations

IEC 60 364, Part 52

Cables and lines are the most important part of a system during planning and configuring. They must be able to withstand the mechanical and thermal stresses and transfer the power from connected equipment with as little loss as possible. This requires the careful dimensioning of the electrical networks. Present-day systems and household appliances are matched to the nominal voltage of the network. This may fluctuate only within established limits, since otherwise a normal power output cannot be ensured and the equipment can be destroyed. This section discusses the voltage drop and the maximum line length for AC and three-phase networks, on the basis of the existing regulations and standards.

13.1
Voltage Regulation

Cables and lines are the means of transfer which enables the transport and distribution of electrical energy, predominantly by way of AC and three-phase current. When an electrical current flows through a cable or a line, heat is generated and is defined according to $P = I^2 R$. The amount of heat generated over a defined period of time is given by $Q = I^2 R t$. This heat loss must be dissipated before the insulation is destroyed.

The line resistance in a network is always assumed to be at 20 °C. For the calculation of the voltage drop, the permissible operating temperature is 70 °C. In low-voltage networks the capacitive current is very small, so that in the equivalent circuit all operating capacities can be neglected. Thus, the cable or line can be mapped with an effective resistance and a reactance. The loads are ohmic-inductive.

For short lines, the Joule heat is decisive, and for long lines the voltage drop is decisive. A phase shift arises between the current an the voltage.

Analysis and Design of Low-Voltage Power Systems. Ismail Kasikci

ISBN: 3-527-30483-5

13.1.1
Permissible Voltage Drop in Accordance With the Technical Conditions for Connection

For a power requirement of more than 100 kVA between the point of supply from the power supply company and the measuring instruments, in accordance with Table 13.1 a greater voltage drop than 0.5 % is permissible.

Table 13.1: Maximum permissible voltage drop according to Technical Conditions for Connection

Power requirement kVA	Max. permissible voltage drop %
< 100	0.50
100 to 250	1.00
250 to 400	1.25
over 400	1.50

13.1.2
Permissible Voltage Drop in Accordance With Electrical Installations in Buildings

The permissible voltage drop in the electrical system before the measuring equipment can be taken from the technical conditions for connection of the power supply company. The voltage drop in the electrical system behind the measuring equipment may not exceed 3 %, in consideration of IEC 60 364 Part 52. The basis for the calculation of the voltage drop is the rated current of the upstream overcurrent protection equipment.

13.1.3
Voltage Drops in Load Systems

IEC 60 364 Part 52
The voltage drop from the intersection between the distribution network and the load system to the point of connection of the consumer equipment (electrical outlet or equipment terminals) may not be greater than 4 % of the nominal network voltage. In accordance with the technical conditions for connection , lines from the power supply company in medium-voltage and high-voltage networks have a voltage drop of +10 % and −10 %.

The calculation of the voltage drop in electrical networks can be done with the following equations:

- For DC currents
  1. Voltage drop in V

$$\Delta U = \frac{2\,l\,I}{\kappa\,S} \tag{13.1}$$

2. Power in W

$$P = U\,I \tag{13.2}$$

- For single-phase AC currents
  1. Voltage drop in V

$$\Delta U = \frac{2\,l\,I\,\cos\varphi}{\kappa\,S} \tag{13.3}$$

  2. Power in W

$$P = U\,I\,\cos\varphi \tag{13.4}$$

- For three-phase currents
  1. Voltage drop in V

$$\Delta U = \frac{\sqrt{3}\,l\,I\,\cos\varphi}{\kappa\,S} \tag{13.5}$$

  2. Power in W

$$P = \sqrt{3}\,U\,I\,\cos\varphi \tag{13.6}$$

- Percent voltage drop

$$\Delta u = \frac{\Delta U}{U_n\,100\,\%} \tag{13.7}$$

For a symmetrically loaded three-phase network:

$$\Delta U = \sqrt{3} I\,l\,(R_L'\,\cos\varphi + X_L'\,\sin\varphi) \tag{13.8}$$

With

$$R_L' = \frac{1}{\kappa\,S} \tag{13.9}$$

for the voltage drop in %:

$$\Delta u = \frac{\sqrt{3}\,I_n\,l\,(\frac{1}{\kappa\,S}\,\cos\varphi + X_L'\,\sin\varphi)}{U_n}\,100\ \% \tag{13.10}$$

13.1.4
Voltage Drops in Accordance With IEC 60 364

For the installation of heavy current systems up to 1 kV it is necessary to take the maximum permissible lengths for cables and lines into account Above all, protection against indirect shock, protection in the event of a short circuit and limitation of the voltage drop must be considered during the planning and configuring of electrical systems. Supplement 5 describes the following parameters for the maximum permissible line lengths, leading in each case to different results.

13.1.5
Parameters for the Maximum Line Length

1. Protection against direct shock
2. Protection against indirect shock
3. Protection against short circuits and overloading
4. Cut-off with the use of an overcurrent protection device, such as
   - Fuses
   - Circuit breakers
   - Power circuit breakers
   - Fault current circuit breakers (RCDs)
5. Compliance with shock hazard protection for the cut-off time t_a:
   - 0.4 s: in circuits up to 35 A rated current with electrical outlets
   - 0.4 s: in circuits of protection class I, for manually operated equipment
   - 5 s: in all other circuits for permanently installed equipment
6. I_a: Cut-off current (breaking current) for:
   - Fuses: upper limit of time-current characteristic
   - Circuit breakers: I_a = tripping current (I_5) I_n, within 0.1 s
   - Power circuit breakers: $I_a \geq 1.2\, I_e$
   - RCDs: $I_a = I_{\Delta r}$ (rated residual current)
7. Single-pole short circuit current: I''_{k1}, at 80 °C
8. Coordination of length limiting
9. Breaking capacity of protective device I''_{k3}

For the calculation of the maximum line length, it is necessary to first calculate the smallest single-pole short circuit current in accordance with IEC 60 364, Supplement 5 (Figure 13.1).

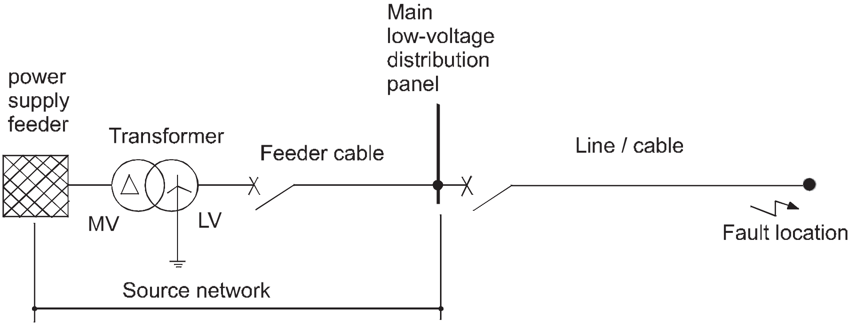


Figure 13.1 Schematic of network

$$I''_{k1min} = \frac{\sqrt{3}\, c_{min}\, U_n}{3 \cdot \sqrt{(2\, l\, R'_L + R_v)^2 + (2\, l\, X'_L + X_v)^2}} \tag{13.11}$$

The source impedance Z_v of the source network (power supply feeder network, transformer and feeder cable) is given by:

$$\underline{Z}_v = R_v + jX_v = \frac{2R_N + R_{0N}}{3} + j\frac{2X_N + X_{0N}}{3} \tag{13.12}$$

The resistance in the positive-sequence system of the source network is:

$$R_N = R_Q + R_T + R_{LN}$$

The resistance in the zero-sequence system of the source network is:

$$R_{0N} = R_{0T} + R_{0LN}$$

The reactance in the positive-sequence system of the source network is

$$X_N = X_Q + X_T + X_{LN}$$

The reactance in the zero-sequence system of the source network is:

$$X_{0N} = X_{0T} + X_{0LN}$$

The resistance of the transformer in the zero-sequence system is:

$$R_{0T} = \text{table value} \cdot R_T$$

The reactance of the transformer in the zero-sequence system is:

$$X_{0T} = \text{table value} \cdot X_T$$

The resistance in the zero-sequence system of the feeder cable is:

$$R_{0LN} = \text{table value} \cdot R_L$$

The reactance in the zero-sequence system of the feeder cable is:

$$X_{0LN} = \text{table value} \cdot X_L$$

For cables and lines with reduced PEN or protective conductor cross-sections:

$$R'_L = \frac{R'_{L1} + R'_{L2}}{2} \tag{13.13}$$

The following conditions must be taken into account here:

- The factor $c_{min} = 0.95$ is taken from Table 12.1.
- The motors are neglected.
- The effective resistances of the lines at 80 °C are used.
- The network layout is chosen so that the smallest short circuit current flows.

In practice, the smallest single-pole short circuit current is calculated with a simplified method. The error in calculation can then be as much as 20 %:

$$I''_{k1min} = \frac{c\,U_n}{\sqrt{3}\,Z_k}$$

The meanings of the symbols are:

c_{min}	Voltage factor
U_n	Nominal network voltage
R_Q, X_Q	Resistance, inductance of source network
R_T, X_T	Resistance, inductance of transformer
R_L, X_L	Resistance, inductance of line network
R_{0T}, X_{0T}	Zero-sequence resistance, inductance of transformer
R_{0L}, X_{0L}	Zero-sequence resistance, inductance of line network
R_v	Loop resistance of source network
X_v	Loop reactance of source network
R'_L	Resistance per unit length of cable
R'_{L1}	Resistance per unit length of external line
R'_{L2}	Resistance per unit length of PEN or protective conductor
X'_L	Reactance per unit length of cable
l	Line length

13.1.6
Summary of Characteristic Parameters

1. Cross-section of line
2. Insulation and type of cable or line
3. Overcurrent protection device
4. Rated current or current setting
5. Cut-off time for shock protection
6. Source impedance
7. Voltage drop limiting
8. Protection against indirect shock in TN, TT and IT systems

In AC and three-phase networks the inductive reactance can be neglected for cables and lines under 16 mm². Here it is sufficient to calculate with the DC resistance. At this point, it is worth mentioning other calculations for the maximum line lengths [31]:

$$l = \frac{\frac{c\,U_n}{\sqrt{3}\,I''_{k1}} - Z_v}{2\,z_L} \tag{13.15}$$

$$l = \frac{\kappa\,S \cdot 10^{-3}\left(\frac{U_0\,10^3}{I''_{k1}} - Z_v\right)}{n} \tag{13.16}$$

For n we can use:

$n = 2$ for identical cross-sections

$n = 3$ for a return line with half cross-section.

Calculation of the maximum transmission length, considering the voltage drop:

$$l_{max} = \frac{U_n \, \Delta u \cos\varphi}{P\,(R_L' \cos\varphi + X_L' \sin\varphi) \cdot 10^{-3}} \tag{13.17}$$

Here the meanings of the symbols are:

I	Current in A
U_0	Line-to-ground voltage in V
U_n	External line voltage in V
P	Power in kW
R_L'	Effective per unit line resistance in Ω/m
X_L'	Effective per unit line reactance in Ω/m
Z_v	Source impedance in mΩ/m
S	Line cross-section in mm^2
κ	Conductivity in $\frac{\mathrm{A}\sqrt{\mathrm{s}}}{\mathrm{mm}^2}$
Δu	Percent voltage drop in %
ΔU	Voltage drop in V
l	Line length in m
$\cos\varphi$	Power factor
$\sin\varphi$	Reactive factor

13.1.7
Lengths of Conductors With a Source Impedance

Tables 13.2 and 13.33 give the line lengths for the cut-off conditions 0.4 seconds and 5 seconds, arranged according to line protection devices. The source impedances in the overhead lines are $Z_v = 300 \cdots 600$ mΩ, according to the distance from the feeder, and in cable networks $Z_v = 100 \cdots 300$ mΩ by comparison.

Table 13.2: Maximum line lengths with source impedances up to the meter mounting board for a cut-off time of $t_a = 0.4$ seconds

Cross-section	OPE	l_{max} in m for		
mm²	A	Z_v = 200 mΩ	Z_v = 400 mΩ	Z_v = 600 mΩ
1.5	B/C10	145/69	138/62	131/55
1.5	B/C13	108/50	101/44	94/37
1.5	B/C16	88/40	81/33	74/26
1.5	B/C20	69/31	62/24	55/17
2.5	B/C16	146/67	135/56	123/44
2.5	B/C25	115/51	103/40	91/28
2.5	B/C32	89/39	78/27	65/16
4	B/C20	182/82	165/64	146/45
4	B/C25	143/62	124/44	106/25
4	B/C32	108/45	89/26	71/3
6	B/C25	215/94	187/66	160/38
6	B/C32	162/67	134/39	107/12
10	B/C32	272/112	225/66	138/20

Table 13.3: Maximum line lengths with source impedances up to the meter mounting board for a cut-off time of $t_a = 5$ seconds

Cross-section mm²	OPE A	l_{max} in m for		
		$Z_v = 200$ mΩ	$Z_v = 400$ mΩ	$Z_v = 600$ mΩ
1.5	B/C10	145	138	131
1.5	B/C13	108	101	94
1.5	B/C16	88	81	74
1.5	B/C20	69	62	55
2.5	B/C16	146	135	123
2.5	B/C25	115	103	91
2.5	B/C32	89	78	65
4	B/C20	182	165	146
4	B/C25	143	124	106
4	B/C32	108	89	71
6	B/C25	215	187	160
6	B/C32	162	134	107
10	B/C32	272	225	138

Table 13.4 gives the effective resistances per unit length.

Table 13.4: Resistance per unit length for (Cu) cable with plastic insulation

Cross-section S mm²	R'_L at 70 °C Ω/km	X'_L Ω/km	Z'_L		
			0.95 Ω/km	0.9 Ω/km	0.8 Ω/km
4 × 1.5	14.47	0.115	13.8	13.1	11.65
4 × 2.5	8.71	0.110	8.31	7.89	7.03
4 × 4	5.45	0.107	5.21	4.95	4.42
4 × 6	3.62	0.100	3.47	3.30	2.96
4 × 10	2.16	0.094	2.08	1.99	1.78
4 × 16	1.36	0.090	1.32	1.26	1.14
4 × 25	0.863	0.086	0.847	0.814	0.742
4 × 35	0.627	0.083	0.622	0.6	0.55
4 × 50	0.463	0.083	0.466	0.453	0.42
4 × 70	0.321	0.082	0.331	0.326	0.306
4 × 95	0.232	0.082	0.246	0.245	0.306
4 × 120	0.184	0.080	0.2	0.2	0.195
4 × 150	0.150	0.080	0.168	0.17	0.168
4 × 185	0.1202	0.080	0.139	0.143	0.144
4 × 240	0.0922	0.079	0.112	0.117	0.121
4 × 300	0.0745	0.079	0.0954	0.101	0.107

The cross-section of the cable cab be taken from Figure2, taking account of the value $\cos\varphi$, the line temperature (70 °C) and the voltage drop (5 %).

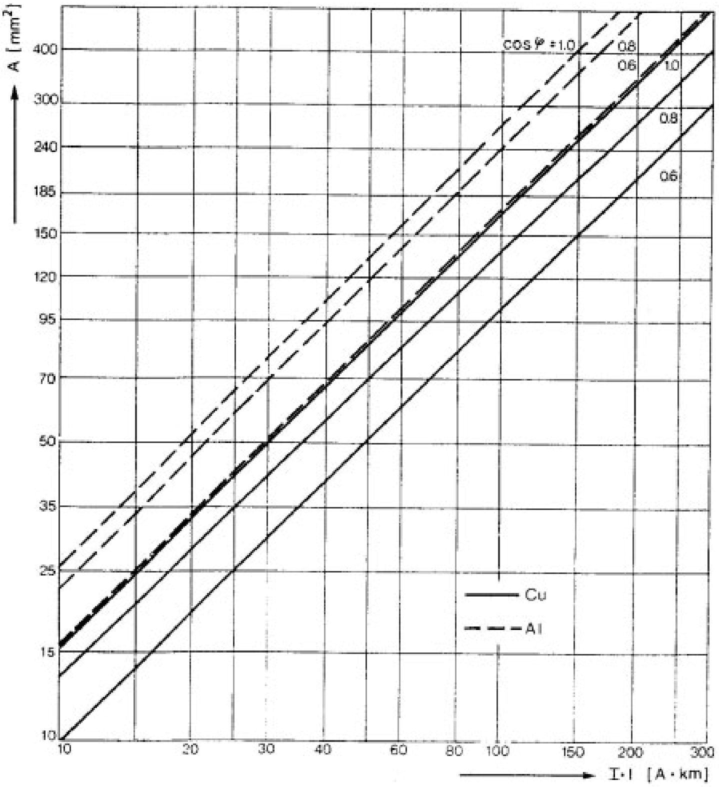


Figure 13.2 Voltage drop for low-voltage cables [35]

13.2
Examples for the Calculation of Voltage Drops

13.2.1
Example 1: Calculation of Voltage Drop for a DC System

Given the DC system shown in Figure 13.3, calculate the voltage drop in %.

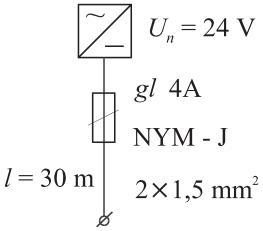


Figure 13.3 Voltage drop for a DC system

$$\Delta U = \frac{2\,l\,I_n}{\kappa\,S} = \frac{2 \cdot 30\,\mathrm{m} \cdot 4\,\mathrm{A}}{56\,\frac{\mathrm{m}}{\Omega\,\mathrm{mm}^2} \cdot 1.5\,\mathrm{mm}^2}$$

$$= 2.85\,\mathrm{V}$$

$$\Delta u = \frac{\Delta U}{U_n} \cdot 100\,\% = \frac{2.85\,\mathrm{V}}{24\,\mathrm{V}} \cdot 100\ \% = 11.875\ \%$$

In accordance with IEC 60 364, Part 52 only 4 % is permissible.

13.2.2
Example 2: Calculation of Voltage Drop for an AC System

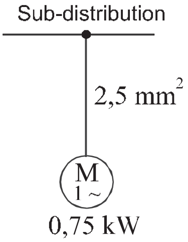


Figure 13.4 Voltage drop for an AC system

Given the motor shown in Figure 13.4 with $l = 30\,\mathrm{m}$, $\cos\varphi = 0.8$ and $\eta = 0.74$, calculate the voltage drop in %.

$$I_b = \frac{P}{U_n\,\cos\varphi\,\eta} = \frac{0.75\,\mathrm{kW}}{230\,\mathrm{V} \cdot 0.8 \cdot 0.74} = 5.5\,\mathrm{A}$$

$$\Delta U = \frac{2\,l\,I\,\cos\varphi}{\kappa\,S} = \frac{2 \cdot 30\,\mathrm{m} \cdot 5.5\,\mathrm{A} \cdot 0.8}{56\,\frac{\mathrm{m}}{\Omega\,\mathrm{mm}^2} \cdot 2.5\,\mathrm{mm}^2} = 1.89\,\mathrm{V}$$

$$\Delta u = \frac{\Delta U}{U_n} \cdot 100\,\% = \frac{1.89\,\mathrm{V}}{230\,\mathrm{V}} \cdot 100\ \% = 0.82\ \%$$

13.2.3
Voltage Drop for a Three-Phase System

In accordance with IEC 60 364, Part 52 the voltage drop must not exceed 4 %. Given the system with a main distribution system and two sub-distribution systems shown in Figure 13.5, check whether this requirement is satisfied.

If no other resistances per unit length exist, we can use the following values [31]:

$X'_L \approx 0.08\,\mathrm{m\Omega/m}$ for cables and lines

$X'_L \approx 0.33\,\mathrm{m\Omega/m}$ for overhead lines

$X'_L \approx 0.12\,\mathrm{m\Omega/m}$ for busbars

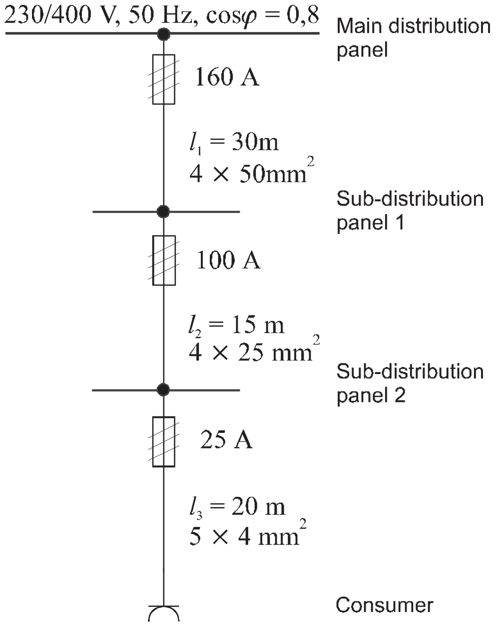


Figure 13.5 Voltage drop for a three-phase system

Here:

$$\Delta U = \sqrt{3} I\, l\, (R_L' \cos\varphi + X_L' \sin\varphi)$$

With

$$R_L' = \frac{1}{\kappa\, S} \qquad \text{and} \qquad \Delta u = \frac{\Delta U}{U_n} \cdot 100\ \%$$

this results in:

$$\Delta u = \frac{\sqrt{3}\, I_n\, l\, (1\kappa\, S \cos\varphi + X_L' \sin\varphi)}{U_n}\ 100\ \%$$

a) Overhead line between main distribution and sub-distribution

$$\Delta u = \frac{\sqrt{3} \cdot 160\,\text{A} \cdot 30\,\text{m} \cdot \left(\frac{1}{56 \frac{\text{m}}{\Omega\,\text{mm}^2} \cdot 50\,\text{mm}^2} \cdot 0.8 + 0.33\,\text{m}\Omega/\text{m} \cdot 0.6 \right)}{400\,\text{V}} \cdot 100\ \%$$

$$= 1\ \%$$

b) Cable between sub-distribution 1 and sub-distribution 2

$$\Delta u = \frac{\sqrt{3} \cdot 100\,\text{A} \cdot 15\,\text{m} \cdot \left(\frac{1}{56 \frac{\text{m}}{\Omega\,\text{mm}^2} \cdot 25\,\text{mm}^2} \cdot 0.8 + 0.33\,\text{m}\Omega/\text{m} \cdot 0.6 \right)}{400\,\text{V}} \cdot 100\ \%$$

$$= 0.5\ \%$$

c) Line between sub-distribution 2 and electrical outlet

$$\Delta u = \frac{\sqrt{3} \cdot 25\,\text{A} \cdot 20\,\text{m} \cdot \left(\frac{1}{56 \frac{\text{m}}{\Omega\,\text{mm}^2} \cdot 4\,\text{mm}^2} \cdot 0.8 + 0.33\,\text{m}\Omega/\text{m} \cdot 0.6 \right)}{400\,\text{V}} \cdot 100\ \%$$

$$= 0.82\ \%$$

The total voltage drop at the electrical outlet is $\Delta u = 2.32\ \%$

13.2.4
Example 4: Calculation of Voltage Drop for a Distributor

Given a distributor with the following data (Figure 13.6):

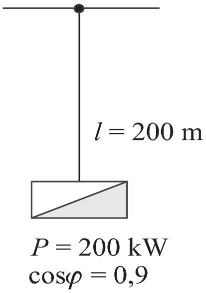


Figure 13.6 Voltage drop for a distributor

$P = 200\,\text{kW},\ U_n = 400\,\text{V},\ l = 200\,\text{m},\ \Delta u = 4\ \%,\ \cos\varphi = 0.9.$

How large is the voltage drop at the distributor?

$$I_b = \frac{P}{\sqrt{3} U_n \cos\varphi} = \frac{200\,\text{kW}}{\sqrt{3} \cdot 400\,\text{V} \cdot 0.9} = 321\,\text{A}$$

$$\Delta U = \frac{\Delta u}{100\ \%} U_n = \frac{4\ \%}{100\ \%} \cdot 400\,\text{V} = 16\,\text{V}$$

$$Z = \frac{\Delta U}{\sqrt{3}\, l\, I}$$

$$= \frac{16\,\text{V}}{\sqrt{3} \cdot 200\,\text{m} \cdot 321\,\text{A}} = 0.144 \frac{\Omega}{\text{km}}$$

From Table 13.4, we obtain a cross-section of $4 \times 185\,\text{mm}^2$ with $Z = 0.143 \frac{\Omega}{\text{km}}$. For this cross-section, the voltage drop is then:

$$\begin{aligned}\Delta U &= \sqrt{3}\, l\, I\,(R_L' \cos\varphi + X_L' \sin\varphi)\\ &= \sqrt{3}\cdot 200\,\mathrm{m}\cdot 321\,\mathrm{A}\cdot(0.143\frac{\Omega}{\mathrm{km}}) = 15.88\,\mathrm{V}\end{aligned}$$

$$\Delta u = \frac{\Delta U}{U_n}\cdot 100\ \% = \frac{15.88\,\mathrm{V}}{400\,\mathrm{V}}\cdot 100\ \% = 3.97\ \%$$

13.2.5
Calculation of Cross-Section According to Voltage Drop

Given the three-phase motor in Figure 13.7 with the following data:

$U_n = 400\,\mathrm{V}$, $P = 5.5\,\mathrm{kW}$, $\eta = 0.83$, $\cos\varphi = 0.85$, with a permissible voltage drop of 5 %.

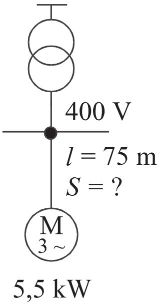


Figure 13.7 Calculation of cross-section according to voltage drop

The rated current of the fuse is $I_n = 63\,\mathrm{A}$ and the threshold current of the non-delayed electromagnetic tripping device is $I = 160\,\mathrm{A}$.

The motor connection is to be made through a line to a transformer. The internal resistance of the network and transformer can be neglected. The length of the line (simple) is $l = 75\,\mathrm{m}$. Find the line cross-section S.

$$I = \frac{P}{\sqrt{3}\, U_n \cos\varphi\, \eta} = \frac{5.5\,\mathrm{kW}}{\sqrt{3}\cdot 400\,\mathrm{V}\cdot 0.85\cdot 0.83} = 11.26\,\mathrm{A}$$

$$\Delta U = \sqrt{3}\, Z\, l\, I$$

$$Z = \frac{\Delta U}{\sqrt{3}\, l\, I} = \frac{20\,\mathrm{V}}{\sqrt{3}\cdot 0.075\,\mathrm{km}\cdot 11.26\,\mathrm{A}} = 13.68\frac{\Omega}{\mathrm{km}}$$

The cable is selected from Table 13.4: 4 × 2.5 mm^2

13.2.6
Example 6: Calculation of Voltage Drop for an industrial plant

In an industrial plant the main distribution system is fused with 200 A at a distance of 200 m. How large is the voltage drop in the line? The basis for the calculation is the upstream overcurrent protection device.

$$\begin{aligned} Z_L &= \frac{\Delta U}{\sqrt{3}\, l\, I_n} = \frac{16\,\mathrm{V}}{\sqrt{3}\cdot 0.2\,\mathrm{km}\cdot 200\,\mathrm{A}} = 0.231\,\Omega/\mathrm{km} \\ \Delta u &= \frac{\sqrt{3}\, l\, I_n\, Z_L}{U_n}\cdot 100\ \% \\ &= \frac{\sqrt{3}\cdot 0.2\,\mathrm{km}\cdot 200\,\mathrm{A}\cdot 0.231\,\Omega/\mathrm{km}}{400\,\mathrm{V}\cdot 100\ \%} = 4\ \% \end{aligned}$$

13.2.7
Example 7: Calculation of voltage drop for an electrical outlet

An electrical outlet is to be installed at a distance of 35 m from a sub-distribution system. A B16 A power circuit breaker is to be used as the protective device. The line cross-section is 2.5 mm^2. Calculate the voltage drop at 20°C.

$$\begin{aligned} \Delta u &= \frac{2\, l\, I\cdot 100\ \%\cos\varphi}{\kappa\, S\, U_n} \\ &= \frac{2\cdot 35\,\mathrm{m}\cdot 16\,\mathrm{A}\cdot 100\,\%\cdot 1}{56\,\frac{\mathrm{m}}{\Omega\,\mathrm{mm}^2}\cdot 2.5\,\mathrm{mm}^2\cdot 230\,\mathrm{V}} = 3.47\,\% \end{aligned}$$

13.2.8
Example 8: Calculation of Voltage Drop for a Hot Water Storage Unit

A 4 kW hot water storage unit is connected at a distance of 40 m from a line. How large is the voltage drop of the selected line?

Current consumption of unit:

$$\begin{aligned} P &= \sqrt{3}\, U\, I \\ I &= \frac{P}{\sqrt{3}\, U} = \frac{4\,\mathrm{kW}}{\sqrt{3}\cdot 400\,\mathrm{V}} = 5.77\,\mathrm{A} \end{aligned}$$

From IEC 60 364, Part 43, the cross-section is $S = 1.5\,\mathrm{mm}^2$

Voltage drop:

$$\Delta u = \frac{\sqrt{3}\, l\, P\cdot 100\,\%}{\kappa\, S\, U_n^2} = \frac{\sqrt{3}\cdot 40\,\mathrm{m}\cdot 4\,\mathrm{kW}\cdot 100\,\%}{56\,\frac{\mathrm{m}}{\Omega\,\mathrm{mm}^2}\cdot 2.5\,\mathrm{mm}^2\cdot (230\,\mathrm{V})^2} = 2.06\ \%$$

13.2.9

Example 9: Calculation of Voltage Drop for a Pump Facility

The following values were determined for a pump facility (Figure 13.8):

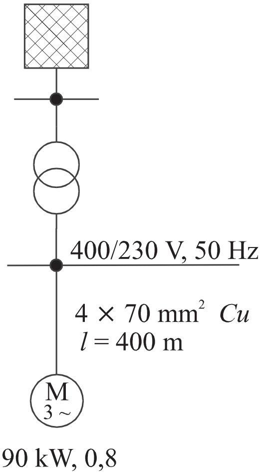


Figure 13.8 Voltage drop for a pump facility

$P = 90\,\text{kW},\ U = 210\,\text{V},\ \cos\varphi = 0.88,\ X_L' = 0.33/\,\text{m}.$

Calculate the voltage drop at the motor:

$$P = \sqrt{3}\,U\,I\,\cos\varphi$$

$$I = \frac{P}{\sqrt{3}\,U\,\cos\varphi} = \frac{90\,\text{kW}}{\sqrt{3}\cdot 210\,\text{V}\cdot 0.88} = 281.18\,\text{A}$$

$$I_w = I\cos\varphi = 281.18\,\text{A}\cdot 0.88 = 247.43\,\text{A}$$

$$I_b = I\sin\varphi = 281.18\,\text{A}\cdot 0.474 = 133.28\,\text{A}$$

$$R = \frac{l}{\kappa A} = \frac{400\,\text{m}}{56\,\frac{\text{m}}{\Omega\,\text{mm}^2}\cdot 70\,\text{mm}^2} = 0.102\,\Omega$$

$$X = 0.33\,\text{m}\Omega/\text{m}\cdot 400\,\text{m} = 0.132\,\Omega$$

$$\begin{aligned}\Delta U &= I\,R\cos\varphi + I\,X\sin\varphi = I_w\,R + I_b\,X\\ &= 247.43\,\text{A}\cdot 0.102\,\Omega + 133.28\,\text{A}\cdot 0.132\,\Omega = 42.8\,\text{V}\end{aligned}$$

$$U_1 = 210\,\text{V} + 22.5\,\text{V} = 252.8\,\text{V}$$

$$\Delta u = \frac{\Delta U\cdot 100\,\%}{U_1} = \frac{42.8\,\text{V}\cdot 100\,\%}{252.8\,\text{V}} = 16.9\,\%$$

14
Lighting Systems

14.1
Interior Lighting

Terms and definitions

- Lamps are technical realizations of artificial light sources primarily intended for lighting purposes, that is for lighting and illumination. They convert electrical energy into light.
- Light fixtures
- Light fixtures serve the purpose of influencing the light beam generated by a light source in such a way as to achieve optimal illumination of a system. Light fixtures are therefore electrical operational equipment containing lamps and accessories, which guide the light radiated from the lamps in the required direction.

For the planning and configuration of interior lighting systems the following definitions, standards and specifications are especially important [67]:

- Dry rooms
  Dry rooms are rooms and places in which as a rule neither condensation water nor air saturated with humidity occurs, with no or very little accumulation of non-flammable dust.
- Damp areas
  Damp areas are rooms and places in which the reliability of the operating equipment can be impaired by humidity, condensation water or by chemical or similar influences.
- Wet areas
  Wet areas are rooms and places in which the floors, walls and equipment are sprayed for the purpose of cleaning.
- Bath and shower room areas
  Rooms with bathtubs and showers are divided into four areas and are regarded according to type of area and use as dry, damp or wet rooms.
- Open air systems
  Protected open air systems are areas protected by roofing against the effects of weather, whereas unprotected systems are exposed to rain.

Analysis and Design of Low-Voltage Power Systems. Ismail Kasikci

ISBN: 3-527-30483-5

- Swimming pools and baths
  Swimming pools and baths are regarded as damp and wet areas.
- Agricultural operating areas
  Agricultural operating areas are stalls and adjoining rooms, rooms for the large- scale housing of animals, storage rooms and supply rooms, which are considered at the same time both damp rooms and operating areas subject to fire hazards.
- Operating areas subject to explosion hazards
  Operating areas subject to explosion hazards are classified as zones according to their condition and the probability of occurrence of a hazardous and potentially explosive atmosphere.
- Operating areas subject to fire hazards
  In operating areas which are endangered by the presence of dust or fibrous materials, readily flammable materials can accumulate in hazardous levels on the electrical operational equipment. Higher temperatures or arcing on this equipment can lead to the outbreak of a fire.
- Garages
- Garages with natural ventilation and adjoining rooms for sheltering vehicles are regarded as dry rooms, damp rooms or operating areas subject to fire hazards.

For the installation of a lighting system, it is necessary to take account of the sections of the Workplace Ordinance and similar standard values for workplaces of relevance for lighting systems. For the installation of a lighting system IEC 60 364 is of paramount importance for the electrical part.

Of particular interest here are:

IEC 60 364, Part 41: Protection against Currents Flowing through the Human Body

IEC 60 364, Part 42: Protection against Thermal Influences

IEC 60 364, Part 43: Protection of Cables and Lines

IEC 60 364, Part 51: Selection and Installation of Electrical Operational Equipment

IEC 60 364, Part 559: Light Fixtures and Illumination Systems

14.2
Types of Lighting

14.2.1
Normal Lighting

- The room is uniformly illuminated.
- The arrangement of the workplaces is variable (light incident from the side is recommended).

Examples: Offices and industrial rooms.

14.2.2
Normal Workplace-Oriented Lighting

- The workstations are arranged in fixed zones within the rooms.
- The illumination level is high.

Examples: Production operations, offices.

14.2.3
Localized Lighting

- Individual workplaces with greater requirements are illuminated more intensely.

Examples: Test benches and lathes.

14.2.4
Technical Requirements for Lighting

1. Illumination level
   A sufficient illuminance is required for the illumination level on which the planning and configuration of a system is based. The nominal illuminance refers to an average age and state of pollution. For systems with normal pollution a planning factor of 1.25 is used, for systems with greater pollution a factor of 1.43, and for systems with a high pollution level a factor of 1.67. The decisive plane is 0.85 m above the floor on the horizontal working surface in which the visually-oriented work takes place. The ratio of the vertical to the horizontal illuminance is given by $E_v = 1/3 \cdot E_h$. The height of the working plane in sport facilities and sport halls is taken as 1.0 m and in areas of traffic 0.20 m above the floor or ground.
2. Uniformity of illumination All workplaces must have identical illumination. The reflection factors must be complied with. The value $E_{min}/\overline{E} = 1/1.5$ must be adhered to.
3. Glare restriction
   Lighting systems must not give rise to direct glare or glare resulting from reflection. For the evaluation of direct glare, the quality classes together with the required nominal illuminance, are decisive.
4. Direction of lighting and modelling
   The viewing direction must always be parallel to the light beam axis. A favorable lighting arrangement is when the light is incident from above to the left. Adequate modelling must also be ensured.
5. Luminous color and color reproduction
   The beam distribution of a lamp is decisive for the luminous color. The luminous color for fluorescent lamps is divided into three groups:
   - warm white (ww): for relaxation and recuperation, with a high red fraction

- neutral white (nw): for trades and industry
- daylight white (dw): for certain workrooms and workplaces

The color reproduction affects the appearance of the illuminated objects. There are six color reproduction property steps. For interior rooms, at least step 3 is required.

14.2.5
Selection and Installation of Operational Equipment

- These must conform with the general rules of engineering practice.
- These must be suited to the intended purpose.
- These must bear a mark of origin.
- These must be marked with the nominal values.
- The effectiveness of the protective measures must be ensured.
- No hazards may result from the use of these electrical systems.

For building installations, the following specifications apply:

Lighting circuits or combined circuits with electrical outlets may be protected only with maximum 16-A-LS breakers. In accordance with the technical conditions for connections, they must have a making and breaking capacity of 6 kA and conform to selectivity class 3. For all other rooms, lighting circuits can be protected with maximum 25 A or less. It must be possible to isolate three-phase circuits by switching so that all ungrounded lines are simultaneously switched.

For selecting light fixtures the following must be taken into account:

- The permissible normal position
- The behavior of the installation are during fire
- The thermal effect on the environment
- The minimum spacing of spotlights
- The suspension attachments - designed for five times their weight, minimum 10 kg
- The wall boxes for concealed installations
- The through-wiring must be implemented with heat-resistant lines.

14.2.6
Lighting Circuits for Special Rooms and Systems

IEC 60 364, Part 700

1. Bath and shower room areas, Part 701
   Lighting circuits can only be installed in class 2 and 3 areas. Light fixtures in class 2 areas must conform to protection class IP X5 or IP X4. Light fixtures in class 3 areas can belong to protection class IP X0.
2. Swimming halls and swimming facilities, Part 702
   Underwater spotlights accessible from the interior of the swimming pool may be operated only with a safety extra-low voltage.

3. Sauna facilities, Part 703
   Light fixtures of protection class I may be operated only with a safety extra-low voltage or an RCD with 30 mA. The manufacturer's instructions must be followed. The lines and light fixtures must be designed to withstand the high operating temperatures (Table 14.1).

Table 14.1: Ambient temperatures of light fixtures

Type of attachment	Maximum ambient temperature °C
line inside, underneath ceiling	140
outside, on ceiling	75
outside, direct on wall	60

4. Agricultural operating areas, Part 705
   For protection by cut-off only an RCD with 30 mA is permissible. Only circuit breakers, and no fuses, can be installed. Light fixtures must belong to protection class IP 54. If the operating condition of the light fixtures cannot be recognized from the operating site, an illuminated signal display is required.
5. Rooms with limited conductivity, Part 706
   Hand lamps may be driven only with a safety extra-low voltage or must have a safety separation from operational equipment. This does not apply for fixed lamps.
6. Operating areas subject to fire hazards, Part 720
   In operating areas subject to fire hazards only lines without a metallic sheath may be used. In case of hazards due to dust or fibrous materials, light fixtures must conform to protection classes IP 4X or IP 5X.
7. Camping vehicles, boats and yachts, Part 721
   For camping vehicles, boats and yachts lighting fixtures of protection class II should generally be used. When different voltages are used, different sockets must be used to clearly identify the different voltages.
8. Overhung constructions, automobiles and apartments for exhibition, Part 722
   Lighting systems may be operated only with a voltage of 250 V relative to ground. Lamps located in the area of public traffic up to a height of 2 m above the floor must be provided with protection against breakage due to mechanical stressing. Lighting chains with illumination through ribbon cables are permitted for non-supported installation only outside the area accessible by hand. In an outside environment, they must have at least protection against splashing water or the sockets must be located below.
9. Systems in furniture and similar objects of furnishing, Part 724
   When a lamp is installed in the hollow space of a cabinet and the presence of readily flammable materials near the lamp cannot be prevented, an additional switch must be installed so that the lamp is automatically switched off

when the cabinet is closed. Furthermore, the highest permissible power rating of the lamp must be specified.

10. Hoisting gear, Part 726
    Here, the lighting circuit is a special circuit. These special circuits, with safety extra-low voltage, must be connected before an existing disconnect switch. Without safety extra-low voltage, they must be connected through a second disconnect switch. Operation must be possible without a collector wire.
11. Emergency lighting circuits, Part 560
    These circuits for safety purposes must be run separately from the other circuits. For the emergency lighting to remain effective even in case of fire, the line must be fire-resistant or correspondingly protected (e.g. F30 line NHXHX).

14.3
Lighting Calculations

In practice the efficiency method has proven very useful. The calculation will be explained in the following. With this calculational procedure, a uniform distribution of lighting fixtures is assumed. For rooms with furnishings which have a sustained influence on the lighting conditions, detailed planning with computer programs is necessary. The calculation for the lighting systems requires information about the

- dimensions of the room
- reflection factors of the ceiling, walls and floor
- type of activity or visual task
- furniture and
- selection and arrangement of lamps and lighting fixtures.

The calculational procedure is as follows:

For each type of light fixture there exists a utilization factor, in relation to a certain room. This utilization factor depends not only on the technical properties of the light fixtures, but also on the room dimensions and the reflection factors of the ceiling, walls and floor forming the boundaries of the room. First, the room index is determined from the relationship:

$$k = \frac{a\,b}{h\,(a+b)} \tag{14.1}$$

with $h = H - l_p - e$

The symbols have the meanings:

a	Length of room
b	Width of room
h	Height of light spot in m
H	Room height in m
e	Height of evaluation plane above the floor
l_p	Length of pendant or suspension in m

After determining the room index k the required number of light fixtures for an average illuminance can be determined from:

$$n = \frac{E_n \, A \cdot 100}{z \, \Phi \, \eta_B \, M} \tag{11.4}$$

The average horizontal illuminance $\overline{E}$ can be determined from the calculated number of light fixtures from:

$$\overline{E} = \frac{N \, z \, \Phi \, \eta_B \, M \, v}{A \cdot 100} \tag{11.5}$$

Here, the symbols have the meanings:

E_n	Nominal illuminance in lx
A	Floor area of room in m^2
z	Number of lamps per light fixture
v	Reduction factor, taking into account pollution and aging of lamps, light fixtures and room
η_B	Utilization factor in % according to data sheet, depending on light fixture properties, reflection factors of ceiling, walls and floor and room dimensions, expressed by the room index k
Φ	Luminous of a lamp in lm according to data sheet
$\overline{E}$	Average illuminance in lx
n	Calculated number of lighting fixtures
N	Selected or specified number of lighting fixtures
M	Multiplier for η_B

14.4
Planning of Lighting with Data Blocks

The average illuminance, the required number of light fixtures and the uniformity of the illuminance can be determined with the use of data blocks. Each data block of a light fixture is divided into six parts, which will now be briefly explained.

14.4.1
System Power

Table 14.2 gives the power consumption for tubular fluorescent lamps with control gear.

Table 14.2: Power consumption in W for fluorescent lamps with low-loss conventional (VVG) and electronic (EVG) control gear [64]

Lamps	VVG	EVG
2 × 11	30	28
2 × 18	42	38
3 × 18	66	57
4 × 18	84	76
3 × 24	90	81
1 × 36	42	36
2 × 36	84	72
1 × 58	66	55
2 × 58	132	110

14.4.2
Distribution of Luminous Intensity

The light radiation from the light fixtures of interest is shown as a relative luminous intensity distribution curve in polar coordinates (Figure 14.1). The luminous intensity distribution is normalized to a luminous flux of 1000 lm for different reference planes as a function of the angle of radiation.

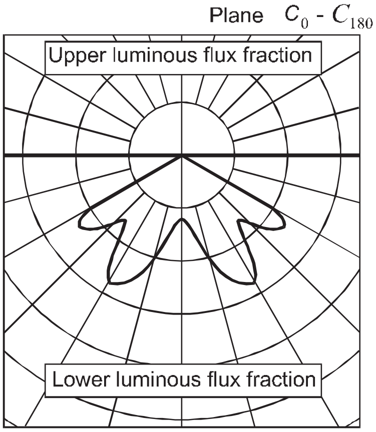


Figure 14.1: Luminous intensity distribution

14.4.3
Luminous Flux Distribution

For the evaluation of the effectiveness of the lighting system in the room, the luminous flux distribution is evaluated. The luminous flux of the lamps consists of the partial luminous fluxes in the lower and the upper half spaces. Light fixtures are identified by a characteristic letter A to E and two characteristic numbers, according to their relative luminous flux distribution. For further classification, in the standard room S has been defined, to which the following light fixture parameters refer.

A50	Identification of the light fixture
$\varphi_u = 1$	Luminance flux fraction from lower half space
$\varphi_{su} = 0.63$	Effective luminance flux fraction in standard room
$\varphi_{so} = 0.01$	Ceiling light current fraction in standard room

14.4.4
Efficiencies

For the planning of lighting systems according to the efficiency method, the utilization factor η_B is decisive. It depends on the technical properties of the light fixtures as well as the dimensions of the room, expressed by the room index k, and the reflection factors of the ceiling, walls and floor (Table 14.3).

Table 14.3: Utilization factors η_B in % [64]

Utilization factor η_B in %										
ρ	Ceiling	0.8		0.7		0.5			0.3	0
	Walls	0.5	0.3	0.5	0.3	0.5	0.3		0.3	0
	Floor	0.3	0.1	0.2	0.1	0.3	0.3	0.1	0.1	0
Room	0.60	37	28	35	28	35	28	28	27	22
index k	0.80	46	36	44	36	43	37	35	35	29
	1.00	53	43	50	42	50	43	41	41	35
	1.25	61	50	57	49	57	51	49	48	42
	1.50	67	55	62	54	62	56	62	53	47
	2.00	75	62	69	61	69	64	60	59	54
	3.00	85	70	77	70	78	74	68	67	63
	5.00	93	77	84	76	84	81	75	73	69

14.4.5
Spacing Between Lighting Elements

The uniformity of the illuminance depends on the luminous intensity distribution of the light fixtures, their spacing (transverse distance x and longitudinal distance y, measured between the middles of the light fixtures) and the height of the room H (Figure 14.2). The diagram gives the uniformity of the illuminance $\frac{E_{min}}{\bar{E}}$ as a function of the light fixture spacing x for two room heights H. The recommendation is 0.67, i.e. 1 : 1.5.

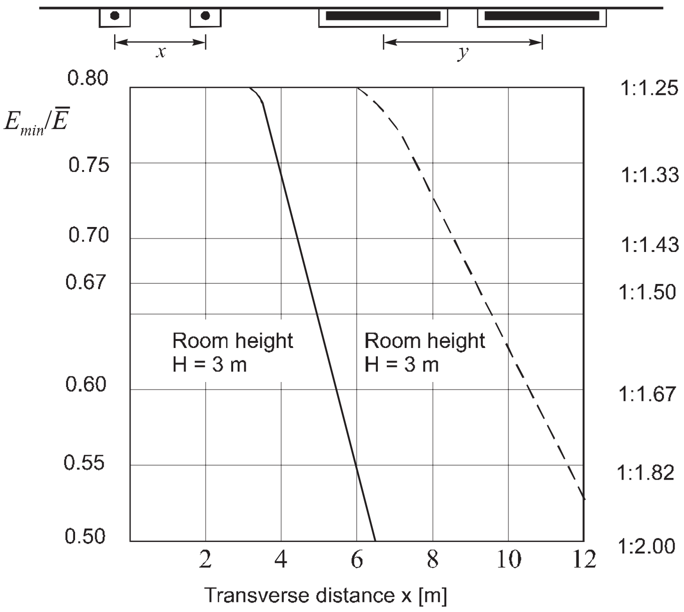


Figure 14.2: Light fixture spacing

14.4.6
Number of fluorescent lamps in a Room

The number of lamps required to obtain a certain illuminance can be read directly for special room conditions (Table 14.4). The number of lamps determined must be rounded off according to technical and installation requirements. The table does not apply for narrow, elongated spaces, such as floorways.

Table 14.4: Number of lamps in a room [64]

Reflection factors: ρ = 0.7/0.5/0.2, v = 0.8									
Lamps 58 W		4100 lm				5200 lm			
E_n in lx		300		500		300		300	
Room height H in m		3.0	5.0	3.0	5.0	3.0	5.0	3.0	5.0
Floor space A in m^2	20	3.6	5.7	6.0	9.5	2.8	4.5	4.7	7.5
	30	4.8	7.4	8.0	12	3.8	5.8	6.3	9.7
	40	6.0	8.8	10	15	4.7	7.0	7.8	12
	50	7.2	10	12	17	5.6	8.1	9.4	13
	60	8.3	12	14	19	6.6	9.1	11	15
	80	11	14	18	24	8.3	11	14	19
	100	13	17	21	28	10	13	17	22
	200	23	28	39	47	18	22	31	37

14.4.7
Illuminance Distribution Curves

Illuminance distribution curves make clear the behavior of the horizontal illuminance on the center line of the utility plane of the room, underneath the light fixture (Figure 14.3).

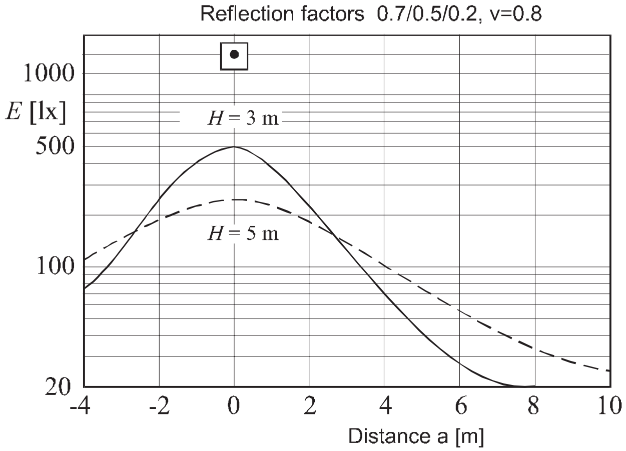


Figure 14.3: Illuminance distribution

14.4.8
Maximum Number of Fluorescent Lamps on Switches

The maximum number of fluorescent lamps on switches with positive action contacts, 250 V / 10 A can be read from Table 14.5.

Table 14.5: Maximum number of fluorescent lamps [64]

Tubular fluorescent lamps				
Lamp power in W	**Conventional control gear with ind.**	**Conventional control gear**	**Conventional control gear**	**EVG compensated with DUO**
18	26	38	50	26
36	22	34	40	26
58	14	22	26	18
Compact fluorescent lamps				
11	60	76	–	–
18	26	38	50	–
24	26	38	50	–
36	22	34	40	–

14.4.9
Maximum Number of Discharge Lamps Per Circuit Breaker

The maximum number of discharge lamps on a circuit breaker with B or C characteristic can be seen from Table 14.6.

Table 14.6: Number of discharge lamps per circuit breaker [64]

Lamp power W	Voltage V	Condenser capacity μF	B/C10 A	B/C16 A	B/C20 A	B/C25 A
Fluorescent lamps with conventional control gear						
L18/20	230	4.5	32	51	64	82
L36/40	230	4.5	32	51	64	82
L58/65	230	7	20	33	41	53
High-pressure mercury vapor lamps						
50	230	7	10/19	15/31	18/39	23/49
80	230	8	6/12	9/19	11/24	14/30
125	230	10	4/7	6/12	7/15	9/19
250	230	18	2/4	3/6	3/7	4/9
400	230	25	1/2	2/4	2/5	2/6
700	230	40	–/1	1/2	1/2	1/3
1000	230	60	–/1	–/1	1/2	1/2
Halogen metal vapor lamps						
150	230	20	7/5	11/8	14/10	17/12
250	230	20	7/5	11/8	14/10	17/12
400	230	32	5/3	7/5	9/6	11/8
1000	230	85	1/–	1/1	3/1	3/2
2000	D400	60	1/–	2/1	2/1	3/2
2000	N400	37	–	1/–	1/1	2/1
3500	400	100	–	–	–	–
High-pressure sodium vapor lamps						
50	230	10	16/11	24/17	31/22	38/27
70	230	12	12/8	18/13	23/16	29/20
100	230	12	10/7	16/11	20/14	25/17
150	230	20	5/5	11/8	14/10	17/12
250	230	36	5/3	7/5	9/6	11/8
400	230	45	3/2	4/3	5/4	7/5
1000	230	100	1/–	1/1	2/1	3/2

14.4.10
Mark of Origin

Lamp fixtures must satisfy the laws for technical working resources. Light fixtures must bear the testing mark of conformity and the symbol for safety testing, with the following details (Figure 14.4).

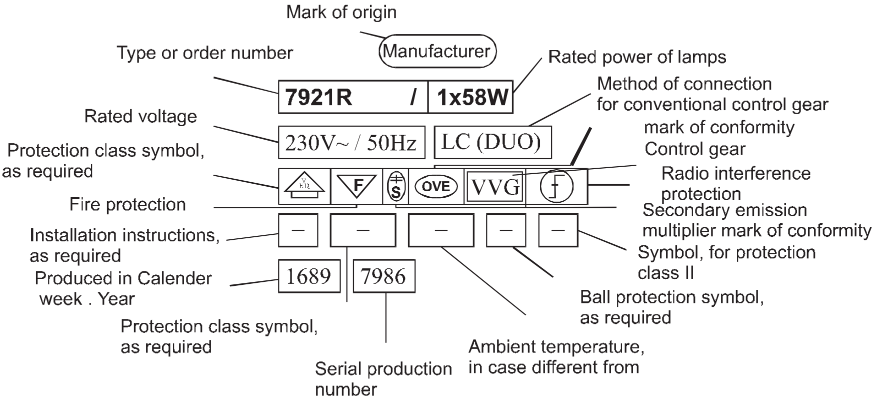


Figure 14.4: Manufacturer's data for light fixtures [66]

14.4.11
Standard Values for Planning Lighting Systems

For the rough calculation of the power requirement and the number of lamps required, we can refer to Tables 14.7 and 14.8.

Table 14.7: Power requirement for a nominal illuminance $E_n = 500$ lx [66]

Room size	Floor space m^2	Power requirement in W/m^2
Average	30	15
Large	150	13

Table 14.8: Light flux requirement for a nominal illuminance $E_n = 100$ lx [66]

Room size	Floor space m^2	Light flux in lm/m^2
Average	30	225
Large	100	200

14.4.12
Economic Analysis and Costs of Lighting

The planning and configuring of the lighting system also includes a cost and economic analysis, which will be described briefly in this section []. The total yearly costs are made up of the

- Capital costs for the purchase and initial installation and the
- Operating costs for power, replacement of lamps and system maintenance.

Capital costs:

$$K_K = n_1 \left[\frac{K_1 \frac{k_1}{100} + K_2 \frac{k_2}{100}}{n_2} \right]$$

Power costs:

$$K_E = n_1 \left[t_B \, a \, P \right]$$

Replacement of lamps and system maintenance:

$$K_{LW} = n_1 \left[\frac{t_B}{t_L} \left(K_3 + K_4 \right) + \frac{R}{n_2} \right]$$

Total yearly costs:

$$K_G = K_K + K_E + K_{LW}$$

The symbols have the meanings:

K_1	Costs of a light fixture
k_1	Capacity costs for K_1 in % for amortization and interest
K_2	Costs for installation material and installation per light fixture
R	Cleaning costs per light fixture per year
n_1	Total number of lamps
n_2	Number of lamps per light fixture
K_3	Price of lamp
K_4	Costs of replacing a lamp
P	Power consumption of a lamp + control gear in kW
a	Costs of electrical power per kWh + basic price
t_L	Useful life of the lamp in h
t_B	Yearly operation period in h

14.5
Procedure for Project Planning

For the planning and configuring of lighting systems, the following recommendations should be considered in the interest of cost effectiveness:

- High luminous efficiency of the light source
  Three-row fluorescent lamps have up to 30% greater luminous efficiency than standard fluorescent lamps.
- Low power loss from the control gear
  Electronic control gear has up to 62% less power loss than conventional control gear.
- High efficiency of the light fixtures

Specular louvre light fixtures, with operating efficiencies of up to 75%, are preferable to opal recessed light fixtures from the standpoint of using energy efficiently.

- High utilization factors as a result of
    1. Dedicated lighting systems and optimal arrangement
    2. Dedicated room layout
    3. Choice of economic light sources
    4. Computer-optimized planning.
- Floor plans and vertical sections of rooms with windows and doors
- Room state (reflection factors)
- Use of rooms
- Specifications of room temperature (reduced light flux at low temperature)
- Period of operation of the lighting system in hours
- Choice of light fixtures

Planning and configuring the lighting in an industrial hall

For an industrial system with normal bookbinding work the lighting planning is to be carried out according to the efficiency method with form sheets. The following data are given:

1. Room dimensions
   Room length $a = 45$ m
   Room width $b = 16$ m
   Room height $H = 7$ m
2. Reflection factors
   Ceiling 0.5
   Walls 0.3
   Floor 0.1
3. Light fixture type requirement
   Continuous reflector row 1 × 58 W, height of suspension 1 m
4. Requirements for the light source
   Tubular fluorescent lamps 58 W with high luminous efficiency. Light color and step of color reproduction properties must be considered.
5. Definition of problem
   - Planning of the lighting system in accordance with the regulations
   - Determination of the required number of light fixtures for an average illuminance with the use of the form sheet.
   - Evaluation of the lighting system with regard to uniformity, light color and color reproduction, glare, modelling and light direction.
   - With what measures can the power consumption of the system be reduced?

Calculational steps for the industrial system:

Table 14.9: Room data

Length a	45	m
Width b	16	m
Area $A = a\,b$	720	m^2
Height H	7	m
Height of evaluation plane above floor e	0.85	m
Length of pendant or suspension l	1	m
Light spot height $h = H - l - e$	5.15	m
Room index $k = \dfrac{a\,b}{h(a+b)}$	2.3	
Reflection factors for ceiling/walls/floor	0.5/0.3/0.1	

Table 14.10: Standard values taken from workspace regulations

Type of room	Bookbinding work	
Nominal illuminance E_n	300	lx
Light color	ww/nw	
Step of color reproduction properties	2A	
Quality class of glare restriction	1	
Reduction factor v	0.8	
Uniformity $g_1 = E_{min}/\overline{E}$	1/1.5	

Table 14.11: Data for light fixtures

Number of light fixture	7921R/58	
Data block number	712	lx
Utilization factor η_B	62	%
Multiplier for η_B M	1	
Number of lamps per light fixture z	1	

Table 14.12: Data for lamps

Power per lamp, without control gear	58	W
Power per lamp, with control gear	66	W
Light color	nw	
Step of color reproduction properties	1B	
Light flux per lamp Φ	5200	lm

Table 14.13: Technical data for lighting systems

Required number of light fixtures $n = \dfrac{E_n\,A \cdot 100}{z\,\Phi\,\eta_B\,M\,v}$	$\dfrac{300\,\text{lx}\cdot 720^2 \cdot 100}{5200\,\text{lm}\cdot 62 \cdot 0.8}$	84	
Selected number of light fixtures	N	87	
Average illuminance $\overline{E} = \dfrac{N\,z\,\Phi\,\eta_B\,M\,v}{A \cdot 100}$	$\dfrac{87 \cdot 5200\,\text{lm} \cdot 62 \cdot 0.8}{720\,\text{m}^2 \cdot 100}$	312	lx
Uniformity	$E_{min}/\overline{E}$	≥ 1/1.5	
Spacing of light fixtures		x in m transverse	y in m longitudinal
a) according to data block		9	4.8
b) selected/specified	6	1.53	

Arrangement of light fixtures: 3 rows of lighting, 29 light fixtures each

Remarks: The power consumption can be reduced with the use of electronic control gear.
The connected load is then: $P = N\,z\,p = 87 \cdot 1 \cdot 55\,\text{W} = 4785\,\text{W}$
The connected load with conventional control gear is: $P = N\,z\,p = 87 \cdot 1 \cdot 66\,\text{W} = 5742\,\text{W}$
Savings with the use of electronic control gear: 957 W

For the evaluation of the uniformity of illumination for this example, the computer-supported planning with the plane of utilizazion, which are shownshown here as graytone steps (Figure 14.5). The TX1 software is included on the accompanying CD-ROM (see also Section 17.1.3).

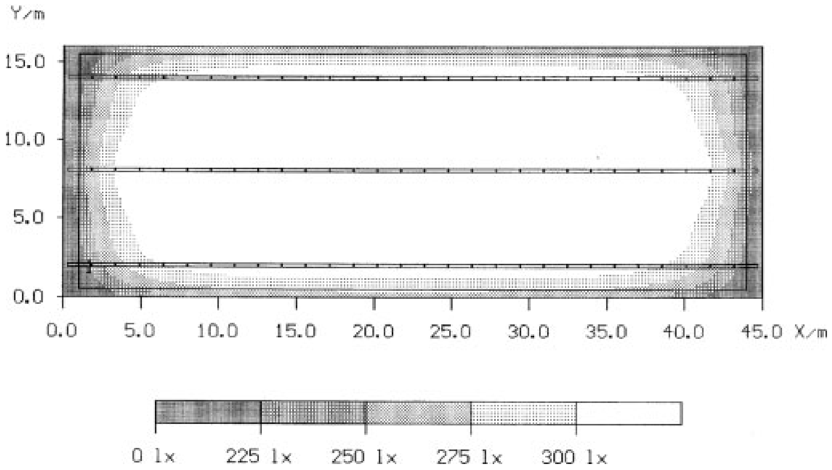


Figure 14.5: Graytone steps

14.6
Exterior Lighting

Exterior lighting must always conform to the requirements and criteria of the Technical Standards Committee for Lighting Technology. The most important standards are listed here.

- Permanently Installed Traffic Lighting – Illumination of Streets for Road Traffic: General Quality Criteria and Standard Values
- Permanently Installed Traffic Lighting – Illumination of Streets for Road Traffic: Calculation and Measurement
- Standard Values for the Illumination of Pedestrian Crossings
- Illumination of Road Tunnels and Underpasses
- Illumination of Parking Lots and Park Houses
- Stadium Lighting
- Illumination of Sluice Systems
- Good Lighting for Safety on Roads, Pathways and Public Squares

Exterior lighting systems are calculated with the point lighting method, and not with the efficiency method. The luminous intensity and the luminous flux can be taken from the manufacturers' catalogs. The horizontal illuminance is calculated from the equation

$$E = \frac{I\,H}{(l^2+H^2)\,\sqrt{(l^2+H^2)}} \tag{14.8}$$

Here, the meanings of the symbols are:

E Illuminance in lx

H Lighting pole height in m

l Distance of point of interest from base of light fixture in m

I Luminous intensity in direction of point of interest in cd

14.7
Low-Voltage Halogen Lamps

General notes on installation:

- The transformer must be designed for the safety extra-low voltage.
- Transformers must be implemented as short circuit - proof safety isolating transformers.
- Electronic overtemperature protection is built in.
- Protection of the transformer against secondary short circuits is possible through fine-wire fusing on the primary side.
- When overload protection is present, the lower voltage side is also protected.
- The transformer power must be matched to the actual loading of all connected lamps.

- The lamps may be operated only within the specified limits.
- For dimming mode it is necessary to observe the manufacturers' special instructions for connecting.
- The dimmer must always be installed on the primary side of the transformer.
- The dimmer must be designed according to the power of all connected lamps, including all connected transformers and any required base load.
- The transformer must be easily accessible.
- The transformer must be installed as closely as possible to the light fixture.
- For safety isolating transformers must be taken into account.
- The voltage drop and the line cross-section on the lower voltage side must be taken into account.
- The maximum permissible voltage in the low-voltage installation is restricted in accordance with IEC 357 to 110%.
- Terminals must be relieved from traction, shear and torsion.
- Junctions must be protected against electric shock.
- At the clamping points permanent low-resistance connections must be made.
- When the cross-section of the line is greater than that of the clamping point on the transformer, a line up to 0.5 m long must be led out of the transformer and the required line then connected through a junction box.

Calculation of the maximum line length for a voltage drop:
In 12 V systems the voltage drop is considerably higher than in 230 V systems with the same power. The high currents and the high voltage drop lead to heating and power losses in the lines installed. For this reason, low-voltage installations must be carefully planned.

Magnitude of the current:

$$I = \frac{P}{U} \tag{14.9}$$

Voltage drop:

$$\Delta U = \frac{2\,l\,I}{\kappa\,S} \tag{14.10}$$

With these values, we can then calculate the line length for the given lamp power:

$$l = \frac{\Delta U\,\kappa\,S}{2\,I} \tag{14.11}$$

Calculation of the cross-section:

$$S = \frac{2\,l\,P}{\Delta u\,U_n^2\,\kappa} \tag{14.12}$$

The symbols have the meanings:

l	Length of line in m
S	Cross-section of line in mm^2
I	Current in line in A
ΔU	Voltage drop in V
κ	Conductivity of line; for Cu: $56\ \text{m}/\Omega\ \text{mm}^2$
P	Lamp power in W
U_n	Nominal voltage in V
Δu	Voltage drop in %

14.8
Safety and Standby Lighting

14.8.1
Terms and Definitions

- Back-up lighting: The backup lighting is a lighting system which is promptly activated in the event of a failure in the power supply to the normal artificial lighting. Here it is necessary to distinguish between
    1. Safety and backup lighting in accordance community facility regulations
    2. Standby Lighting in accordance with the regulations.
- Safety lighting: Safety lighting is required for safety reasons (general safety, accident prevention). It has a protective function.
- Stand-by lighting: Stand-by lighting consists of a backup lighting system which takes over the function of the normal artificial lighting in order to enable continued operation for a limited period of time. When no safety lighting is required, a stand-by lighting system can still be installed.
- Emergency lighting: Emergency lighting consists of a light fixture with its own or with an emergency source of power, which is used to generate the emergency lighting.

14.8.2
Circuits

- Floating circuit:
  Emergency light fixtures or the emergency-symbol light fixtures connected to emergency lighting power supplies are activated for both normal power and in case of a failure of normal power. The normal power supply is monitored at the main distribution board of the safety power source.
- Stand-by circuit:
  Emergency light fixtures or the emergency-symbol light fixtures connected to emergency lighting power supplies are activated only in the event of a failure of normal power. The power supply for the normal lighting is monitored in the sub-distribution system for this part.

For emergency-symbol or safety lighting systems, in accordance with EN 60598, Part 2.22 and no glow starter or discharge lamps with integrated glow starter may be used; EN 60924 and EN 60925 specify only electronic control gear.

14.8.3
Structural Types for Groups of People

The requirements for safety and backup lighting depends on the use of the room or building.

Table 14.14: Requirements for safety and backup lighting according to use of the room or building, in accordance with community facility regulations

Type of structure	**E_{min}** lx	**t_{um}** s	**t_b of SVS** h	**DS for illumination of emergency symbol**	**DS for SB of RW**
Emergency ways in production/office areas	1	15	1	no	no
Exhibition areas > 2000 m^2	1	1	3	yes	yes
Restaurants with > 400 seats	1	1	3	yes	yes
Lodging facilities with > 60 beds	1	15	3	yes	no
Garages with > 1000 m^2 useable area	1	15	1	yes	no
Stores with > 2000 m^2 sales area	1	1	3	yes	yes
Multi-storey buildings > 22 m	1	15	3	yes	no
Schools with floor area > 3000 m^2	1	15	3	yes	no
Places of gathering, movie houses, theater for > 100 persons	1	1	3	yes	no
Meeting rooms for > 200 persons	1	1	3	yes	yes
Stage scene area	3	1	3	yes	no
Circus rings, sport race courses	15	1	3	yes	no
Workplaces with special dangers	min. 15	0.5	min. 1	no	no

DS: Floated circuit, SB: Safety lighting, RW: Emergency way
t_{um}: Switch-over time, t_b: Operating time,
SVS: Stand-by voltage source

14.8.4
Planning and Configuring of Emergency-Symbol and Safety Lighting

- Emergency light fixtures
  Emergency symbols must have white pictorial markings and a green background and be clearly recognizable during the required time in operation. A minimum size is therefore required. The required recognition widths can be determined from formulas or from the manufacturer's information and must be taken into account during planning. In accordance with the accident prevention regulations, the aspect ratio must be 1 : 1 or 1 : 2.

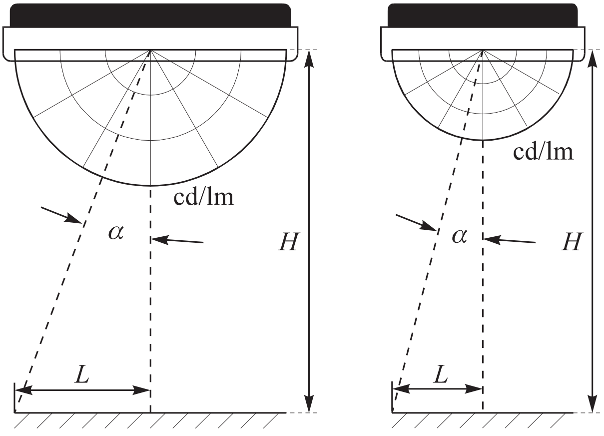


Figure 14.6: Emergency way lighting

The calculation of the illuminance requires the:

- Luminous intensity distribution of the light fixture
- Luminous flux at the end of the nominal operating life
- Height of suspension of the light fixture or type of light mounting

The recognition width of the emergency-symbol light fixture is given by:

$$e = hz \tag{14.13}$$

The illuminance (Figure 14.6) can be calculated using the point lighting method, according to the relationship:

$$E = \frac{I \cos^3 a}{H^2} \qquad 14.14$$

The spacing between the light fixtures is calculated from the relationship:

$$L = H \tan \alpha \tag{14.14}$$

Here, the meanings of the symbols are:

e Recognition width in m
h Height of emergency symbol in m
z Distance factor 200 for internally illuminated emergency symbols, 100 for externally illuminated emergency symbols
E Illuminance in lx
H Height of light fixture – 0.2 in m
a Light emergence angle in °

$E = 1\,\text{lx} \times 1.25$ between light fixtures
$E = 0.5\text{lx} \times 1.25$ between light fixture and wall or door

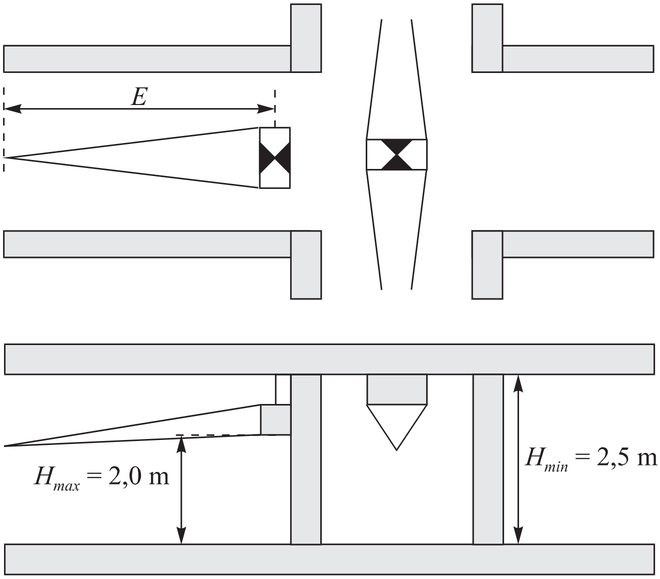


Figure 14.7: Installation of emergency-symbol lighting

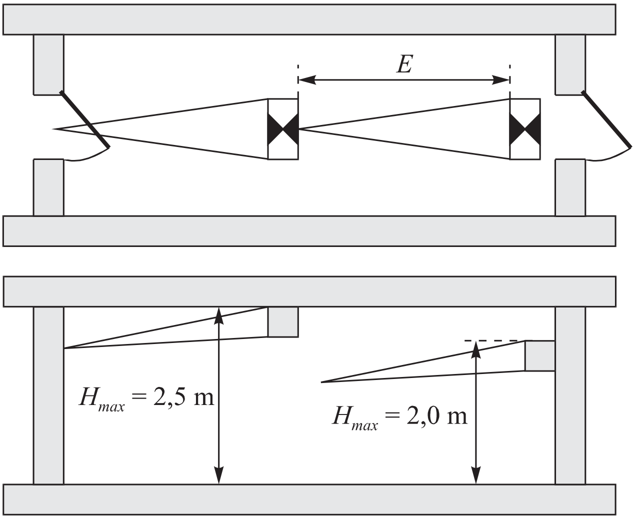


Figure 14.8: Installation of emergency-symbol lighting

- Safety lighting The safety lighting identifies and illuminates emergency ways and must have the uniformity specified before:

$$g = \frac{E_{min}}{E_{max}} \geq \frac{1}{40}$$

at a height of 0.2 meters and 1 lx and a nominal operating time of at least one hour or three hours. The locations of these light fixtures are: main entrances and exits, floors, stairs, emergency balconies, emergency tunnels and workplaces with special dangers. For the planning of emergency-symbol and safety light fixtures, the following points must be taken into account (see Figures 14.7 to 14.11):

- Choice of light source
- Covers for light fixtures
- Type of protection
- Protection class
- Light fixture housing (material, design)
- Type of installation (wall, ceiling, pendant, built-in, mounting)
- Version with single battery, central battery system or groups of batteries

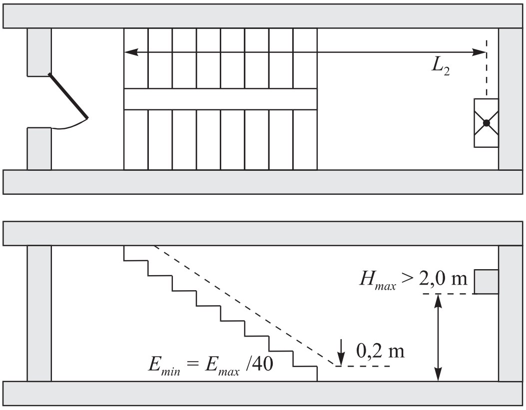


Figure 14.9: Installation of safety lighting

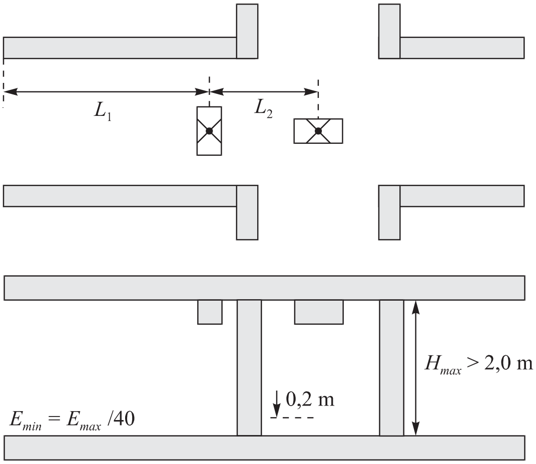


Figure 14.10: Installation of safety lighting

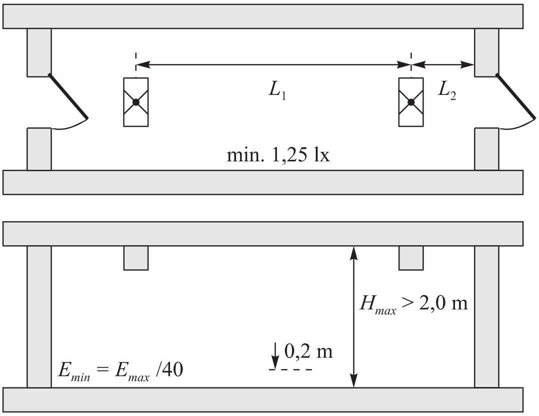


Figure 14.11: Installation of safety lighting

14.8.5
Power Supply

The main distribution system for the safety power supply and the normal power supply must be located in electrical operating areas and isolated from each other so that no arcing can pass between them. Isolation of the walls and ceilings must be carried out with F30 and doors with T30, for a normal fire hazard, and F90, T30 for a greater fire hazard.

14.8.6
Notes on Installation

1. Electrical operating areas
   Isolation of the walls and ceilings from other rooms must be carried out with F30, for a normal fire hazard, and F90 with an increased fire hazard, and doors with T30 for a greater fire hazard. In this area there must be no switchgear over 1 kV, no standby generating systems and no operational equipment for other systems.
2. Battery space
   These rooms must be protected from extreme temperatures and gassing. The width of the gangway must be at least 0.5 m or 1.5 times the cell depth.
   The calculation of the ventilation for the battery space can be made according to the following equation:

$$Q = 0.05\, n\, I f_1 f_2 \tag{14.16}$$

Air intake and exhaust air opening:

$$A = 0.0028\, Q \tag{14.17}$$

Battery charging capacity:

$$P = 4\, U\, I = 4 U_{\text{cell}}\, I\, n_{\text{cell}} \tag{14.18}$$

Forced ventilation is not required
with a charging capacity < 3 kW for Pb-acid batteries
with a charging capacity < 2 kW for Ni-Cd batteries.

Here, the meanings of the symbols are:

Q	Volume rate of air flow in m^3/h
n	Number of cell
I	Current in A
f_1	Reduction factor
f_2	Reduction factor
A	Air intake and exhaust air opening in m^2
U	Charging voltage in V
I	Charging current in A

14.8.7
Testing During Operation

- Automatic monitoring of charge in cycles of five minutes
- Automatic function testing (maximum five minutes)
- Automatic operating time testing (minimum 40/120 minutes)
- Automatic monitoring of lines
- Registration and storing of faults (minimum two years), maintenance log book
- Display and printout of test results

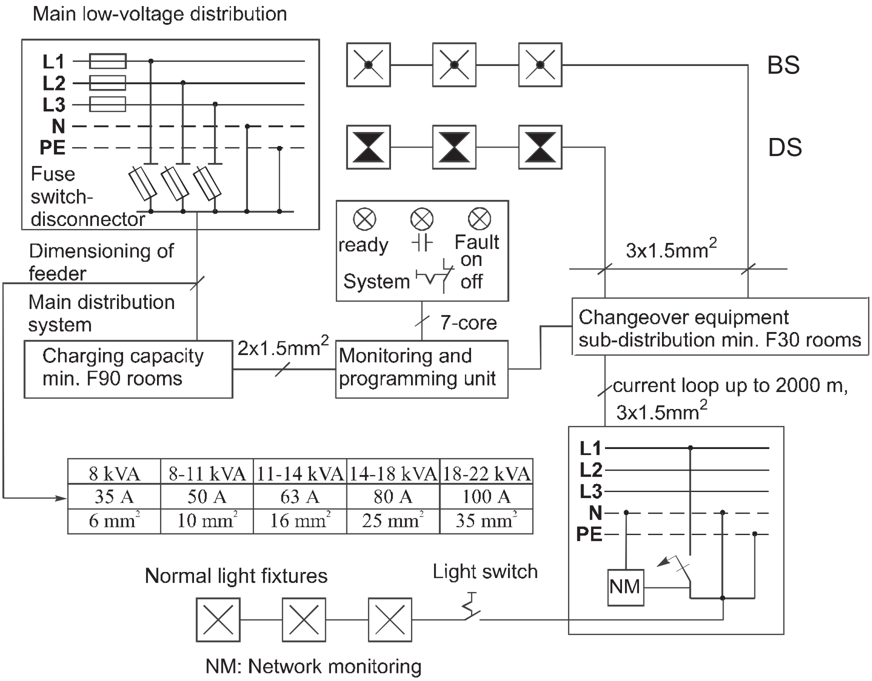
14.9
Battery Systems

14.9.1
Central Battery Systems

The most recent version of community facility regulations specifies that in the event of a power failure the standby system must not be supplied from the battery as long as a voltage is still present at the main distribution board of the safety lighting system. Accordingly, the fusing in the main low-voltage distribution system must be designed for the entire safety system distribution. For maintenance purposes, a fuse switch-disconnector is recommended. The central battery system is described in detail as follows (see Figures 14.12 to 14.15):

1. Components
   - Battery (open, closed or sealed Pb-acid or Ni-Cd batteries)
   - Charging equipment (recharging to 90% in 10 or 20 hours)
   - Changeover equipment (standby and/or floated circuit)
   - Rectifier for discharge lamps (single/groups/central)
   - Internal displays (central fault, operating mode, ready state, battery discharge warning activated, isolation monitor activated, ventilation monitor activated)

   - External display (central fault, operating mode, ready state)
2. Technical data
   - Power unrestricted
   - Number of light fixtures unrestricted (maximum 12 light fixtures per circuit and maximum 6 A current load per circuit)
3. Monitoring equipment
   - Circuit monitoring
   - Individual monitoring
   - Phase monitoring
4. System properties
   - Phase selection circuit for three-phase connection
   - Battery operation only in the event of a complete power failure
   - Separate monitoring and changeover equipment is required for floated circuit and standby circuits.
   - The technical fire protection requirements do not apply for branch circuits of the safety lighting.



8 kVA	8-11 kVA	11-14 kVA	14-18 kVA	18-22 kVA
35 A	50 A	63 A	80 A	100 A
6 mm²	10 mm²	16 mm²	25 mm²	35 mm²

Figure 14.12: Central battery system

The abbreviations have the meanings:

BS	Standby lighting system
DS	Floated circuit
SL	Safety light

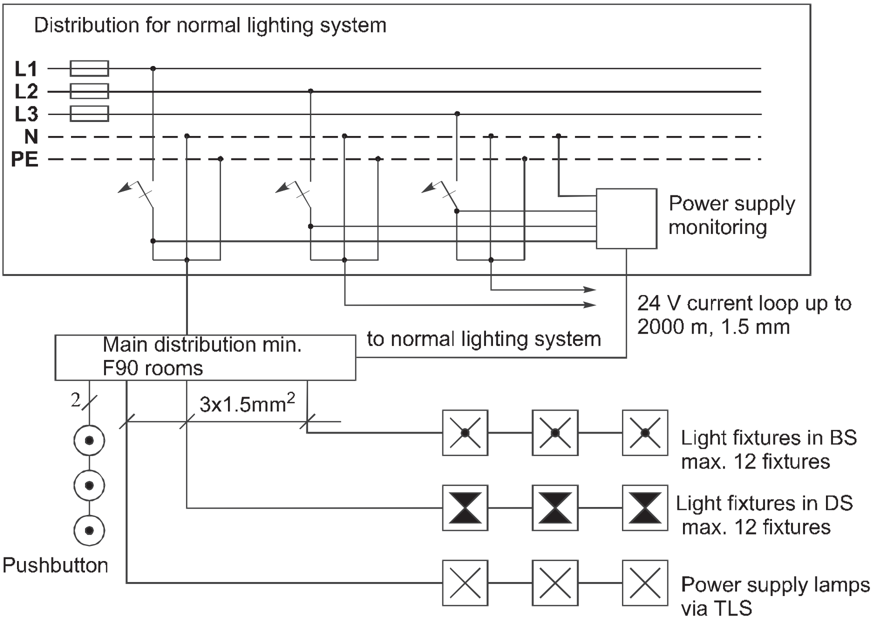


Figure 14.13: Central battery system

For fire protection it is necessary to take account of the following points (Figures 14.17 and 14.19):

Sections

2.2.22 Main distribution board for safety power supply is first distribution point in building which is fed directly from standby power source of safety lighting system.

5.2.1.2 Rooms for main distribution board of normal power supply must be separated from rooms with greater fire hazards with at least F90 and from other rooms with at least F30. Doors must be fire-retardant.

5.2.2.1 Sub-distribution systems of the normal power supply must be installed with their own enclosures.

6.6.6 Sub-distribution systems of the safety lighting system must be installed separately from system sections of the normal power supply, with their own enclosures.

6.7.4 For each circuit of the safety power supply, separate cables and separate lines must be used. These cables and lines must be run separately from other line systems. Separate line systems are not required for installation of the branch circuits of the safety lighting system (Figures 14.16 and 14.18).

Lines must be at least F30 up to the first light fixture of the circuit. Thereafter, in the same fire-protected section, F30 is no longer required. Central and sub-stations must be run separately and multi-core lines must be run short circuit and ground fault – proof only for a main circuit and for auxiliary circuits and must not be run through explosion hazard areas (Figure 14.16).

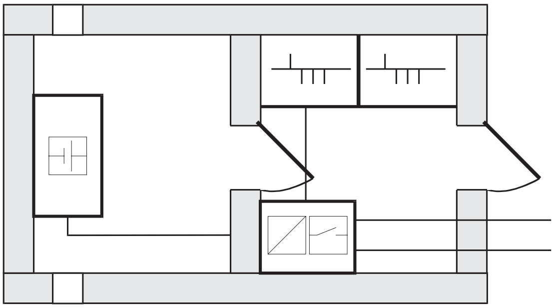


Figure 14.14: Installation of lines

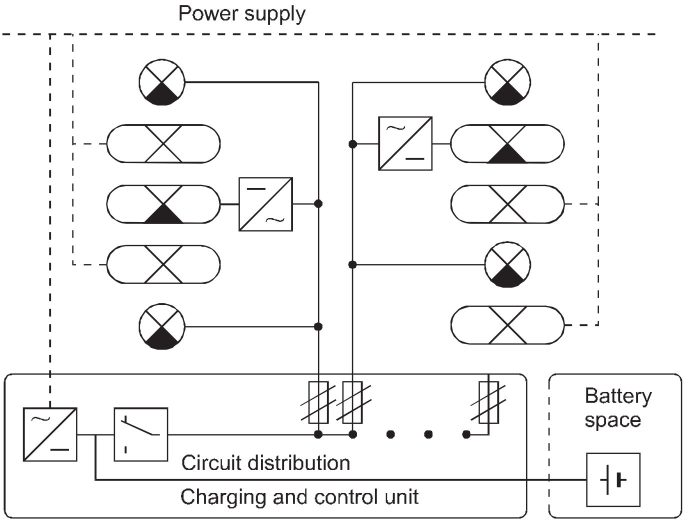


Figure 14.15: Emergency lighting with central battery

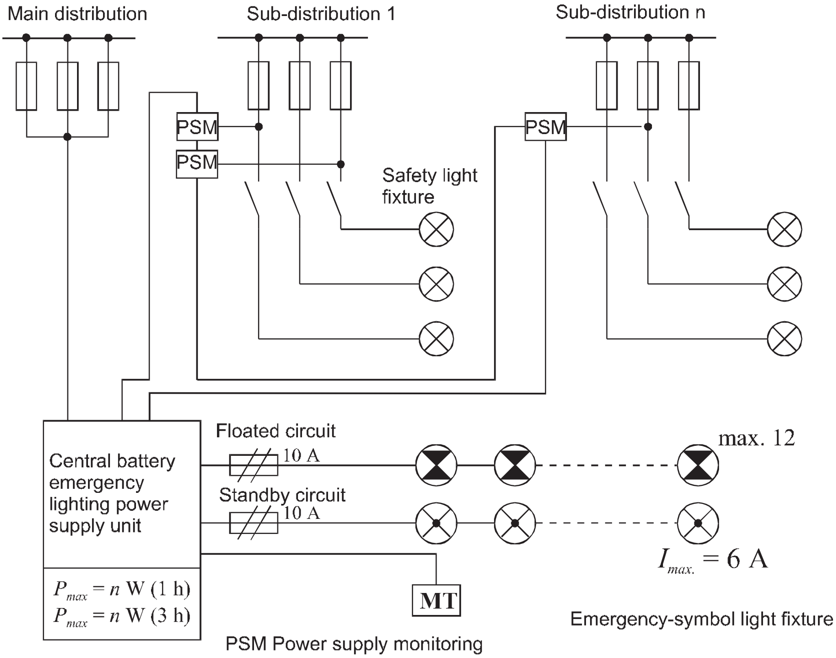


Figure 14.16: Central battery systems

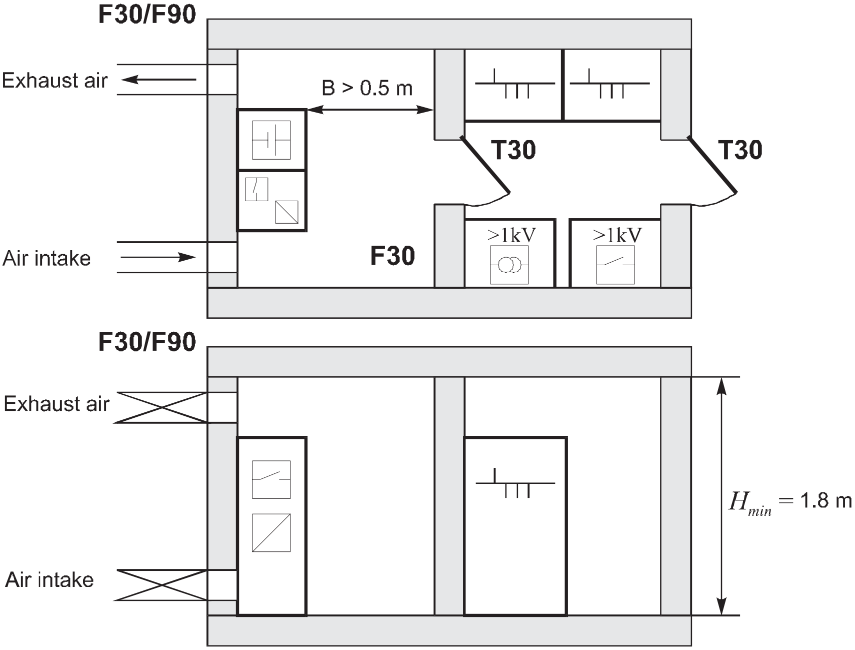


Figure 14.17: Installation of battery groups and central batteries

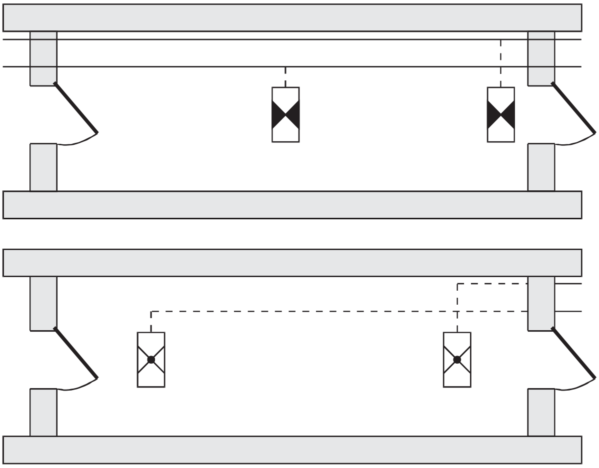


Figure 14.18: Installation of lines

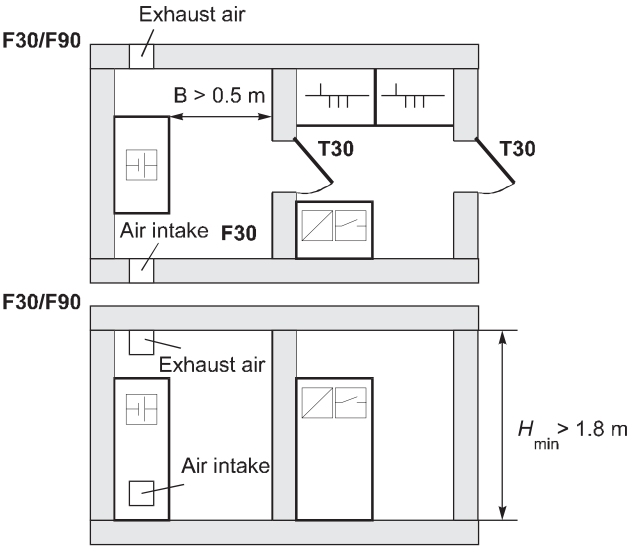


Figure 14.19: Installation of battery groups and central batteries

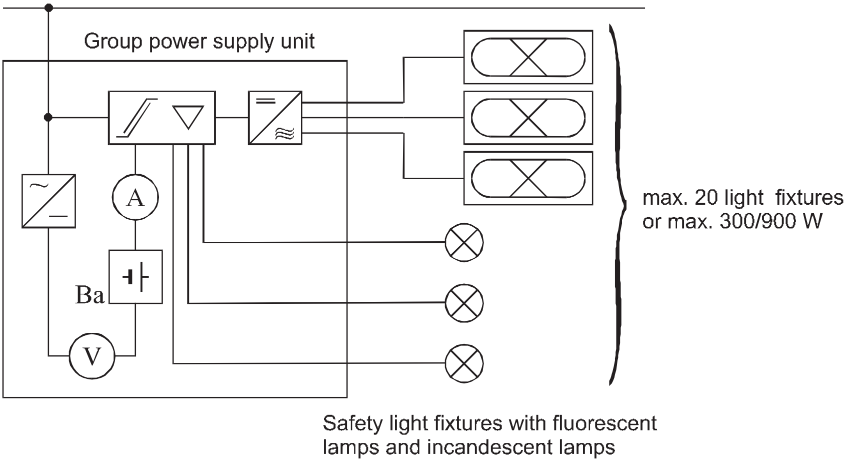


Figure 14.20: Emergency lighting with battery group

14.9.2
Grouped Battery Systems

Grouped battery systems (Figures 14.20 and 14.21) are described as follows:

1. Components
   - Battery (sealed Pb-acid or Ni-Cd batteries)
   - Charging equipment (recharging to 90% in 10 or 20 hours)
   - Changeover equipment (standby and/or floated circuit)
   - Rectifier for discharge lamps (single/groups/central)
   - Internal displays (central fault, operating mode, ready state, battery discharge warning activated, isolation monitor activated, ventilation monitor activated)
   - External display (central fault, operating mode, ready state)
   - Technical data
2. Power 900 W for one hour or 300 W for 3 hours
3. System properties
   - A maximum of 20 safety light fixtures can be connected.
   - The current consumption of group rectifiers must not exceed 6 A.
   - Separate monitoring and changeover equipment is required for floated circuit and standby circuits.
   - The technical fire protection requirements do not apply for branch circuits of the safety lighting.

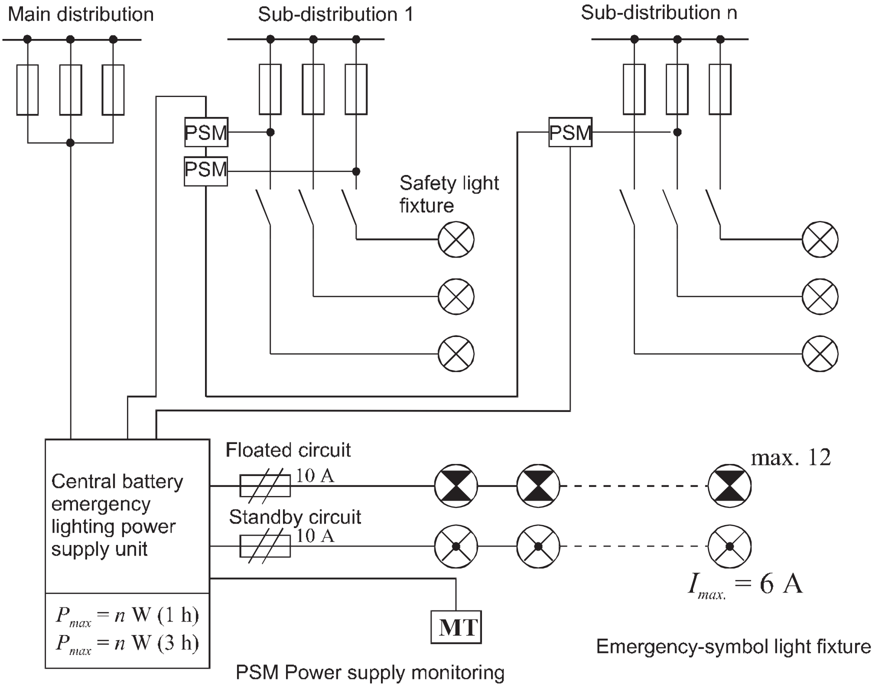


Figure 14.21: Grouped battery systems

14.9.3
Single Battery Systems

Single battery systems are rechargeable sealed battery constructions, which have a service life of three years and in accordance with IEC 598-2-22 have a service life of four years. One battery system may not supply more than two safety light fixtures. Single battery light fixtures must be subjected to a function test every seven days and at least once a year to a continuous operation test. The self-monitoring takes place with LEDs. These indicate the status of the light fixture. The display and results must be entered in a testing log book. The testing log book must then be saved for a period of two years. Every seven days, the status of the light fixtures must be documented. Figure 14.22 illustrates the structure of a safety light fixture.

1. Components
   - Battery (sealed Pb-acid or Ni-Cd batteries)
   - Charging equipment (recharging to 90% in 20 hours)
   - Changeover equipment (standby and/or floated circuit)
   - Rectifier for discharge lamps (single) or electronic control gear
   - Internal displays (battery charge state)
   - External display
   - Monitoring equipment for monitoring light fixtures

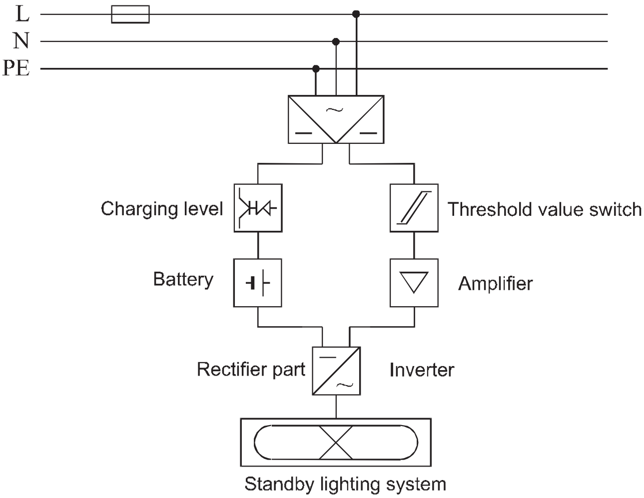


Figure 14.22: Single battery system

2. Technical data
   - Power unrestricted
   - Maximum two light fixtures connected
3. Lines: F30 is not required. No specifications exist for the connection of the power supply units and light fixture connections to a power source.
4. Light fixtures must be distributed over at least two circuits when there is more than one light fixture in the room.

Figure 14.23 depicts a single battery system with floated circuit and backup lighting.

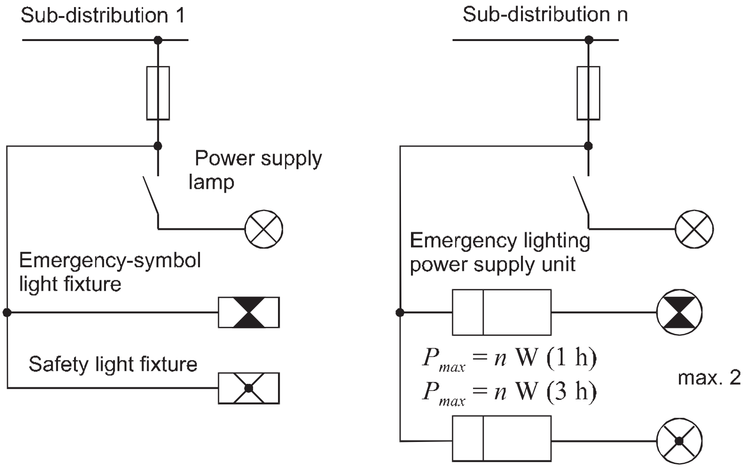


Figure 14.23: Single battery system

Figure 14.24 shows a single battery system with monitoring system for the connection of one or two light fixtures with fluorescent lamps and electronic control gear and low-voltage lamps with electronic transformer. The electronic control gear must be suitable for DC operations.

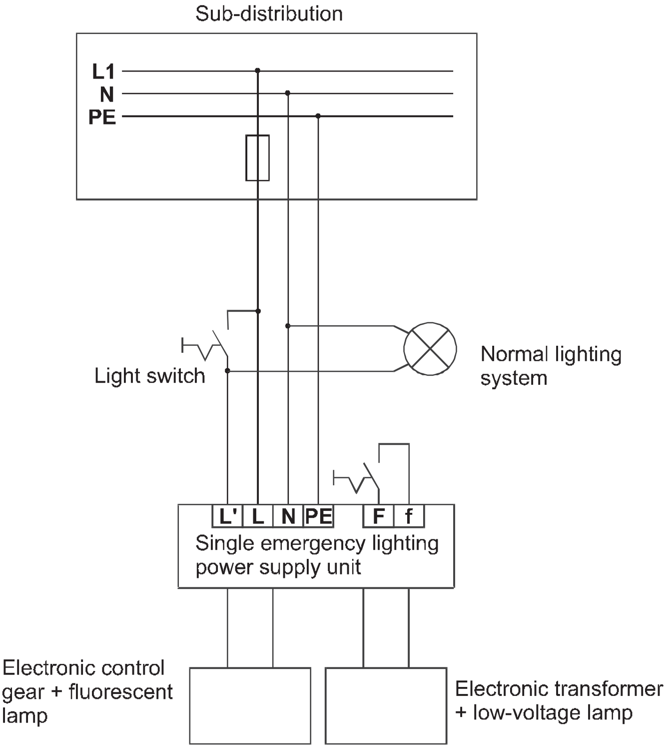


Figure 14.24: Single battery system

Community facilty regulations require regular testing for safety lighting systems, such as daily and weekly function tests with the safety lighting system operating fully and without exception a yearly continuous operation test outside of the normal operating time. With the emergency lighting system, single battery emergency light fixtures and single battery emergency light power supply units can be tested through a bus line. Figures 14.25 and 14.26 illustrate the system design of the test equipment.

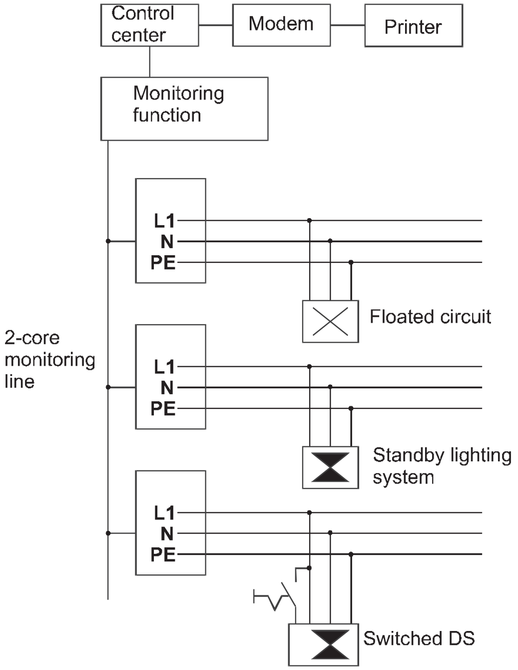


Figure 14.25: Single battery system

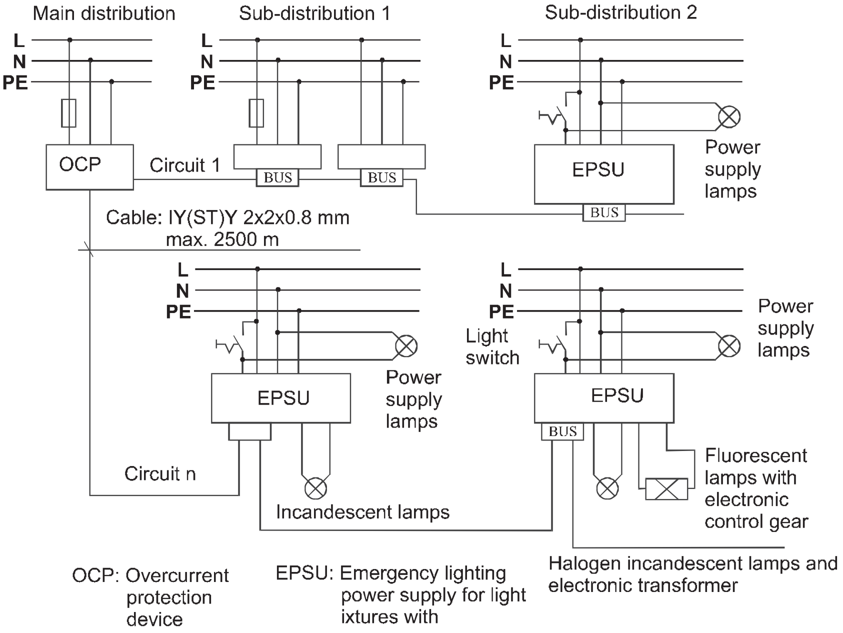


Figure 14.26: Single battery system

Single battery systems can be put to good use for on the order of 10 to 20 units. All single batteries, while they have a high reliability, also have an accumulator which reacts sensitively to high temperatures (i.e. >20 °C). At 30 °C the accumulator has only half its normal useful life and at 40 °C only one fourth its normal useful life.

The meanings of the abbreviations are:

ENLVG	Single emergency lighting power supply unit
ET	Electronic transformer
Ba	Battery
La	Charging level
Gl	Rectifier part
Ve	Amplifier
Schw	Threshold value switch
We	Inverter
SL	Safety lighting system
FC	Floating circuit
SLS	Standby lighting system

14.9.4
Example: Dimensioning of Safety and Standby Lighting

100 light fixtures with 55 W and electronic control gear were installed in a lighting system. Calculate:

he total power of the lighting system:

$$P = U\,I = 100 \cdot 55\,\mathrm{W} = 5.5\,\mathrm{kW}$$

The charging capacity (P_L) of the battery:

$$\begin{aligned} U &= 108 \text{ cells of } 2\,\mathrm{V} \text{ each} = 216\,\mathrm{V} \\ I &= \frac{5500\,\mathrm{W}}{216\,\mathrm{V}} = 25.46\,\mathrm{A} \text{ per hour} \\ P_L &= U\,I \cdot 4 = 2\,\mathrm{V} \cdot 2 \cdot 4 = 16\,\mathrm{W\,h} \text{ per cell} \end{aligned}$$

16 W per cell for 108 cells gives a total of 1728 W. For power levels ≤ 3 kW, no forced ventilation is required.

The battery space:

We can calculate the ventilation of the battery space as follows:

$$Q = 0.05\,n\,I = 0.05 \cdot 108 \cdot 2\,\mathrm{A} = 10.8\,\mathrm{m}^3\,\mathrm{h}$$

Air intake and exhaust air opening:

$$A \geq 28\,Q$$

$$A \geq 28\ \cdot 10.8\ \mathrm{m}^3/\mathrm{h} = 302.4\ \mathrm{m}^3/\mathrm{h}$$

When the room is smaller than 28^3 the openings can be on the same side.

15
Compensation for Reactive Power

15.1
Terms and Definitions

- Reactive power: Power required to build up the electromagnetic fields. It cannot be converted into useful energy.
- VAr controller: Measures the reactive power which arises and gives switching commands to the contactors, which switch capacitors on or off as required.
- Power factor: Ratio of effective power to apparent power.
- Compensation: Through compensation the economy of operation of electrical systems, i.e. the power factor, is improved. This relieves the electrical operational equipment, so that a greater effective power can be transmitted.
- Individual compensation: A capacitor is connected directly to the terminals of the load and switched together with this (e.g. a motor).
- Group compensation: The compensation equipment (controller unit) is connected to the load (e.g. a motor group or fluorescent lamp group).
- Central compensation: The compensation equipment (controller unit) is installed centrally for all loads.
- Permanent compensation: One or more capacitors are connected to a load.
- Harmonic: Oscillation at a whole-number multiple of the basic frequency of oscillation.
- Filter circuits: Series resonance circuits consisting of chokes and capacitors, tuned to the frequencies of the harmonic currents.

Reactive current arises in every electrical system. Not only large loads, but smaller loads as well require reactive power. Generators and motors produce reactive power, which causes unnecessary burdens to and power losses in the lines. Figure 15.1 shows the block diagram for the network loading.

Reactive power is necessary to generate magnetic fields, e.g. in motors, transformers and generators. This power oscillates between the source and the load and represents an additional loading. Power supply companies and the consumers of this electrical energy are interested in reducing these disadvantages as well as possible. On the other hand, non-linear loads and phase-controlled inverters cause harmonics, which lead to voltage changes and a decrease in the power factor. In order to reduce these harmonics, series resonant (filter) circuits are used.

Analysis and Design of Low-Voltage Power Systems. Ismail Kasikci

ISBN: 3-527-30483-5

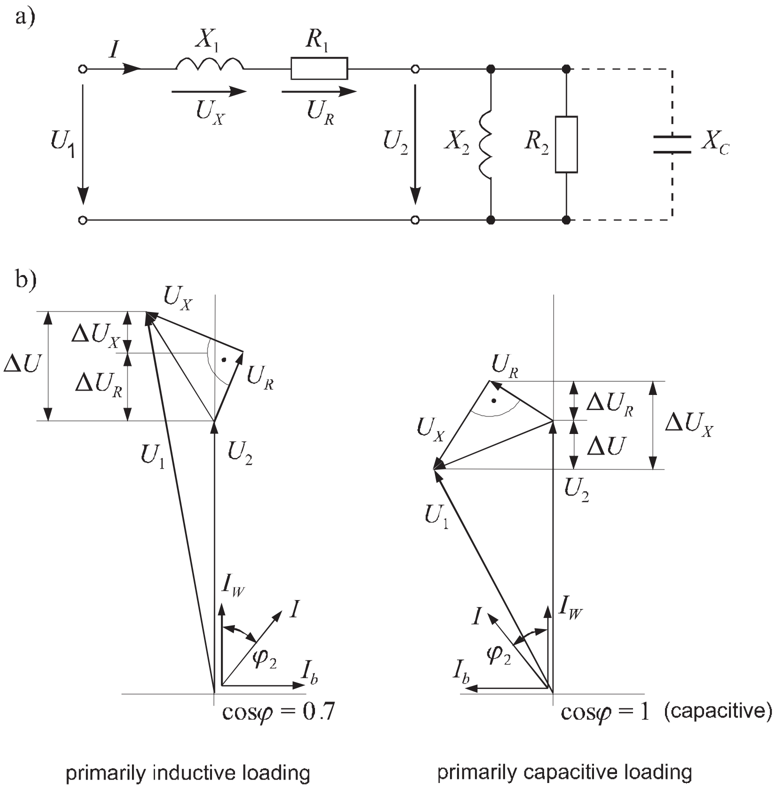


Figure 15.1: Equivalent circuit diagram of a network with different loading; a) Equivalent circuit, b) phasor diagram

For resistive, inductive and capacitive loads, the power factor $\cos\varphi$ is different because the relationships between the voltage and current are different. Figure 15.2 shows the different phase relations for resistive, inductive and capacitive loads.

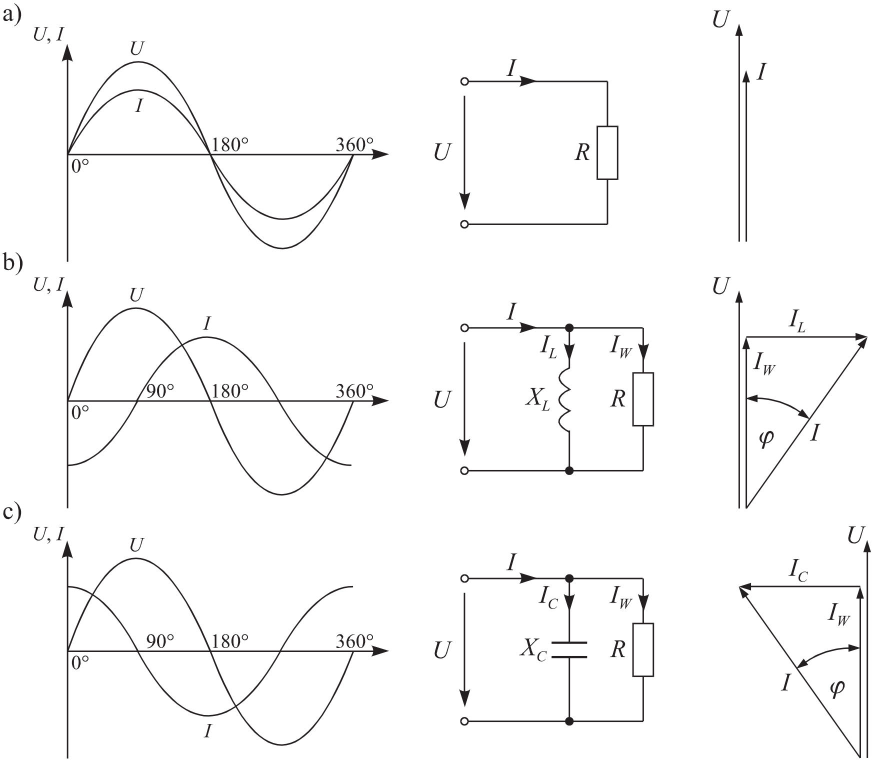


Figure 15.2: Relation between current, voltage, and power for a) a resistive load, b) an inductive load, c) a capacitive load

Figure 15.3 illustrates current and power triangles and Figure 15.4 power triangles with compensation.

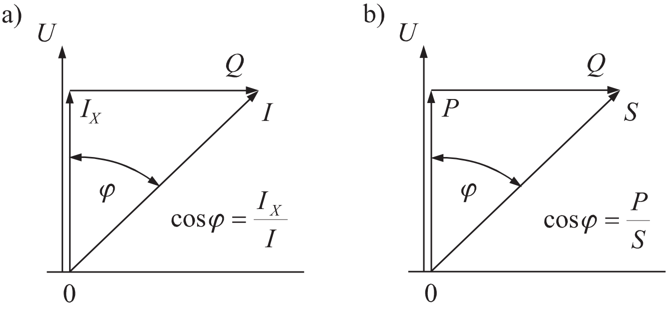
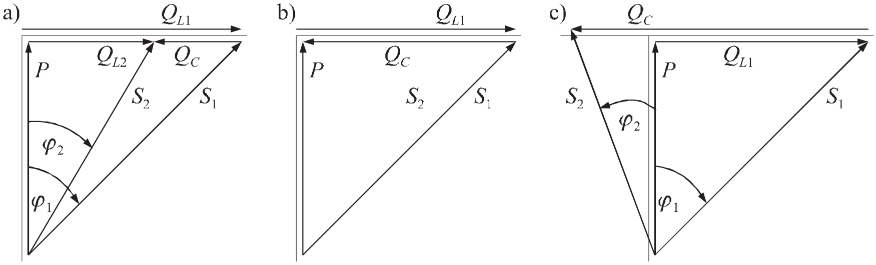


Figure 15.3: Current and power phasors in networks; a) Current triangle, b) power triangle



Index 1: Values without compensation, Index 2: Values with compensation

Figure 15.4: Power triangle with compensation; a) Partial compensation, b) Full compensation, c) Overcompensation

The apparent power absorbed in an electrical network is:

$$S = U\,I \qquad \text{or} \qquad S = \sqrt{3}\,U\,I \qquad [\text{VA}] \tag{15.1}$$

The effective power is:

$$P = U\,I\cos\varphi \qquad \text{or} \qquad P = \sqrt{3}\,U\,I\cos\varphi \qquad [\text{W}] \tag{15.2}$$

The reactive power is:

$$Q = \sqrt{S^2 - P^2} \qquad [\text{kvar}] \tag{15.3}$$

The reactances are:

$$X_L = \omega\,L \qquad \text{and} \qquad X_C = \frac{1}{\omega\,C} \tag{15.4}$$

the power factor is:

$$\cos\varphi = \frac{P}{S} \tag{15.5}$$

The effective current is:

$$I_w = I_n\cos\varphi \tag{15.6}$$

The reactive current is:

$$I_b = I_n\sin\varphi \tag{15.7}$$

15.2
Effect of Reactive Power

In electrical networks, voltage drops occur due to loading of the internal resistances of the network.

$$\Delta U = \sqrt{3} I_b \, l \, (R_L' \cos\varphi + X_L' \sin\varphi) \tag{15.8}$$

$$\Delta u = \frac{\Delta U}{U_n} \cdot 100\,\% \tag{15.9}$$

The voltage drop can be calculated from the power as follows:

$$\Delta u = \frac{S}{S_k'' \sqrt{1+(\frac{R}{X})^2}} \left(\frac{R}{X} \cos\varphi + \sin\varphi \right) \cdot 100\,\% \tag{15.10}$$

Neglecting the resistive part, then:
If

$$Q = S \sin\varphi \tag{15.11}$$

then

$$\Delta u = \frac{Q}{S_k} \cdot 100\,\% \tag{15.12}$$

15.3
Compensation for Transformers

Transformers are designed according to the reactive power absorption and not the maximum required reactive power. Usually standard values can be taken from tables, irrespective of the power and the rated voltage. It is also possible to calculate the reactive power of transformers from the following relationship:

$$Q_T \approx S_0 = \frac{I_0}{100} \, S_{rT} \tag{15.13}$$

The meanings of the symbols are:

Q_T	Transformer no-load reactive power in kvar
I_0	No-load current in A
S_{rT}	Rated power of transformer
S_0	Transformer no-load apparent power in kVA

15.4
Compensation for Asynchronous Motors

In practice, the capacitor power is at maximum 90 % of the motor power with no load, so that no dangerous self-excitation can occur. The maximum permissible capacitor power is then given by:

$$Q_C = 0.9\,\sqrt{3}\,I_0\,U_n\,\sin\varphi_0 \cdot 10^{-3}\ \text{kvar} \tag{15.14}$$

Under no-load conditions, with $\sin\varphi_0 \approx 1$, we obtain:

$$Q_C = 0.9\,\sqrt{3}\,I_0\,U_n \cdot 10^{-3}\ \text{kvar} \tag{15.15}$$

Usually, the motor power and $\cos\varphi$ are known, and the no-load current cannot be measured. In this case, the calculation is based on the motor power P_{rM}:

- up to 40 kW, 40 % of the rated motor power
- above 40 kW, 35 % of the rated motor power

$$Q_C = \frac{P_{rM}}{\eta}(\tan\varphi_1 - \tan\varphi_2) \tag{15.16}$$

The meanings of the symbols are:

η	Efficiency of motor
I_0	No-load current in A
0.9	Factor for required no-load reactive power

15.5
Compensation for Discharge Lamps

Modern lighting systems are normally operated with inductive control gear, for which the power factor is between 0.3 and 0.6. By comparison, with electronic control gear the power factor is 0.95. Single-phase or three-phase group compensation for discharge lamps is also possible. For the uniform distribution of light fixture groups over the individual phases, only one third of the capacitor power is required, which is calculated from:

$$Q_C = (P_L + P_v)(\tan\varphi_1 - \tan\varphi_2) \tag{15.17}$$

The required capacity of the condenser is then:

$$C = \frac{Q_C}{2\,\pi f_n\,U^2} \tag{15.18}$$

$$C_{str} = \frac{Q_C}{3\,U_n^2\,2\,\pi f_n} \tag{15.19}$$

Here, the meanings of the symbols are:

P_L	Lamp power
P_v	Power loss of control gear
C_{str}	Capacity of winding phase
f_n	Network frequency

15.6
c/k Value

The c/k value defines the magnitude of the required reactive power which must be present before a connection or shut-off takes place. In practice, this response threshold is set to about 60 % of the smallest step. The c/k value is calculated from:

$$c/k = (0.6 \cdots 0.8) \frac{C}{\sqrt{3}\, U_n\, k} \tag{15.20}$$

Here, the meanings of the symbols are:

c	Smallest power step
C	Capacitor power in var
U_n	Voltage of external line in V
k	Transformation ratio of transformer (e.g. 100 A/5 A)

15.7
Resonant Circuits

Resonant circuits are undesirable phenomena in networks. A series resonant circuit (Figure 15.5) consists of an inductance L and a capacitance C. Since the effective resistance is small relative to L and C, it can be neglected. At low frequencies, the reactance of the capacitor predominates, i.e. the series resonant circuit is capacitive. Above the resonance frequency f_r, the series resonant circuit behaves inductively. Figure 15.6 shows the behavior of the impedance, current and voltage.

A parallel resonant circuit consists of an inductance, on the one hand, and a capacitance and resistance, on the other hand, in parallel (Figure 15.7). Here, the behavior is the opposite of that for the series resonant circuit (Figure 15.8).

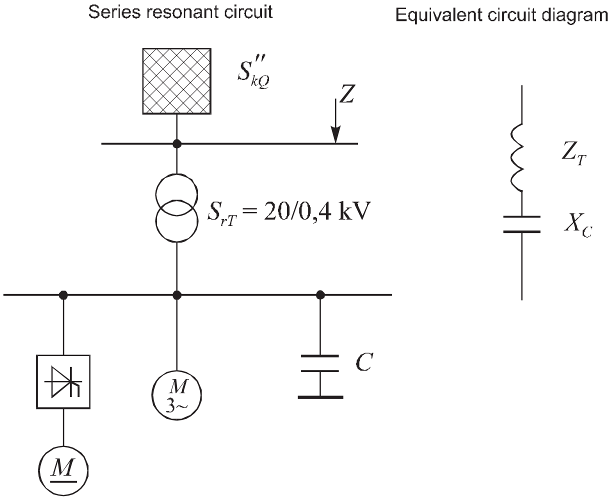


Figure 15.5: Series resonant circuit and equvalent circuit diagramm

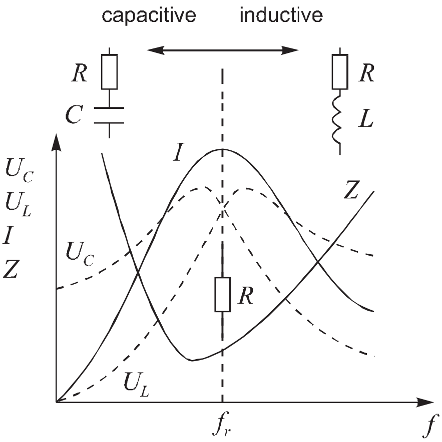


Figure 15.6: Resonance curve for a series resonant circuit

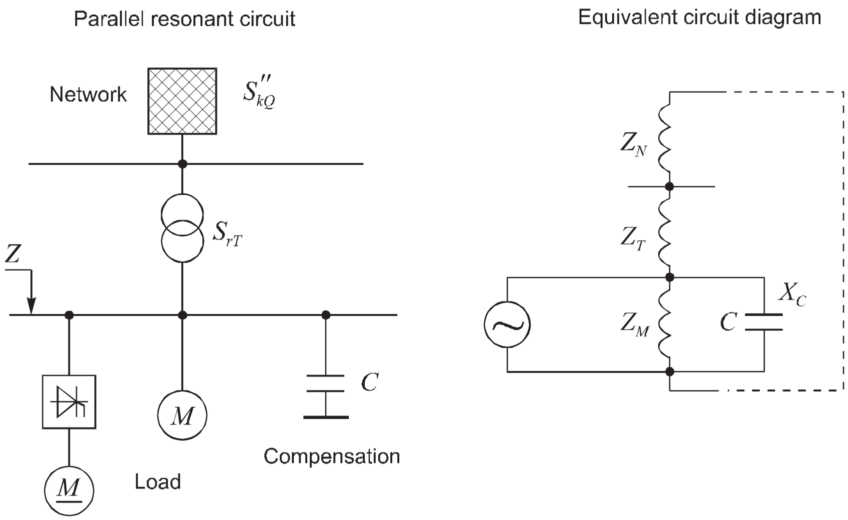


Figure 15.7: Parallel resonant circuit

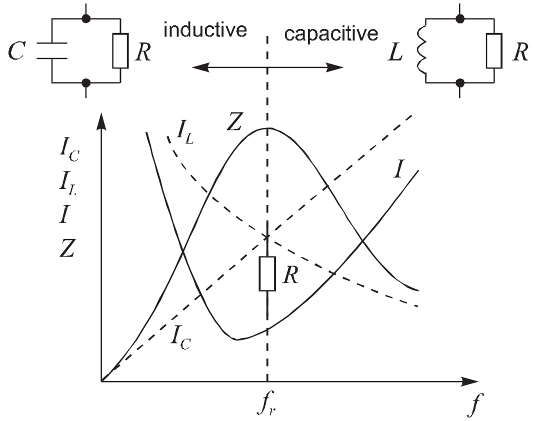


Figure 15.8: Resonance curve for a parallel resonant circuit

15.8
Harmonics and Voltage Quality

The supply system is 230/400V, 50 Hz and has sine-wave form current and voltage curves. Non-linear loads produce undesirable harmonics (Figure 15.9 illustrates the principle), which flow directly into the network and thus give rise to the following problems:

1. Asymmetry
2. Meter errors
3. Power cable errors
4. Voltage distortions
5. Series and parallel resonances
6. Decrease in the power factor
7. Temperature rise and overloading of transformers
8. Communication errors
9. Reduction of motor powers

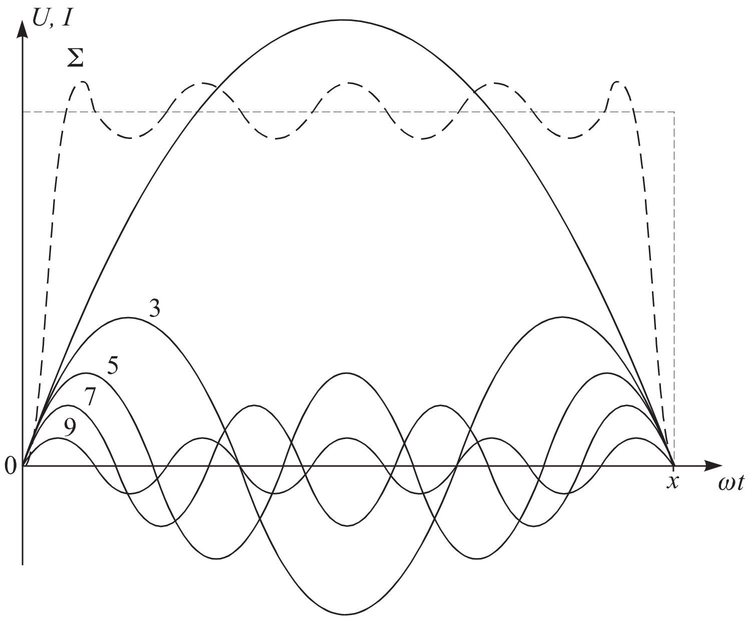


Figure 15.9: Harmonics

15.8.1
Compensation With Non-Choked Capacitors

Capacitors combine with the reactance of the transformer to form a resonant circuit (Figure 15.10). Figure 15.11 shows the impedance curve for the network, as seen by the consumer generating the harmonics.

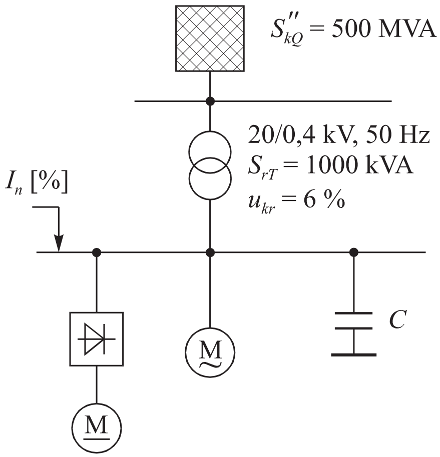


Figure 15.10: Non-choked compensation system

The capacitor power for a given harmonic order ν is found from the relationship:

$$Q_C \leq \frac{S_{rT} 100}{\nu^2 \, u_k} \tag{15.21}$$

This corresponds to a frequency:

$$f_r = fn \sqrt{\frac{S_{rT} \, 100}{Q_C \, u_k}} \tag{15.22}$$

In order to prevent resonances, the installed reactive power must be less than the calculated (critical) reactive power. In general, no overcurrents occur in networks with non-linear loads amounting to less than 20 % of the total load.

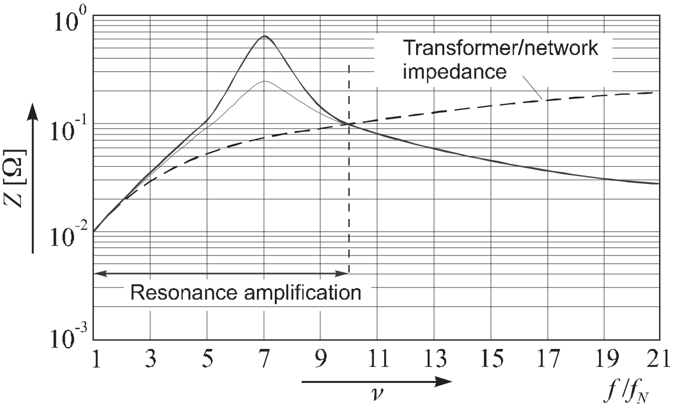


Figure 15.11: Impedance characteristic of a non-choked network

15.8.2
Inductor-Capacitor Units

With a choked system the capacitor and the choke coil are in series (Figure 15.12). Figure 15.13 shows the impedance curve for such a network.

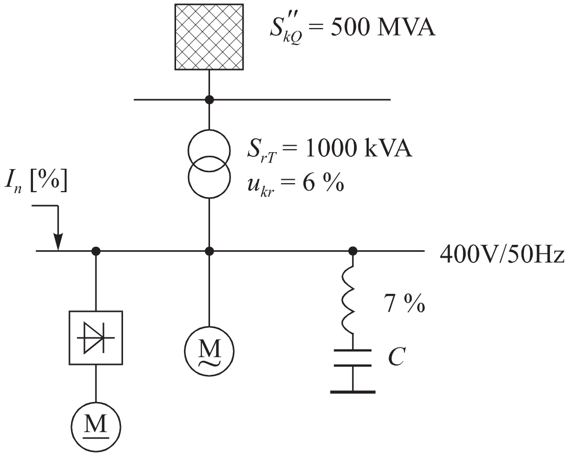


Figure 15.12: Compensation system with 7 % choking

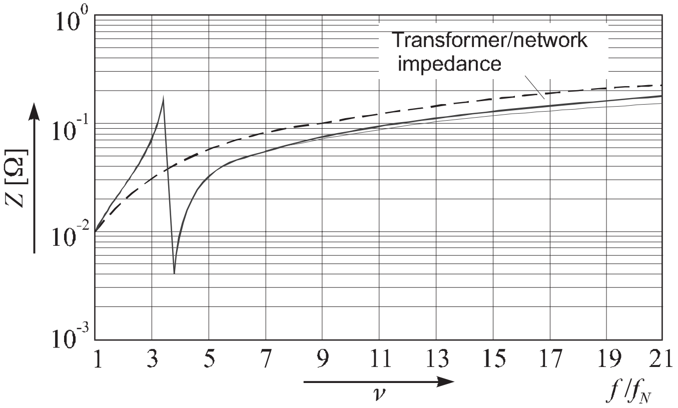


Figure 15.13: Impedance characteristic of a choked network

When the non-linear components constitute more than 20 % of the total load, critical overcurrents arise. The choking factor can be calculated by summing the powers of the harmonic components and dividing by the nominal power of the transformer, i.e.:

$$V_{PV} = \frac{\sum S_H}{S_{rT}} \tag{15.23}$$

When the capacitor and choke coil are properly matched, the resonance frequency lies below the frequencies of critical harmonic currents.

With the use of choke coils, it is necessary to take the voltage increase of the capacitor into account. Increasing the dielectric strength prolongs the useful life. The increase in the voltage and the capacitor power can be calculated as follows:

$$U_C = \frac{U_n}{1-p} \tag{15.24}$$

$$Q_C = \frac{Q_{Cn}}{1-p} \tag{15.25}$$

The choking factor p in % gives the ratio of the choked reactance to the capacitive reactance at the network frequency:

$$f_r = f_n \frac{1}{\sqrt{p}} \tag{15.26}$$

The relative resonance frequency is:

$$n_r = \frac{f_r}{f_n} \tag{15.27}$$

$$p = \frac{1}{n_r^2} \tag{15.28}$$

The choking factor is also a measure for the suppression of harmonics, i.e. the smaller the value of p the more effective is the filtering.

15.8.3
Series Resonant Filter Circuits

In order to prevent resonance phenomena, choke coils are placed upstream of the capacitors (choking). Filter circuits are tuned exactly to the frequencies of the harmonic currents and therefore suppress up to 90% of these currents. In general it can be said that the filter circuits serve not only for the compensation of reactive power loads, but also for the suppression of harmonic currents. Figure 15.14 schematically illustrates the principle of filter circuits.

Figure 15.15 gives the impedance characteristic of a network with load attenuation.

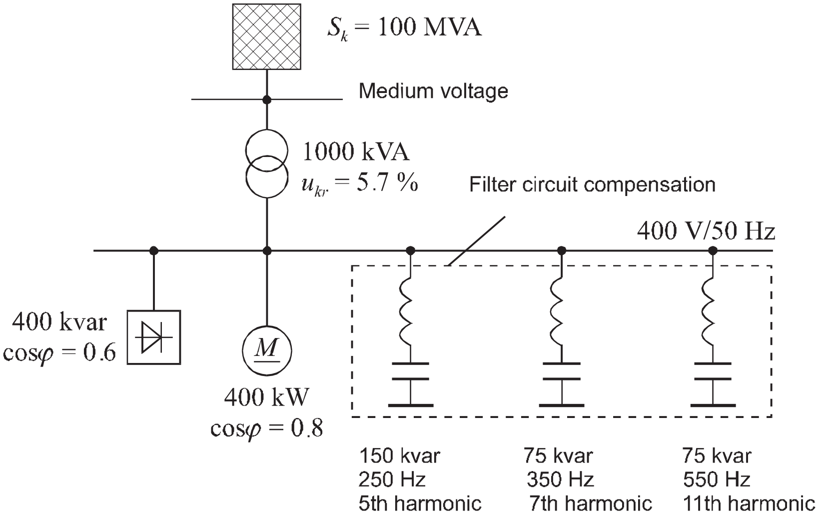


Figure 15.14: Series resonant filter circiuts

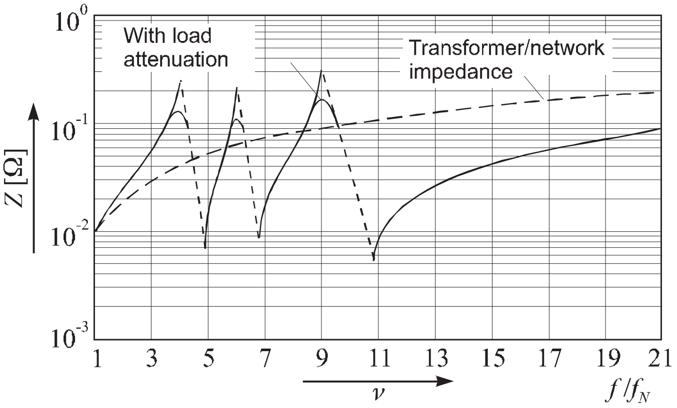
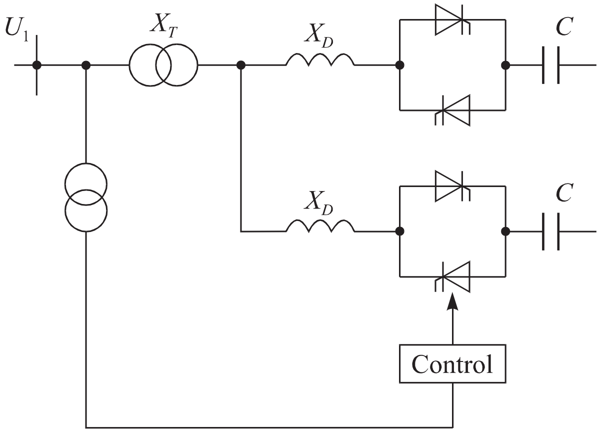


Figure 15.15: Frequency-impedance characteristic

15.9
Static Compensation for Reactive Power

Reactive power can be controlled quickly and precisely with power electronics components. Continuous control and the improved stability of networks are possible []. This section provides a brief description of the equipment used in electrical systems for reactive power compensation.

1. Inductances Inductances are in parallel with the networks in order to absorb the reactive power. They are connected to the tertiary winding of a transformer, e.g. to 12 kV, or directly to the busbar of a generator.
2. Capacitances Capacitances are connected either as a permanent capacitor or as a capacitor bank to the network in order to reduce the reactive power. The economic solution is voltage-controlled reactive power compensation with improved power factor.
3. Thyristor-controlled static compensation These static compensators are reactive power units connected in parallel, in which the thyristor control generates or absorbs reactive power.
4. Thyristor-switched capacitances Figure 15.16 schematically illustrates the principle of these capacitances. The capacitance C is switched on and off by the thyristor. The inductance L limits the current rise through the thyristors and causes resonances within the system.



15.16: Thyristor-switched capacitances

Properties of these systems are:
- High costs
- No transients
- Stepped control
- Avoidance of or generation of compensating harmonics
- Very low losses at the output of the compensator.

5. Thyristor-controlled inductances
Figure 15.17 schematically shows the principle of this method of compensation.

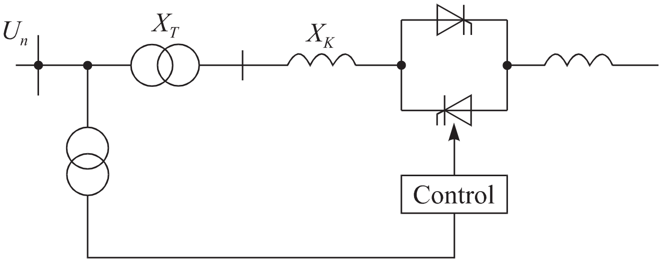


Figure 15.17: Thyristor-controlled inductances

Properties of these systems are:

- High costs
- Generation of compensating harmonics
- Continuous control
- Continuously applied voltage
- Losses at the output of the compensator.

6. Capacitances in series Capacitances connected in series are well suited to reactance compensation, but not to reactive power compensation. However, they of course also affect reactive power compensation for transmitted power. Figure 15.18 illustrates this principle. The reactive power generated in these capacitances increases with the power transmitted. The reactive power is between 100 and 800 Mvar. The greatest problem is protecting the capacitances from fault currents.

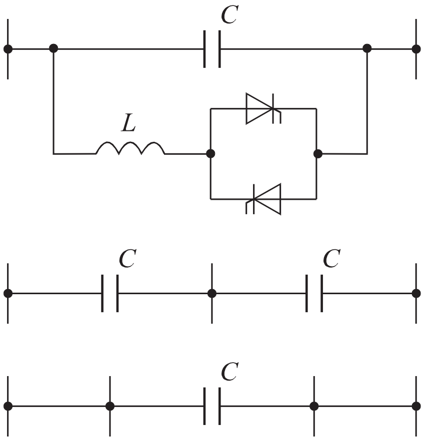


Figure 15.18: Capacitances in series

Planning of compensation systems

For the planning and configuration of compensation systems it is necessary to distinguish between existing and new electrical systems. The actual state of existing networks must be determined by measurements at the substation and on the primary loads. Possible methods are e.g. bills from the power supply company, meter readings, effective and reactive power recorders and harmonic current analysis. Following the analysis of the measured values and the ambient influences, the type of compensation can be decided.

For new systems, it is necessary to work partly with estimated data. Concurrence, utilization factor and extensions of electrical operational equipment must all be considered. It is recommended that the system be dimensioned with a relatively low compensation power and that the correct power level of the capacitors be determined following installation of the system. The calculation and arrangement of a reactive power compensation system can be done best with the use of computer simulations [73].

15.10
Examples of Compensation for Reactive Power

15.10.1
Example 1: Determination of Capacitive Power

A load has an effective power of $P = 50\,\mathrm{kW}$ at 400 V and the power factor is to be compensated from $\cos\varphi_1 = 0.75$ to $\cos\varphi_2 = 0.95$. Determine the required capacitive power. The power and current before compensation are:

$$\begin{aligned} S_1 &= \frac{P_1}{\cos\varphi_1} = \frac{50\,\mathrm{kW}}{0.75} = 66.66\ \mathrm{kVA} \\ &= \frac{S_1}{\sqrt{3}\,U} = \frac{66.66\,\mathrm{kVA}}{\sqrt{3}\cdot 400} = 96.22\,\mathrm{A} \end{aligned}$$

The power and current after compensation are:

$$\begin{aligned} S_2 &= \frac{P_1}{\cos\varphi_2} = \frac{50\,\mathrm{kW}}{0.95} = 52.63\,\mathrm{kVA} \\ &= \frac{S_2}{\sqrt{3}\,U} = \frac{52.63\,\mathrm{kVA}}{\sqrt{3}\cdot 400} = 76\,\mathrm{A} \end{aligned}$$

The required capacitive power is:

$$\begin{aligned} Q_C &= P\,(\tan\varphi_1 - \tan\varphi_2) \\ &= 50\,\mathrm{kW}\,(0.88 - 0.32) = 28\,\mathrm{kvar} \end{aligned}$$

15.10.2
Example 2: Capacitive Power With *k* Factor

The capacitive power can be determined with the factor k for a given effective power. The k factor is read from a table [72] and multiplied by the effective power. The result is the required capacitive power.

For an increase in the power factor from $\cos\varphi = 0.75$ to $\cos\varphi = 0.95$, from the table [72] we find a factor $k = 0.55$:

$$Q_C = P\,k = 50\,\mathrm{kW}\cdot 0.55 = 27.5\,\mathrm{kvar}$$

15.10.3
Example 3: Determination of Cable Cross-Section

A three-phase power of 250 kW, with $U_n = 400\,\mathrm{V}$, at 50 Hz is to be transmitted over a cable 80 m in length. The voltage drop must not exceed $4\,\% \mathrel{\hat{=}} 16\,\mathrm{V}$. The power factor is to be increased from $\cos\phi = 0.7$ to $\cos\phi = 0.95$.

What is the required cable cross-section?

$$P = \sqrt{3}\,U\,I\cos\varphi$$

The current consumption before compensation is:

$$I = \frac{P}{\sqrt{3}\,U\cos\varphi} = \frac{250\,\mathrm{kW}}{\sqrt{3}\cdot 400\cdot 0.7} = 515.5\,\mathrm{A}$$

The current consumption after compensation is:

$$I = \frac{P}{\sqrt{3}\,U\cos\varphi} = \frac{250\,\mathrm{kW}}{\sqrt{3}\cdot 400\cdot 0.95} = 379.8\,\mathrm{A}$$

The effective resistance per unit length for 516 A is:

$$\begin{aligned}(R'_L\cos\varphi + X'_L\sin\varphi) &= \frac{\Delta U}{\sqrt{3}\,I\,l}\\ &= \frac{16\,\mathrm{V}}{\sqrt{3}\cdot 515.5\,\mathrm{A}\cdot 0.08\,\mathrm{km}}\\ &= 0.224\,\Omega/\mathrm{km}\end{aligned}$$

According to Table 13.4 we must choose a cable with a cross-section of 4×95^2.

The effective resistance per unit length for 380 A is:

$$
\begin{aligned}
(R_L' \cos\varphi + X_L' \sin\varphi) &= \frac{\Delta U}{\sqrt{3}\, I\, l} \\
&= \frac{16\,\mathrm{V}}{\sqrt{3}\cdot 380\,\mathrm{A}\cdot 0.08\,\mathrm{km}} \\
&= 0.304\,\Omega/\mathrm{km}
\end{aligned}
$$

Here, a cable cross-section of $4 \times 70\,\mathrm{mm}^2$ is required.

As this example illustrates, the improved power factor leads to lower costs because of the reduced cross-section.

15.10.4
Example 4: Calculation of the *c/k* Value

Given a 150 condenser battery, i.e. 5 stages of 30 each, a supply voltage of 400 V, and an instrument transformer with a k of 500 A/5 A, how large is the c/k value?

The ratio c/k is given by:

$$
c/k = 0.65\frac{C}{\sqrt{3}\, U_n\, k} = 0.65\,\frac{30\,\mathrm{kvar}}{\sqrt{3}\cdot 400\,\mathrm{V}\cdot \frac{500\,\mathrm{A}}{5\,A}} = 0.281\,Ar
$$

The controller is set to 0.3.

16
Lightning Protection Systems

IEC 62305

IEC 62305 considers new technical knowledge and is based on the current state of technology. Its use is for the planning and installation of lightning protection systems up to 60 m high and offers safe protection of buildings.

This draft standard provides information about the following areas:

- Lightning protection classes
- Specifications for exterior lightning protection
- Specifications for ground electrodes
- Exposure distance determination
- Equipotential lightning protection bonding

For the installation, planning, extension and modification of lightning protection systems IEC 62305 apply. In the applicable building ordinances there is information about the need for lightning protection in buildings. Lightning protection is necessary for buildings which lightning can easily enter and cause severe damage. Such buildings include e.g. schools, churches, apartment buildings, administrative buildings, hospitals, railroad stations, telecommunications towers, banks, airports, sport arenas, museums, explosion hazard areas, kindergartens, commercial buildings and high-rise buildings.

Lightning protection systems include

1. Exterior lightning protection
2. Interior lightning protection
3. Overvoltage protection of electronic equipment.

HD 637 S1 Grounding Systems in AC Systems above 1 V and IEC 60 364, Parts 20 and 54 Heavy Current Systems up to 1 V provide comprehensive explanations and terms for grounding systems. Figure 16.1 explains the terms necessary for understanding.

Analysis and Design of Low-Voltage Power Systems. Ismail Kasikci

ISBN: 3-527-30483-5

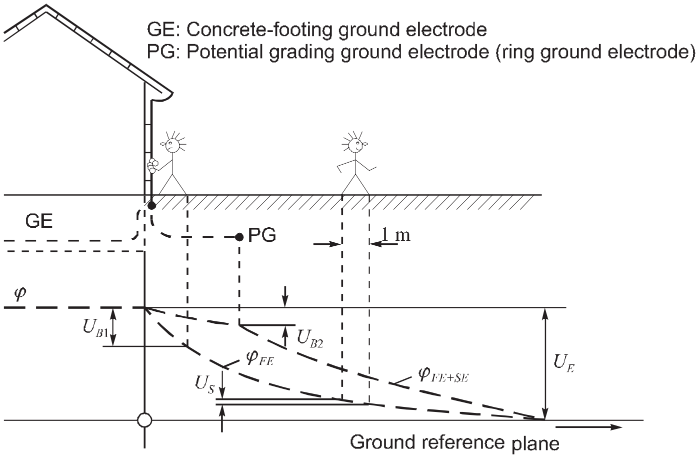


Figure 16.1: Ground-to-electrode potential and voltages for grounding electrodes with current flow [80]

Here, the meanings of the symbols are:

U_S	Step voltage
φ	Ground-to-electrode potential
FE	Concrete-footing ground electrode
SE	Potential grading ground electrode (ring ground electrode)
x	Distance to concrete-footing ground electrode
U_E	Ground potential rise
U_B	Touch voltage
U_{B1}	Touch voltage without potential grading ground electrode (on concrete-footing ground electrode)
U_{B2}	Touch voltage without potential grading ground electrode (on concrete-footing ground electrode and potential grading ground electrode)

- Ground resistance:
  In accordance with HD 637 S1 the ground resistance is the resistance of the grounding system between the grounding electrode and the ground reference plane.
- Touch voltage:
  The touch voltage is a part of the ground potential rise which can be shunted out through the human body.
- Ground reference plane:
  The ground reference plane is the part of ground, in particular the area outside the range of influence of a ground electrode or a grounding system, in which no measurable voltages occur between any two points as a result of the grounding current.
- Ground termination network:
  Grounding for leading the lightning discharge current to ground.

- Ground:
  Ground is the conductive soil.
- Ground potential rise:
  The ground potential rise is voltage occurring between a grounding system and the ground reference plane.
- Soil resistivity:
  The resistivity of the ground in Ωm.
- Potential grading ground electrode:
  The potential grading ground electrode is a grounding electrode which, due to its shape and arrangement, serves for controlling the potential.
- Step voltage:
  The step voltage is the part of the ground potential rise which can be shunted out in a one meter long section, such that the current flows through the human body from foot to foot.

16.1
Lightning Protection Class

In order to be able to plan a lightning protection system it is first necessary to determine the protection class for the building in planning. Lightning protection classes I to IV are assigned according to different values of the efficiency of the lightning protection system, the mesh size and the lightning sphere size (Table 16.1)). For each protection class, we can determine the shielding angle of a building according to the height of the air terminal above the ground (Figure 16.2). For the determination of the position of the air terminal, in general three methods are used:

1. The shielding angle method (α) for simple shapes
2. The lightning sphere method (radius r) for complicated cases
3. The mesh method (w) for flat surfaces.

Table 16.1: Characteristic of the lightning protection classes

Lightning protection class	Radius of sphere m	Mesh size m	Efficiency %
I	20	5 × 5	98
II	30	10 × 10	95
III	45	15 × 15	90
IV	60	20 × 20	80

Examples for protection classes [74]:

Class I	Biological and nuclear installations
Class II	Telecommunications towers, cathedrals, industrial facilities
Class III	Apartment buildings, yards, schools, theaters, banks
Class IV	Weather-protected structures, refuge shelters

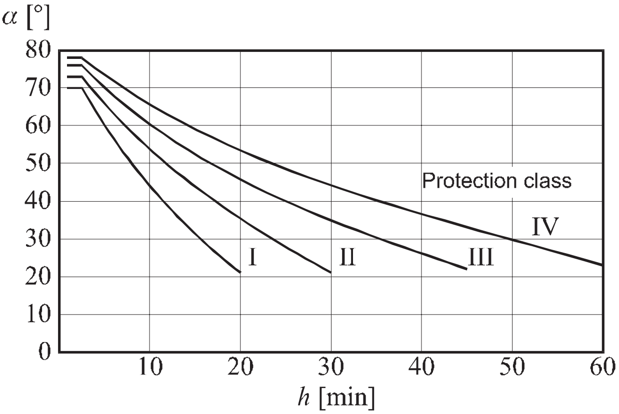


Figure 16.2: Shielding angle [80] [80]

16.2
Exterior Lightning Protection

Exterior lightning protection includes all equipment for collecting and leading off lightning discharge current to the grounding system (Figure 16.3).

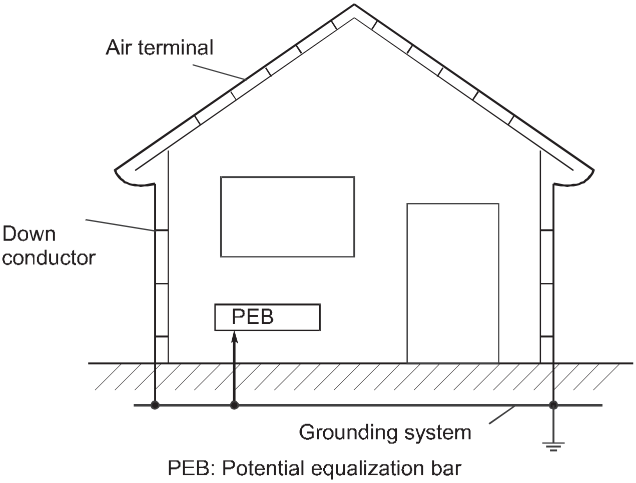


Figure 16.3 Exterior lightning protection

16.2.1
Air Terminal

The air terminal (Figure 16.4) serves as the striking point for lightning. The mesh size of the air terminals is 10 m × 20 m maximum for normal buildings, and 10 m × 10 m for hospitals. The mesh must be installed so that no point on the surface of the roof is more then five meters from an air terminal conductor (Figure 16.5). The height of the lightning rod may not be more than 20 m, and the distance from the building must be at least 2 m (Figure 16.6). The building is regarded as protected when the angle is 45°. The area protected by the lightning rods is shown for H < 30 m in Figure 16.7 and for H > 30 m in Figure 16.8. The roof superstructures, of electrically non-conductive material, may not be longer than 0.3 m (Figure 16.9)). A roof ventilation system may not be attached without being first included in the lightning protection concept. If the roof ventilation system is protected by a lightning rod, then the distance between the ventilation system and the lightning rod must be determined in accordance with Figure 16.10.

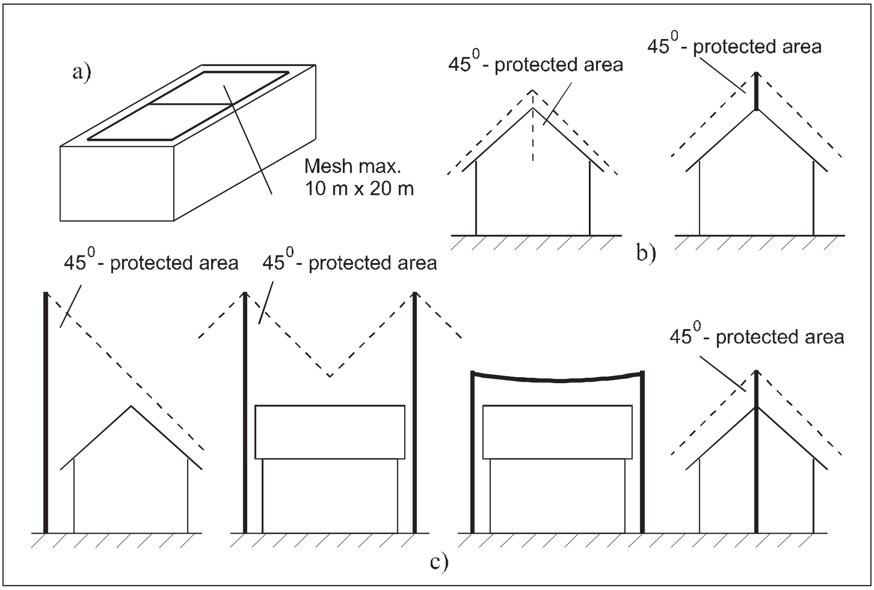


Figure 16.4: Air terminals [79]

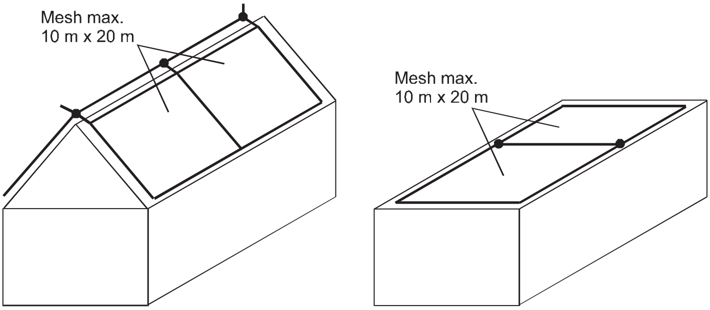


Figure 16.5: Air terminal – mesh [79]

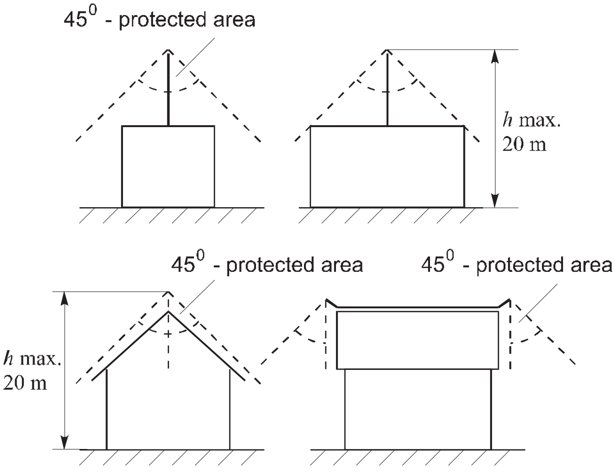


Figure 16.6: Air terminal with protected area [79]

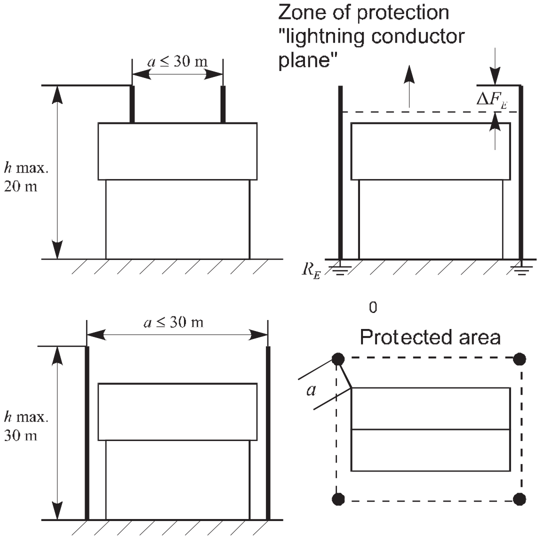


Figure 16.7: Air terminal – lightning rod with protected area up to max. 30 m [79]

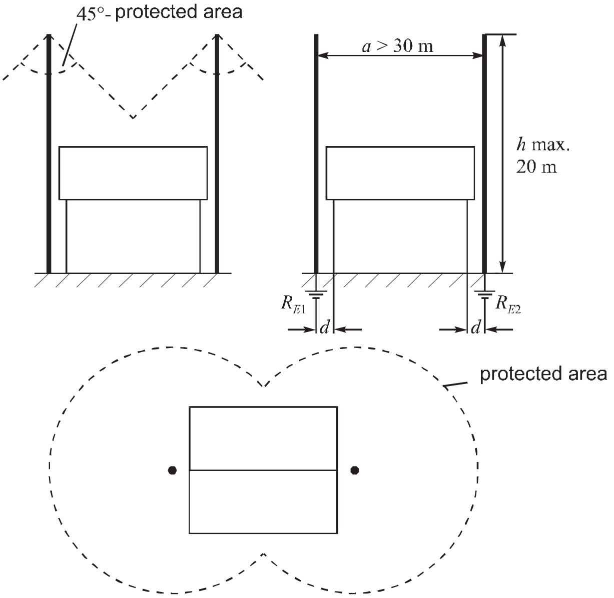
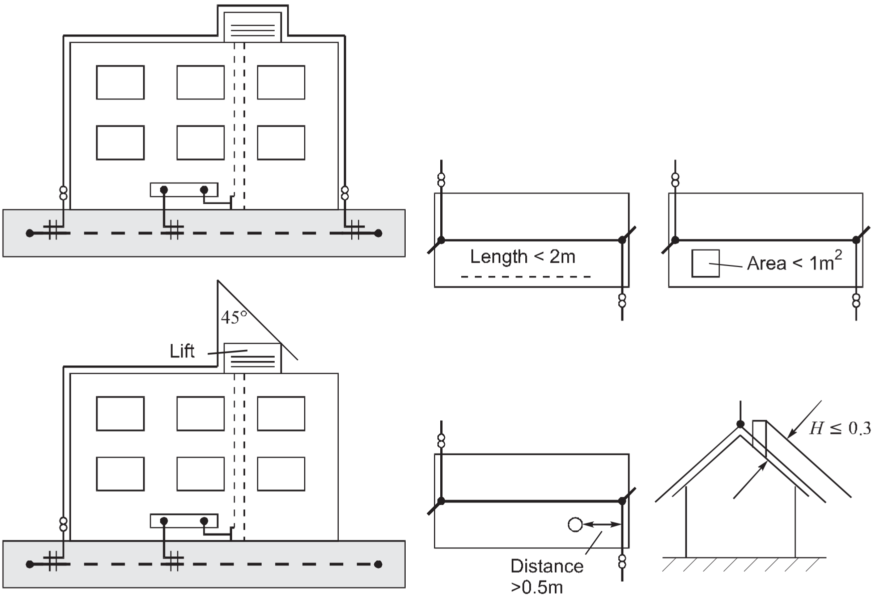


Figure 16.8: Air terminal – lightning rod with protected area greater than 30 m [79]



With connection to grounding system

Without connection to grounding system

Figure 16.9: Air terminal – roof superstructures of electrically conductive material [79]

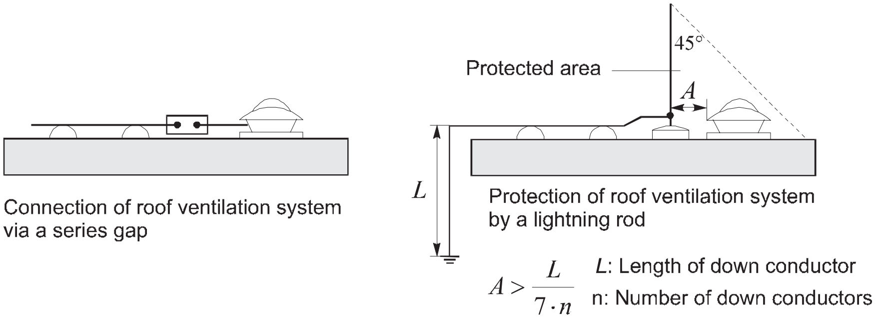
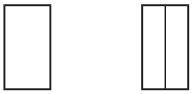
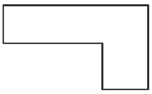
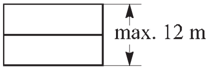


Figure 16.10: Air terminal for smaller roof superstructures [79]

16.2.2
Down Conductors

The down conductor (Table 16.2) connects the air terminal to the grounding system. For every 20 m, measured along the edges of the roof, a down conductor must be installed, outwards from the corners of the building. Through the air terminal, a zone of protection with a shielding angle of 45° is then formed.

Table 16.2: Down conductors [79]

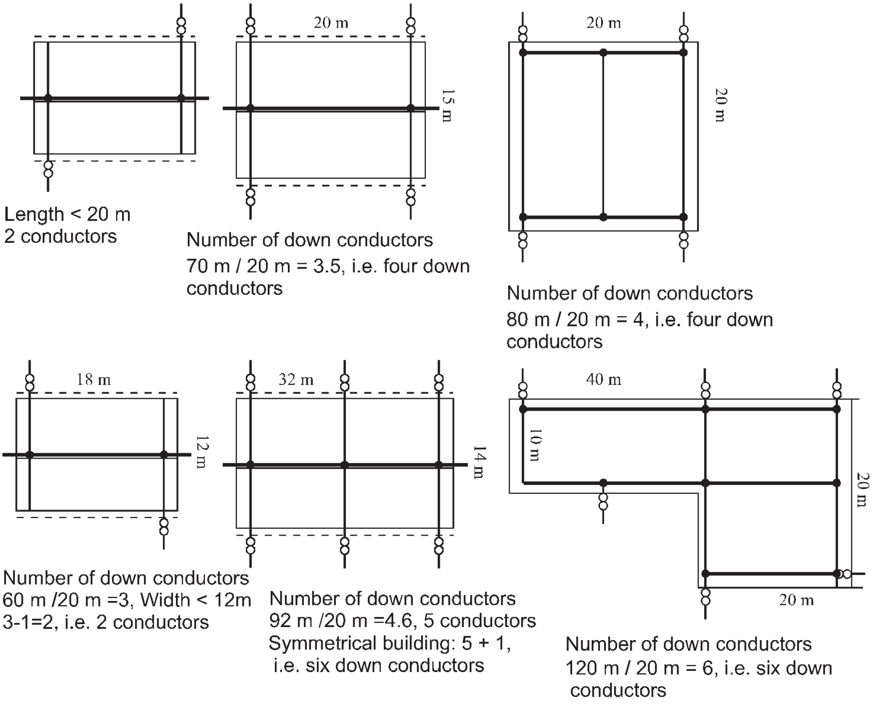
Length of outer roof edges	Number of down conductors		
	Symmetrical building	Unsymmetrical building	Ridged roof up to max. 12 m width or length
			
...20 m	1	1	1
21...49 m	2	2	2
50...69 m	4	3	2
70...89 m	4	4	4
90...109 m	6	5	4
110...129 m	6	6	6
130...149 m	8	7	6

Down conductors must have test joints in order to enable later measurements on the system. The required number of down conductors for buildings can be calculated as follows (in any case, at least two down conductors must be arranged):

$$n = \frac{\text{Circumference of the building in m}}{20} \tag{16.1}$$

Figure 16.11 shows different arrangements of down conductors. Down conductors must be installed so that

1. Several parallel current paths exist
2. The length of the current paths must be kept as short as possible
3. Connections to the equipotential bonding are made
4. The down conductors have no effect on safety areas
5. They can be connected to each other near the ground.



Length < 20 m
2 conductors

Number of down conductors
70 m / 20 m = 3.5, i.e. four down conductors

Number of down conductors
80 m / 20 m = 4, i.e. four down conductors

Number of down conductors
60 m /20 m =3, Width < 12m
3-1=2, i.e. 2 conductors

Number of down conductors
92 m /20 m =4.6, 5 conductors
Symmetrical building: 5 + 1, i.e. six down conductors

Number of down conductors
120 m / 20 m = 6, i.e. six down conductors

Figure 16.11: Arrangement of down conductors [79]

The connection of the down conductor to the grounding system must be as short as possible (Figure 16.11), and the connection points must be protected against corrosion.

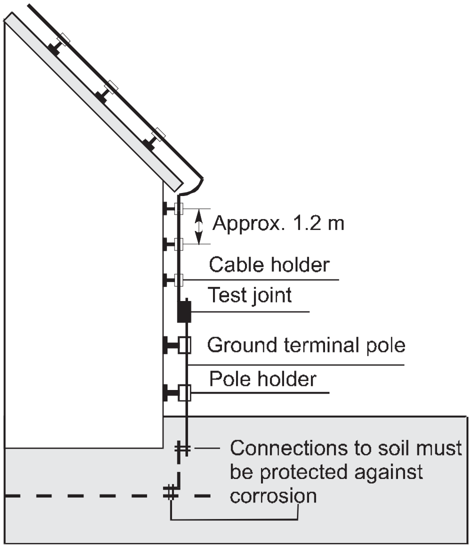


Figure 16.12: Down conductor in accordance with

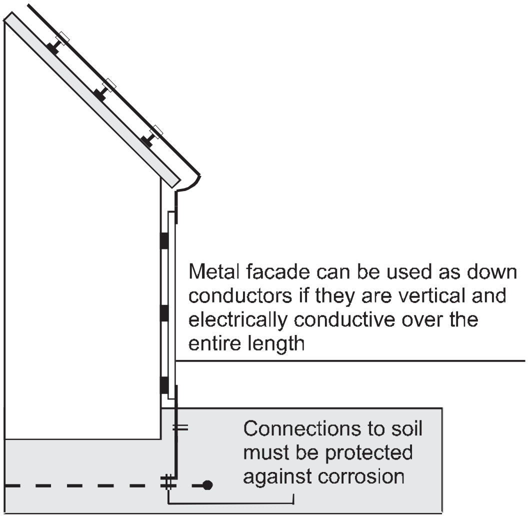


Figure 16.13: Down conductor in accordance with

16.2.3
Grounding Systems

The grounding system can be in the form of a concrete-footing ground electrode, ring ground electrode or single ground electrode. The down conductor is connected to this grounding system.

In accordance with IEC 1312-1, the grounding resistance must not be more than 10 Ω. We distinguish here between two types of grounding systems:

1. Type A arrangement
   - Surface ground electrode
   - Buried ground electrode
2. Type B arrangement
   - Ring ground electrode
   - Concrete-footing ground electrode.

1. Type A arrangement: Surface ground electrode
   A surface ground electrode is a ground electrode which is generally installed at a depth of less than 0.5 m and is connected over a length of 5 m to each down conductor (Figure 16.14).

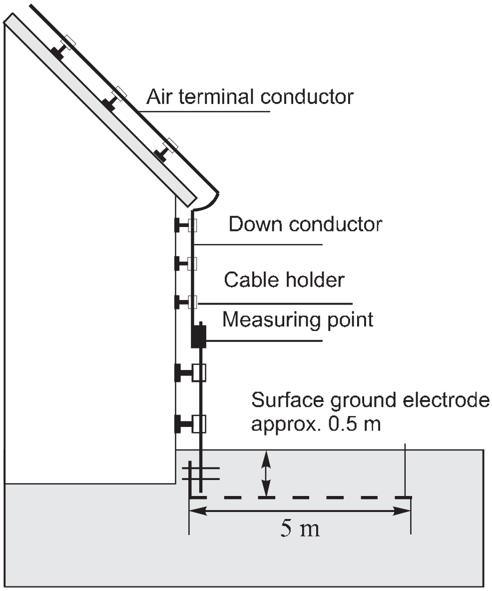


Figure 16.14: Surface ground electrode

It can consist of round or flat conductors and be in the form of a ring, radial or mesh ground electrode:
The ground resistance of the surface buried ground electrode is given by:

$$R_E = \frac{\rho_E}{\pi L} \ln \frac{2\,L}{d} \qquad (16.2)$$

We can calculate the ground electrode resistance with the approximate relationship
for $L \leq 10$ m

$$R_E \approx \frac{2\,\rho_E}{L} \tag{16.3}$$

for $L \geq 10$ m

$$R_E \approx \frac{2\,\rho_E}{L} \tag{16.4}$$

The symbols have the meanings:

L Length of surface ground electrode
d diameter of surface ground electrode

2. Type A arrangement: Buried ground electrode
   It is not possible in all cases to use concrete-footing ground electrodes or ring ground electrodes as lightning protection ground electrodes. In such cases, IEC 1024-1, Part 1 offers the possibility of installing a single ground electrode for each down conductor. As a single ground electrode, either a surface ground electrode with a length of 20 m or a buried ground electrode (Figure 16.15) with a length of 9 m is placed vertically in the ground 1 m

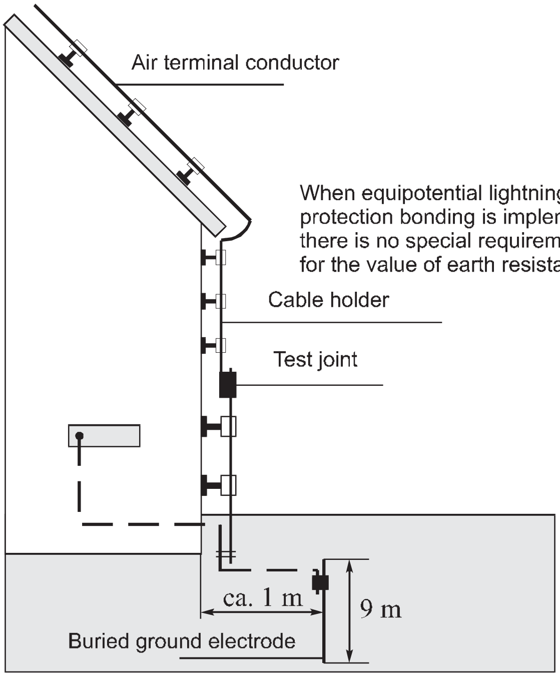


Figure 16.15: Buried ground electrode

away from the foundation of the building. Buried ground electrodes have the advantage that they are placed at further into the ground, where the soil resistivity is less than towards the surface. With vertically placed ground electrodes, frost conditions have no negative effects on the ground resistance. The ground resistance of a buried ground electrode is given by [36]:

$$R_E = \frac{\rho_E}{2\,\pi\,L}\ln\frac{4\,\mathrm{L}}{\mathrm{d}} \tag{16.5}$$

This can be approximated by the relationship:

$$R_E \approx \frac{\rho_E}{L} \tag{16.6}$$

The symbols have the meanings:

L	Length of buried ground electrode
d	Diameter of ground electrode rod

Figure 16.16 shows the ground resistance for buried ground electrodes.

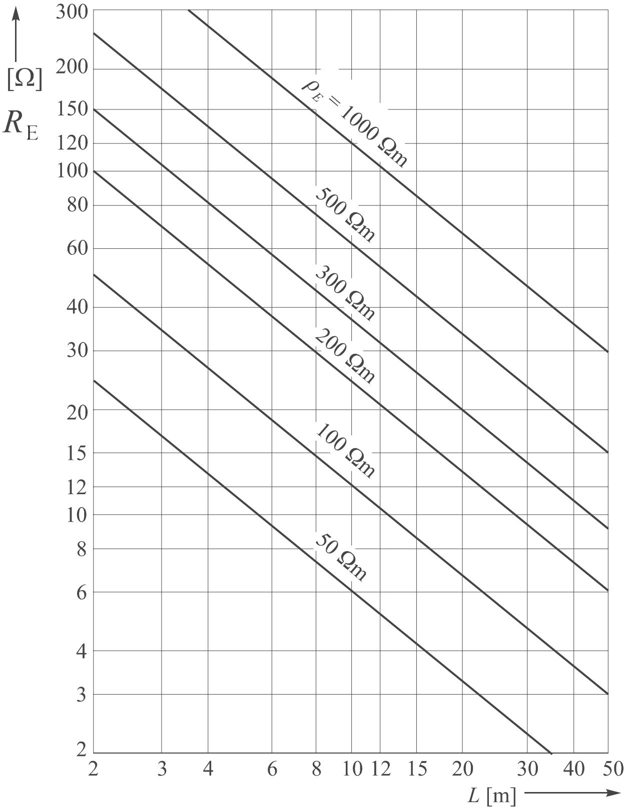


Figure 16.16: Ground resistance for buried ground electrodes [75]

3. Type B arrangement: Ring ground electrode
   A ring ground electrode is a surface ground electrode at a depth of at least 0.5 m and, as well as possible, as an enclosed ring installed at a distance of 1 m (Figure 16.17) from the exterior foundation of the building.

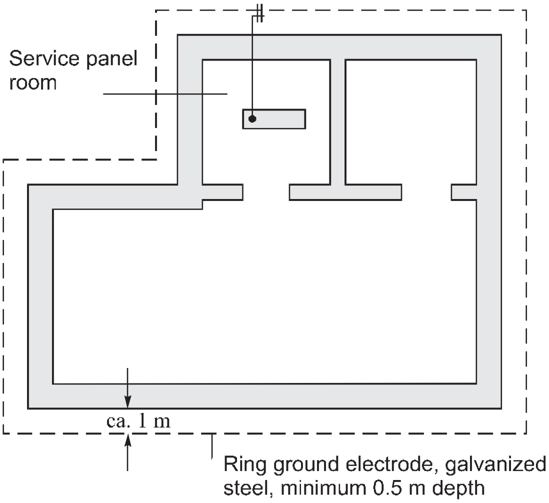


Figure 16.17: Enclosed ring ground electrode

The ground resistance of a ring ground electrode is given by [36]:

$$R_E = \frac{\rho_E}{\pi^2 D} \ln \frac{2\pi D}{d} \qquad (16.7)$$

This can be approximated by the relationship:

$$R_E \approx \frac{2\rho_E}{3D} \qquad (16.8)$$

Here, the symbols have the meanings:

D	Diameter of ring ground electrode $D = 1.13\sqrt{A}$
A	Area of the enclosed ring ground electrode surface
d	Diameter of grounding cable or half-width of a grounding strip
ρ_E	Soil resistivity in Ωm

4. Type B arrangement: Concrete-footing ground electrode
   For optimal functioning, the main equipotential bonding requires an effective and long-term functioning grounding system. The concrete-footing ground electrode is very well suited to this purpose (Figure 16.18).

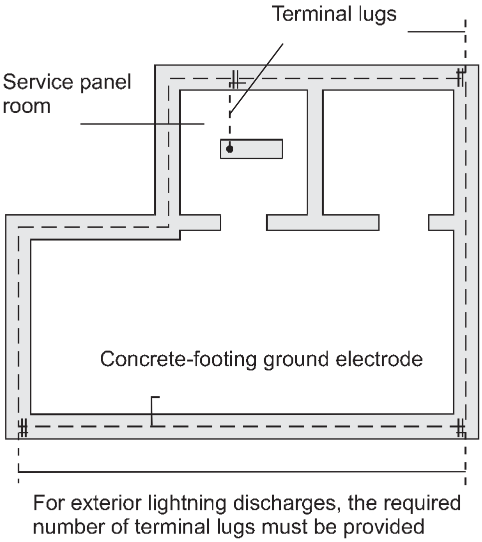


Figure 16.18: Concrete-footing ground electrode

Furthermore, it can also be used as a ground electrode for lightning protection, communications systems and low-voltage systems. It must be in the form of an enclosed ring installed in the foundations of the outer walls of the building. For concrete-footing ground electrodes, steel strips with a cross-section of at least 30 mm × 3.5 mm or steel bars of at least 10 mm diameter must be used. The ground resistance of a buried ground electrode is given approximately by [37]:

$$R_E \approx \frac{2\,\rho_E}{\pi\,D} \tag{16.9}$$

$$D = \sqrt{\frac{4\,L\,B}{\pi}} \tag{16.10}$$

The symbols have the meanings:

L	Length of the concrete-footing ground electrode
B	Width of the concrete-footing ground electrode
D	Diameter of the equivalent circuit area

Figure 16.19 shows the ground resistance for steel strip and steel bar ground electrodes.

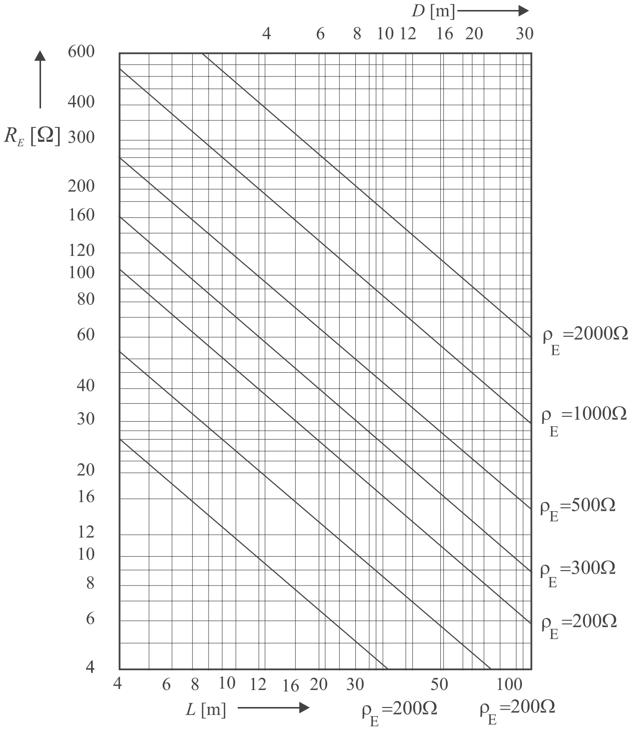


Figure 16.19: Ground resistance for steel strip and steel bar ground electrodes [75]

Minimum length of ground electrodes

The minimum length of ground electrodes must not be considered when the measured grounding resistance is less than 10 Ω. For type B (ring or concrete-footing ground electrodes) the average radius *r* of the area enclosed by the ground electrode may not be less than l_1. The length l_1 can be taken from Figure 16.20.

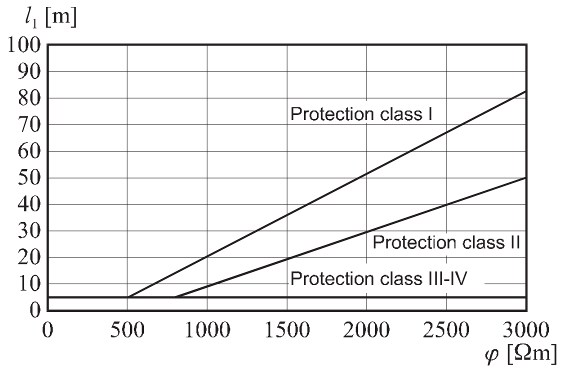


Figure 16.20: Minimum length of a ground electrode

Here:

$$r \geq l_1 \tag{16.11}$$

$$r = \sqrt{\frac{A}{\pi}} \tag{16.12}$$

When the required value l_1 is greater than the value of r, radial or buried ground electrodes must then be added, for which the lengths l_h (horizontal) and l_v (vertical) are calculated as follows:

$$l_h = l_1 - r \tag{16.13}$$

$$l_v = \frac{l_1 - r}{2} \tag{16.14}$$

The number of additional ground electrodes must not be less than the number of down conductors, and must be at least two.

The meanings of the symbols are:

r	Average radius
A	Circular area
l_1	Minimum length of a ground electrode
l_h	Length of horizontal ground electrode
l_v	Length of vertical ground electrode

The ground resistance of a ground electrode depends on the soil resistivity, the dimensions and the arrangement of the ground electrode and the length of the ground electrode, and less on its cross-section [36]. Figures 16.19 and 16.16 show the ground resistance of steel strip, ring and buried ground electrodes as a function of the ground electrode length and the soil resistivity.

The soil resistivity of different soil types is required for the calculation of the ground resistance of a ground electrode. It is usually given in Ωm and is defined as the resistance of a 1 m^3 cube of ground with 1 m edge length, measured between two opposite cube surfaces. Table 16.3 [36,37] lists frequently measured soil types.

Table 16.3: Soil resistivity for different types of soil

Type of soil	ρ_E in Ω m (average values)	Type of soil	ρ_E in Ω m (average values)
Marshland	30	Granite	2500
Loam, clay, humus	100	Rock	> 10000
Sand (damp)	200	Pure water (13 °C)	56
Sand (dry)	1100	Pure water (39 °C)	34
Gravel (damp)	500	Rain water	30–300
Gravel (dry)	3000	Sea water	0.22
Stony soil	1000		

16.2.4
Example 1: Calculation of Grounding Resistances

For a soil resistivity of $\rho = 150\,\Omega\text{m}$ we want to find the ground resistance of a ring and a concrete-footing ground electrode with the dimensions 14 m length and 10 m width and of a buried ground electrode 9 m in length.

$$R_E = \frac{2 \cdot \rho_E}{3 \cdot D} = \frac{2 \cdot 150\,\Omega\text{m}}{3 \cdot 13.3\,\text{m}} = 7.518\,\Omega$$

The diameter of the equivalent ground electrode is:

$$D = 1.13\sqrt{A} = 1.13\sqrt{14 \cdot 10} = 13.3\,\text{m}$$

The ground resistance of the concrete-footing ground electrode can be approximated by:

$$R_E = \frac{2\,\rho_E}{\pi\,D} = \frac{2 \cdot 150\,\Omega\text{m}}{\pi \cdot 13.3\,\text{m}} = 7.183\,\Omega$$

The ground resistance of the buried ground electrode is:

$$R_E = \frac{\rho_E}{2\,\pi\,L} \ln\frac{4\,L}{d} = \frac{150 \cdot \Omega\text{m}}{2\,\pi \cdot 9\,\text{m}} \ln\frac{4 \cdot 9\,\text{m}}{0.02\,\text{m}} = 19.89\,\Omega$$

The ground resistance of the buried ground electrode can be approximated by:

$$R_E = \frac{\rho_E}{L} = \frac{150 \cdot \Omega\text{m}}{9\,\text{m}} = 16.66\,\Omega$$

16.2.5
Example 2: Minimum Lengths of Grounding Electrodes

For a system of protection class II a soil resistivity of 2000 Ωm was measured. From Figure 16.21 we obtain a minimum length of $l_1 = 30$.

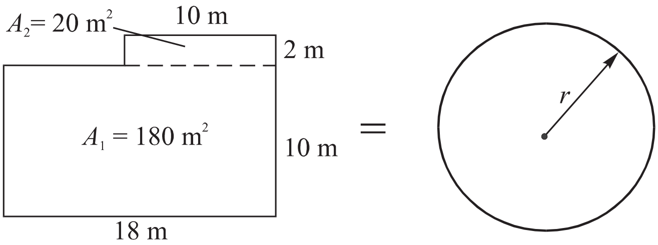


Figure 16.21: Layout of the building

From Figure 16.21, the area $A = A_1 + A_2 = 200\,\mathrm{m}^2$. The average radius is then found from:

$$r = \sqrt{\frac{A}{\pi}} = \sqrt{\frac{200\,\mathrm{m}^2}{\pi}} = 7.98\,\mathrm{m}$$

$$l_v = \frac{l_1 - r}{2} = \frac{30\,\mathrm{m} - 7.98\,\mathrm{m}}{2} = 11.01\,\mathrm{m}$$

This means that an additional buried electrode 11 in length must be installed,

16.2.6
Exposure Distances in the Wall Area

In accordance with IEC 1024-1, an exposure is too short a distance between a lightning protection system and metal installations or electrical systems for which there is a danger of flashover or breakdown. Exposures of air terminals and down conductors to metal installations of all types must be prevented or eliminated by increasing the distance or by connecting the installations directly to the lightning protection system or through series isolation gaps. The exposure distance is give by:

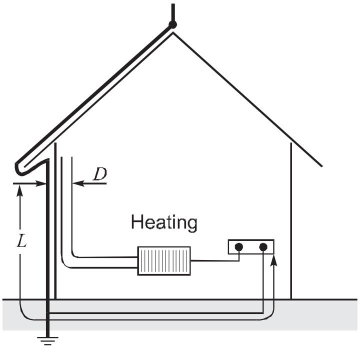


Figure 16.22: Exposure distance with equipotential bonding

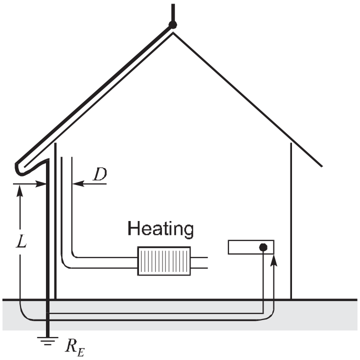


Figure 16.23: Exposure distance without equipotential bonding

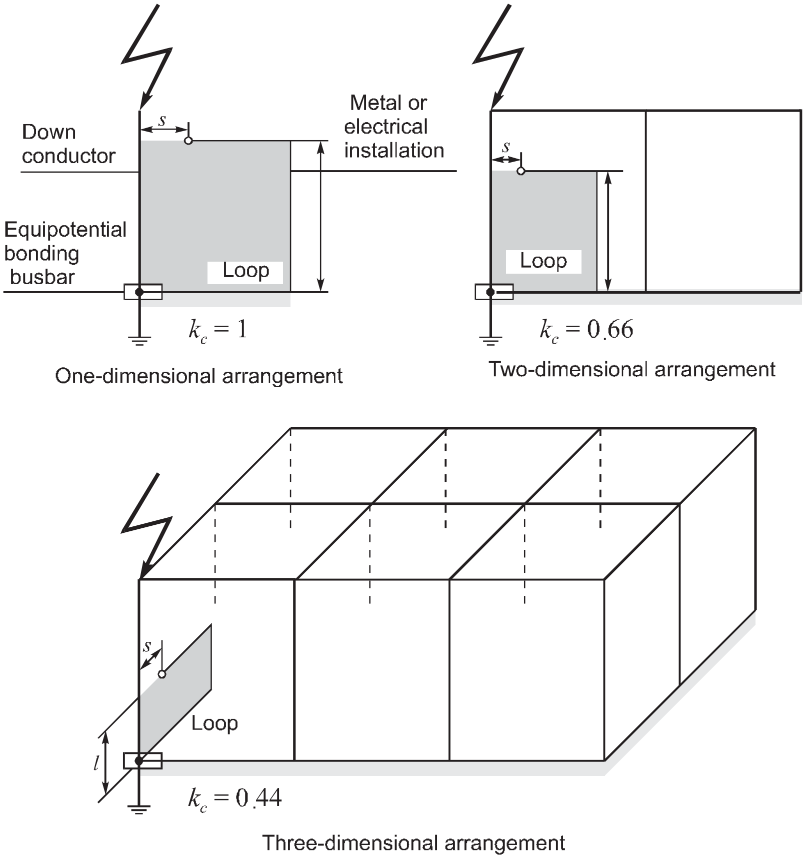


Figure 16.24: Exposure of installations to a lightning protecx-tion system with the value k_c

$$d = k_i \frac{k_c}{k_m} l \qquad \text{mit} \qquad s \geq d \tag{16.19}$$

Here, the symbols have the meanings:

s Safety distance in m
d Exposure distance in m
k_c Geometrical arrangement – dependent current distribution coefficient (see Figure 16.24)
k_m Isolating path material-dependent coefficient [76] from Table 16.4
l Length of lightning protection conductor
k_i Lightning protection class-dependent coefficient [76] from Table 16.4

For the determination of the current distribution coefficient k_c there are three possibilities:

- First method
  a) For free-standing lightning conductor poles and conductor cables located between these.
  b) With air terminal conductor on the ridge and down conductors

$$k_C = \frac{c+f}{2c+f} \qquad (16.20)$$

- Second method
  With a mesh air terminal conductor network on flat roofs, when no ring feeder is provided.

$$k_C = \frac{1}{2n} + 0.1 + 0.2\sqrt[3]{\frac{c}{h}} \qquad (16.21)$$

- Third method
  With a mesh air terminal conductor on flat roofs, when one or more ring feeders are provided.

The symbols have the meanings:

h	Height or spacing of ring feeder
n	Total number of down conductors
c	Distance from next down conductor
l	Length of air terminal conductor

Table 16.4: Values of the coefficients

Lightning protection class	k_i	Material	k_m
I	0.1	air	1
II	0.075	solid state material	0.5
III–IV	0.05		

16.2.7
Grounding of Antenna Systems

In accordance with IEC 1024-1, Part 1, IEC 60 364 and antennas connected to a lightning protection ground electrode, concrete-footing ground electrode, integrated antenna ground electrode, steel constructions or conductive buried tubular metallic networks (Figure 16.25) must have a minimum cross-section of 16 mm^2 Cu (insulated or blank), 25 mm^2 Al (insulated) or 25 mm^2 steel (Figure 16.25).

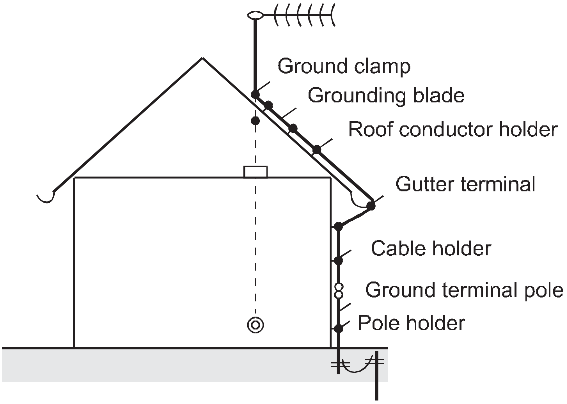


Figure 16.25: Antenna installed on a roof [80]

For room antennas, antennas under a roof or exterior antennas for which the distances depicted in Figure 16.26a are complied with a grounding system is not required. The equipotential bonding must be implemented as in Figure 16.26b.

16.2.8
Examples of Installations

For the technically correct planning of a lightning protection system, the description of the building is of great importance. DIN 48830 gives detailed information about the scope of the building description. In the preliminary planning phase, it is necessary to coordinate the lightning protection class to be used with the customer on the basis of the existing specifications. For the installation and realization of the system, the installation plan (Figure 16.27) and the specifications of work and services [81] must be written. Detailed information about planning, installing and testing can be found in the book [77]. The section numbers used are:

1	Roof conductors	13	Universal trusses
2.3	Roof conductor holders	14	Steel wire down conductors
4	Lightning conductor peak	15	Cable holders
5	Gutter terminals	16	Ground terminal poles
6	Snow fence terminals	16a	Measuring point
7	Rain conduits	17	Rain conduits
8	KS connectors	18	Grounding blade ditch
9	Series gap	19	Steel wire grounding blade
10	Lightning rods	20.22	Parallel connectors
11.12	Grounding conduits	23	Equipotential bonding busbar

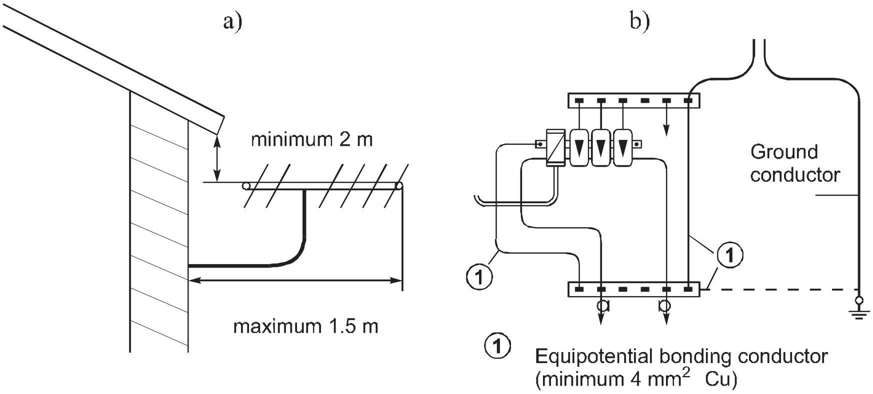


Figure 16.26: a) Window antenna b) Equipotential bonding of antennas [80]

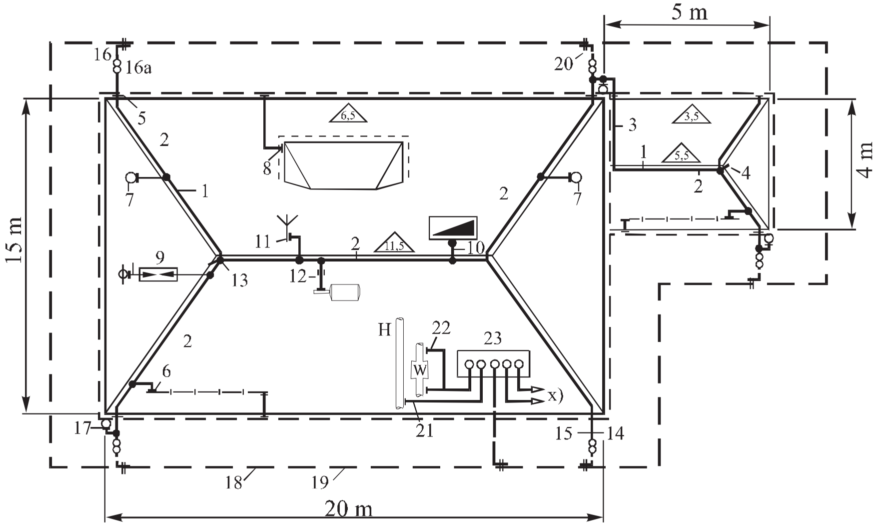


Figure 16.27: Drawing of an exterior lightning protection system [80]

16.3
Interior Lightning Protection

It is necessary to protect electrical installations within buildings against the effects of a lightning discharge current and the resulting electrical and magnetic fields. The main part of the interior lightning protection is the equipotential bonding, to which all metallic tubing, as well as heavy current and information technology systems are connected. For the information technology equipment, the lightning protection zone concept offers the best protection. The principle of this concept is based on room shielding (Figure 16.28).

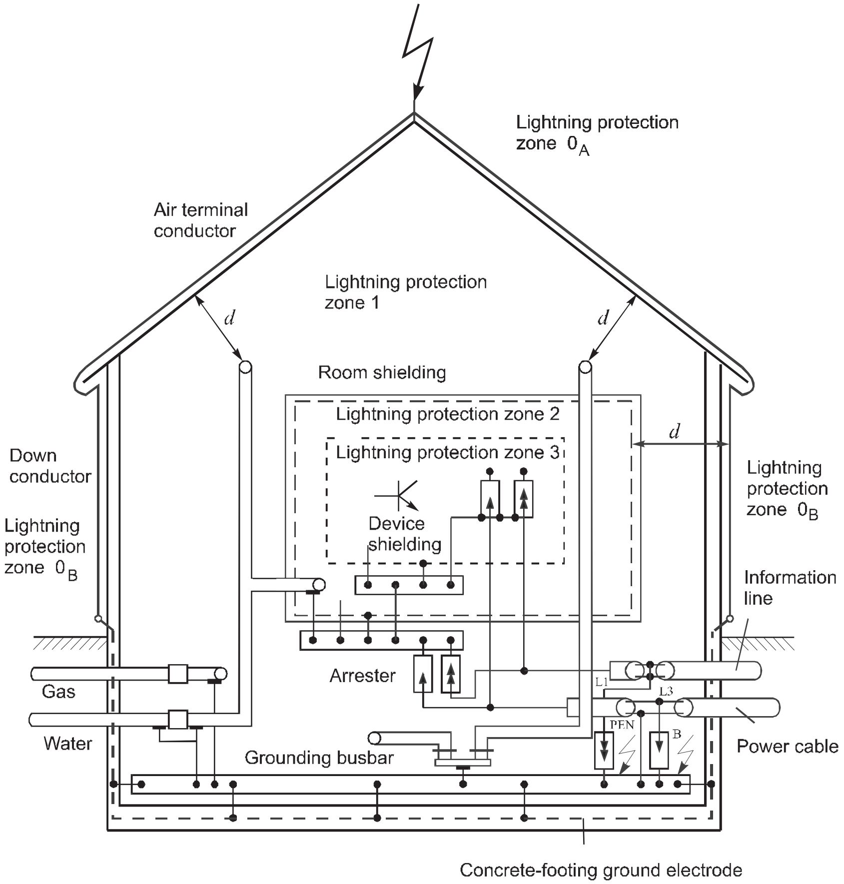


Figure 16.28: Lightning protecxtion zones

16.3.1
The EMC Lightning Protection Zone Concept

The buildings are divided into lightning protection zones, and matched protective equipment and devices provided from the exterior area up to the most sensitive interfaces (Figure 16.29).

The EMC-oriented lightning protection zone concept has been included in international standards. This concept is especially recommended for buildings with extensive electronic equipment. The principle consists of the step-wise suppression of the electromagnetic fields and their effects which result from defined lightning protection zones.

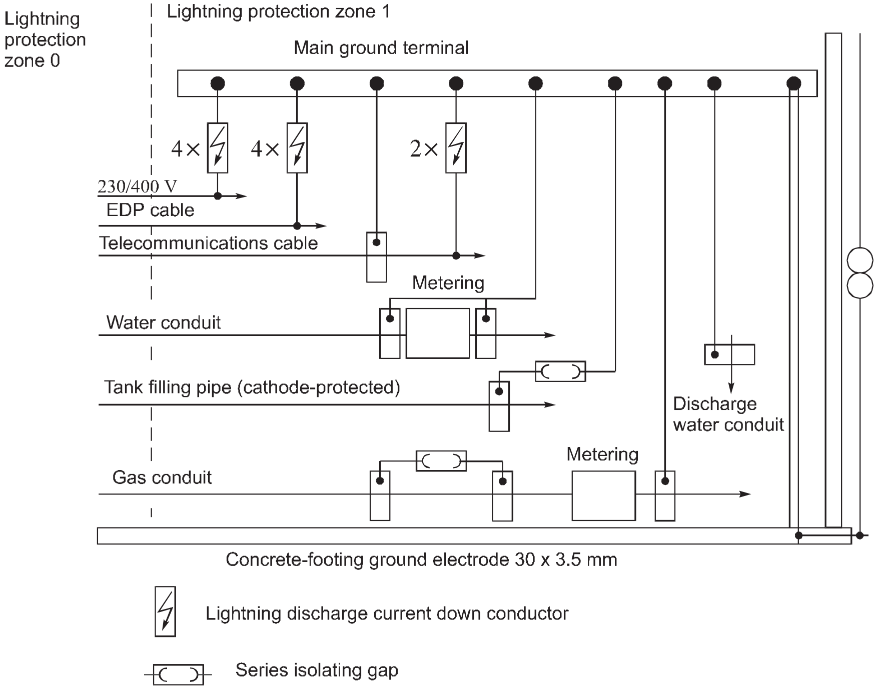


Figure 16.29: Interior lightning protection

With the EMC lightning protection concept, we can distinguish between four zones:

1. Exterior lightning protection
2. Building shielding
3. Room shielding
4. Equipment shielding.

The interfaces between the individual zones must be taken into account in the equipotential bonding, and special down conductors must be installed. Table 16.37 describes the individual lightning protection zones.

Table 16.5: Definition of zones

Zone	**Definition**
Lightning protection zone 0	Direct effect of lightning possible No shielding against electromagnetic fields
Lightning protection zone 0/E	Zone protected by air terminal against direct effect of lightning discharges No shielding against electromagnetic fields
Lightning protection zone 1	Partial lightning currents cause high-energy transients which can lead to switching operations
Lightning protection zone 2	The electromagnetic field is further attenuated
Switching operations and electrostatic	discharge processes (ESD) take place
Lightning protection zone 3	The electrostatic field is reduced to a minimum

The minimum cross-sections of the equipotential bonding lines are:

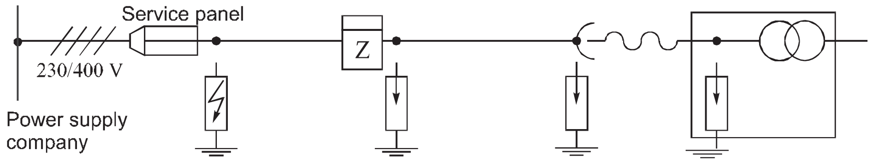
Cu	16 mm^2
Al	25 mm^2
Steel	50 mm^2.

16.3.2
Planning Data for Lightning Protection Systems

For the planning and configuration of lightning protection systems the new lightning protection standard EN 61024-1 and overvoltage protection standard IEC 1312-1 are available. The decision, which standard to use lies with the planner and the customer. The specifications of work and services must be written in accordance with the Lightning Protection Systems or the contract procedure for the building industry. This section describes the locations of protective devices in lightning protection systems.

According to the overvoltage categories, down conductors in the main distribution systems are used as overall protection, overvoltage arresters in the sub-distribution systems as intermediate protection and down conductors in the electrical outlets and the electronic equipment as fine protection. Figures 16.30 to 16.36 give examples for different low-voltage systems and telecommunications systems.

Overvoltage category	IV	III	II	I
Rated peak voltage	6 kV	4 kV	2.5 kV	1.5 kV



Requirement class	B	C	D	none
Down conductor	Lightning discharge current down conductor	Overvoltage arrester	protector	protector
Protection level	4 kV	approx. 1 to 1.5 kV	approx. 1 kV	approx. 1 kV
Nominal discharge current		5 to 15 kA (8/20)	2.5 kA (8/20)	2.5 kA (8/20)

Figure 16.30: Installation locations for overvoltage arresters [55]

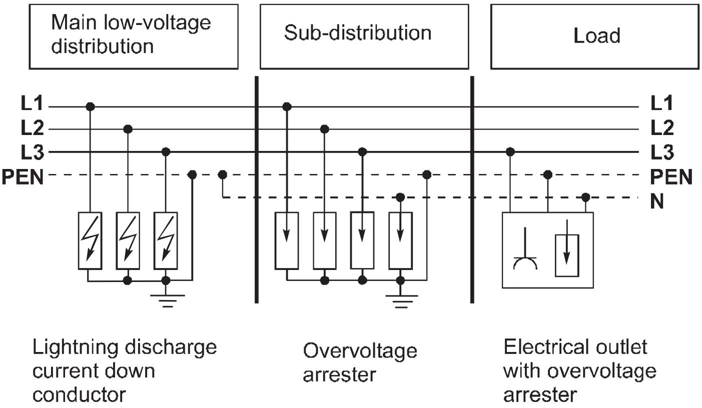


Figure 16.31: TN system with overvoltage arresters [55]

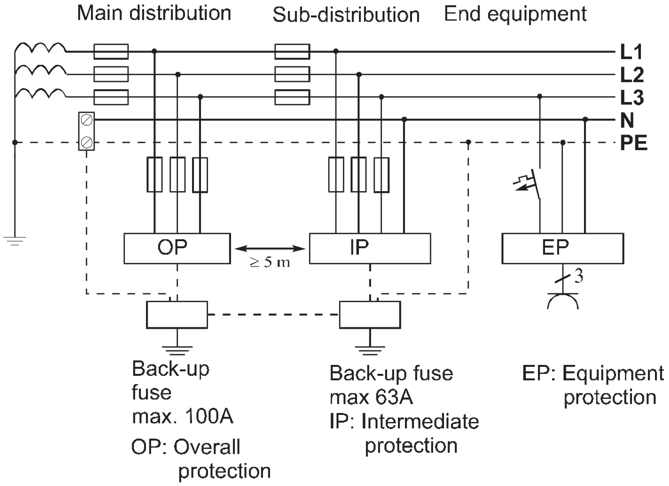


Figure 16.32: TN system with overvoltage arresters [55]

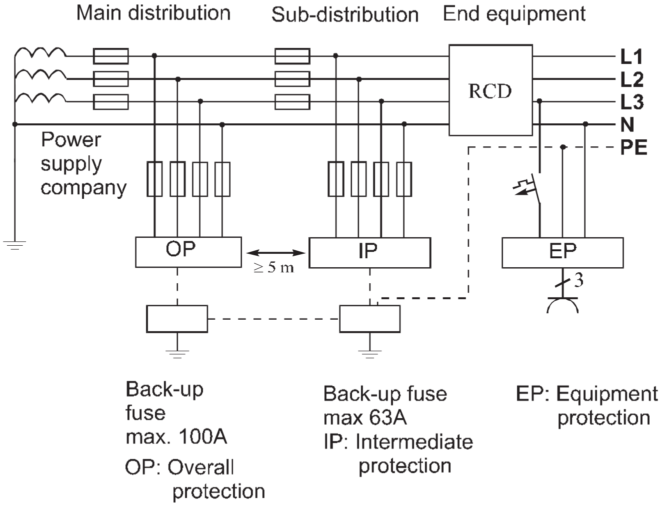


Figure 16.33: TT system with overvoltage arresters [55]

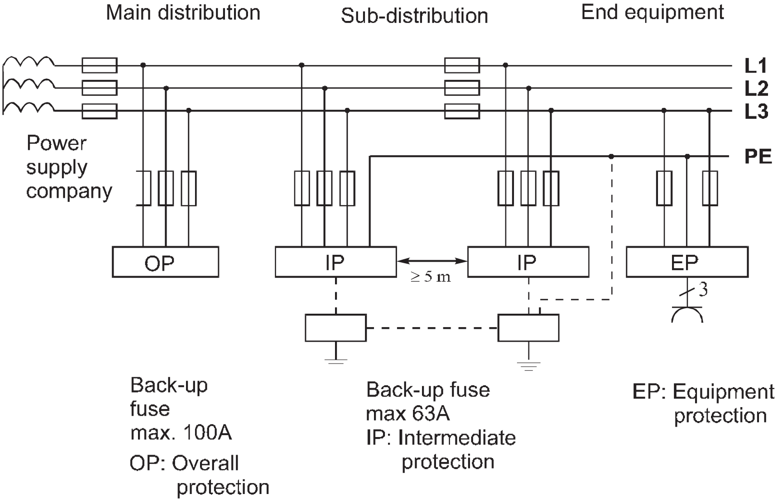


Figure 16.34: IT system with overvoltage arresters [55]

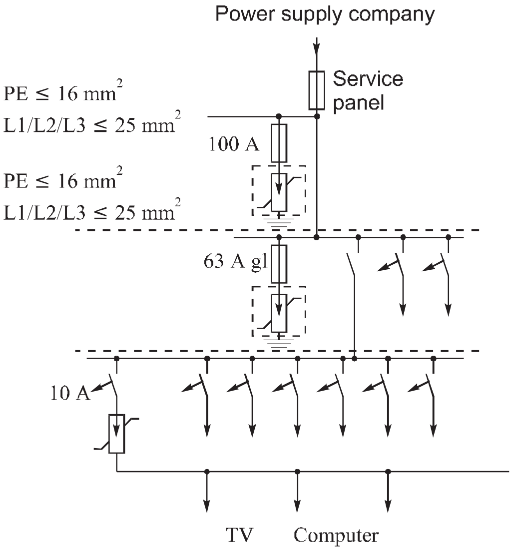


Figure 16.35: IT system with overvoltage arresters [55]

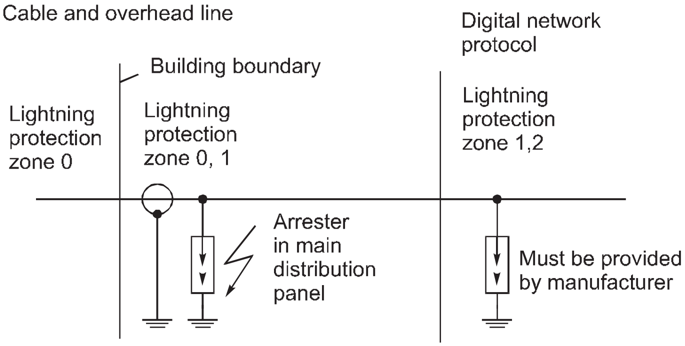


Figure 16.36: Heavy current system, treatment of active lines at the interface [55]

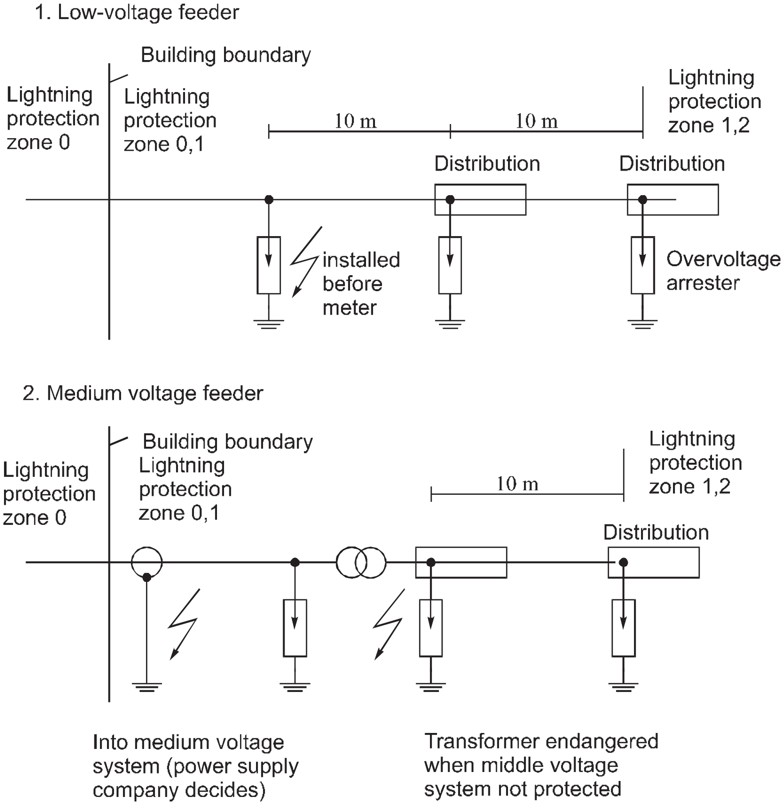


Figure 16.37: Telecommunications system, treatment of active lines at the interface [55]

A very useful aid for the planning of overvoltage protection concepts is the "Trab-tech-select" software, included on the CD-ROM accompanying this book (see also Section 17.15).

17
Using the CD-ROM

17.1
Use of CAD Systems

The competition, shorter planning times (quickness) and greater market demands compel the planner to carry out project planning with the use of computers. Powerful and extensive CAD-supported planning and calculation software packages for a PC or workstation are available at reasonable prices for use with the Unix, OS2, Windows and DOS operating systems. These enable the dimensioning and selection of electrical operational equipment, the calculation of mechanical and thermal short circuit strengths, short circuit currents, selectivity and Backup protection for the selection of overcurrent protective equipment, and also the calculation of temperature rises in control cabinets. Six different computer programs are supplied on the CD-ROM accompanying this book.

17.1.1
SIKOSTART: Dimensioning and Calculation of Startup Time for a Motor

17.1.1.1 Program description

For the calculation of the startup time of a three-phase asynchronous motor it is necessary to input the characteristic data for the motor. Program SIKOSTART calculates the startup time (direct-start and startup time for motor), starting current and speed-torque characteristic during running and can display the results of the calculation graphically.

As important information for planning and configuration, a recommendation for the SIKOSTART to be used is also given. It is especially important to make sure that the maximum ambient temperature and the starting frequency are adhered to. Section 5 of this book shows a sample calculation with SIKOSTART.

17.1.1.2 Program structure

The calculation and selection program is structured as follows:

- Customer and project inputs
- Input of characteristic motor data

Analysis and Design of Low-Voltage Power Systems. Ismail Kasikci

ISBN: 3-527-30483-5

- Input of characteristic load data
- Input of startup conditions, i.e. requirements to be satisfied with the use of SIKOSTART (e.g. maximum starting current)
- Output of the results calculated, e.g. startup time for direct-start and with the use of SIKOSTART. For the results calculated it is necessary to make sure these can be output after selecting *Calculate* in the menu. This of course also applies when changes have been made, i.e. after *Modify* go to *Calculate* and then *Print*.
- The results calculated can be displayed graphically.

17.1.1.3 **Guidance using the Help function**

Actuating the F1 key shows the entire Help menu. For questions referring to a specific Help function, this must then be selected. From every Help function it is possible to exit to the Help menu by actuating the F1 key. Actuating the *Esc* key exits the Help function and returns to the place in the calculation and selection program 3RW22 from which the program was interrupted to call the Help function.

17.1.1.4 **Principle of soft start with the SIKOSTART**

Voltage ramp, current limitation: The soft start is achieved by changing the voltage at the motor terminals, i.e. by forming a voltage ramp. The ramping time, in which the terminal voltage of the motor is increased from about 40% to nearly 100% of the nominal operating voltage can be set over eight steps. It is possible to limit the maximum starting current to a range from 250% to 450% of the nominal equipment current, where the smallest starting current which can be set depends on the breakaway starting current of the motor.

17.1.1.5 **Inputting the nominal data**

The nominal data for the motor are used as parameters for displaying the characteristics. For this reason, they must be inputted completely and exactly. The size of the data is limited by the input format.

17.1.1.6 **Inputting the characteristics**

For inputting the characteristics it is necessary to make sure that no rotational speed value is repeated. Furthermore, for the selection of the characteristic points it must be ensured that the original characteristic of the motor is reproduced as exactly as possible. This can be done by choosing points for the inputs lying within the range of the characteristic and in which the curve shows marked changes. An exact reproduction of the motor characteristics requires the values at 0% and 100% of the synchronous rotational speed of the motor, which can be calculated from the number of poles of the motor.

17.1.1.7 **Inputting the nominal data**

The nominal load data are required for the calculation of the motor loading. For this reason, they must be inputted completely and exactly. The size of the data is limited by the input format. Load rotational speeds below one rpm cannot be input. In such cases it is necessary to convert the nominal load data to the rotational speed of the motor.

17.1.1.8 Voltage ramp

The control unit (microprocessor) increases the terminal voltage of the motor during the ramping time, beginning with about 40% of the nominal operating voltage and increasing this linearly to 100% of the nominal operating voltage. the motor current increases accordingly roughly linearly and proportional to the voltage increase until reaching the breakdown torque (at about 95% of the nominal rotational speed), and then returns to the operating current. The ramping time set has a considerable influence on the startup time of the motor.

17.1.1.9 Current limitation

On reaching the starting current setting the voltage ramp is stopped, i.e. the terminal voltage of the motor remains constant until the motor current becomes smaller than the starting current setting. The ramping time is extended by this time. If the maximum operating time of the current limitation is exceeded, SIKOSTART increases the terminal voltage in the remaining ramping time to the nominal operating voltage.

17.1.1.10 Danger of overloading from SIKOSTART and motor

Table 17.1: Maximum permissible starting current in relation to nominal equipment current for different ramping time settings

Ramping time in s	Max. permissible starting current (overcurrent factor N)
60	2.5
30	2.5
20	3.0
10	3.0
5	4.5
3	4.5
1	4.5
0.5	4.5

These values apply when the nominal motor current is the same as the nominal equipment current, IP00 and when the maximum ambient temperature and the starting frequency are adhered to.

17.1.1.11 Start-up time

The startup time of a drive depends mostly on the mass moment of inertia and the accelerating torque. In order to obtain a comparative value for the startup time, the calculation of the result for direct-start and SIKOSTART will be output separately.

The longer startup times with SIKOSTART result from the torque reduction, i.e. because the terminal voltage of the motor lies below the nominal operating voltage during startup the motor torque falls off roughly with the square of the terminal voltage.

17.1.1.12 Shunting

In cases of application in which for thermal reasons the heat loss arising during nominal operation of SIKOSTART must be avoided, SIKOSTART can be shunted out after a specified time. A difference between this time and the startup time results from the fact that the drive reaches the nominal rotational speed before the terminal voltage of the motor reaches the nominal operating voltage.

17.1.1.13 Selection of SIKOSTART

The main criterion for the equipment size of SIKOSTART is the calculated startup time characteristic as a function of the startup time. The current loading is compared with the characteristic value for the equipment type and a corresponding SIKOSTART is selected. The user can select a possible type of protection.

After the complete MLFB is generated, it is necessary to make sure that the technical data, as given in the NS2 and SA2 catalogs and the operating instructions, are adhered to. If any of the technical data is exceeded, the selection of SIKOSTART must take place under special conditions.

17.1.1.14 Characteristics

The characteristics are intended to serve to make clear the calculated and the input values. When there are several characteristics in one diagram, they are assigned as follows:

upper characteristic $\hat{=}$ upper text block
average characteristic $\hat{=}$ middle text block

17.1.2
TXI: Calculations for Lighting Systems

The computer-supported planning of a lighting system enables exact, object-specific calculations (e.g. the point illuminance and the average illuminance), the evaluation of the glare restriction and the design of the room and light fixture layouts. The TXI program was selected for this book, because it has the following features:

- Simple operation and system optimization
- Short computation and printout times
- Clearly presented documentation printouts of the results calculated
- Understandable graphic diagrams
- Planning results can be output in the form of tables, as distribution curves, as isoilluminance curves or as area diagrams.

17.1.3
TRABTECH-Select: Planning Software for Overvoltage Protection Concepts

With the Trabtech-select planning software it is possible to develop comprehensive overvoltage protection concepts quickly, simply and reliably. The program generates a complete documentation, which can be used for invitations to bids and general planning documentation, as well as instructions for the installation. Furthermore, working on practice-oriented problems with the software provides a strong learning effect, which is of great advantage for the user and leads within a short time to confidence in the principles of overvoltage protection and the most important applications.

17.1.3.1 Hardware requirements

- PC with min. 8 Mbyte main storage (for faster processing times, 32 MB are recommended)
- 486 DX 2/66 or larger processor
- CD-ROM drive
- Graphics hardware with min. 640 × 480 points resolution and min. 256 colors
- Operating system:
- Windows or WfW 3.11
- Windows 95
- Windows NT 3.51 or higher

17.1.3.2 Description of capability

The software offers the possibility to plan a comprehensive and effective protection concept. It takes into account the power supply, as well as all interfaces of the data processing and transfer in the areas of administration and telecommunications and also the automation technology interfaces. The user can decide between the *Catalog Selection* and *Consultation* program parts. The *Catalog Selection* includes a product list for the direct selection of individual protective devices. The *Consultation* program part includes a catalog of questions which are addressed to the user concerning the required information about the system to be protected. Trabtech-select also offers the best suited protective device for the particular application. As required, the user can call up information with the F1 key concerning the current screen page from the extensive context-sensitive Help.

17.1.3.3 Planning results

- Project tree, showing the structure of the planned system
- Parts list for the selected products, organized by installation position
- Invitations for bids
- Application pictures for lightning current down conductors and overvoltage arresters

17.1.3.4 **Exporting**

All planning results can be stored as a complete project file. The project tree, invitations for bids and parts lists can also be stored separately as txt files in other files.

17.1.4

MODLCON (MODL Power Conditioning): Calculation of Compensating Systems for Reactive Currents

The planning of systems to compensate for reactive currents can be carried out with the MODLCON PC program. The MODLCON program has the following features:

- Selection with calculating rule enables calculation of the required compensating power. The effective power, rated voltage, actual cos φ value and desired cos φ value are needed.
- Selection with power bill enables the evaluation of a power bill and calculation of the required compensating power. The effective power, active power consumption, reactive power consumption, rated voltage and desired cos φ value are needed.
- Selection with harmonics problems enables calculation of the required choking factor. The installed compensating power, transformer power, short circuit voltage of the transformer, drive power of the harmonic current generator and ripple control frequency of the power supply company are needed.
- For selection with decision matrix, a particular system can be selected.
- For the calculated or selected systems, invitations for bids with prices can be generated.
- Calculation of air conditioning of switchgear and control cubicles.
- Calculation of inrush currents of capacitors with series connected inductivity.
- Calculation of power losses of transmission lines trough reactive power compensation.
- MODLCON is also able to check the cost effectiveness of the compensation system.
- Calculated results can be printed out, stored or copied to the clipboard.

17.1.5

KUBS plus: Short Circuit Calculations

The KUBS plus program provides support for the short circuit current calculation, the selection of circuit breakers and the line dimensioning.

The input data for the incoming supply (transformer and medium voltage network or known I_k'') as well as the steady-state currents of the individual phase windings are entered. The program suggests suitable line cross-sections. On the basis of the defined line

line cross-sections the program calculates the impedances as well as the short circuit currents. taking the steady-state and short circuit currents into account, KUBS plus selects the required power circuit breakers.

Selectivity limits which result from the relationship between upstream and downstream breakers, are also indicated.

For the choice of circuit breakers, backup protection is also considered when required, i.e. the switching capacity of a downstream breaker can be increased because the upstream breaker trips at the same time and thus limits the current.

The program divides the network calculation into network feed-ins and network distribution. To the feed-ins belong up to 10 transformers, which feed simultaneously, or a defined input position (known I_k''). The following sequence of windings is mandatory for the feeder lines:

1. Transformer or defined input position
2. Winding with cable or busbar connection
3. Winding with power circuit breaker and downstream cable or busbar connection

All feeder lines converge at the common feed-in position. The common feed-in position is represented as a horizontal bar, which however behaves electrically as a point, i.e. has no impedance.

In the distribution part the user can choose whether to build in a winding with or without circuit breaker.

With the exception of the common feed-in position, KUBS plus can consider all the busbar impedances by mapping these in the form of vertical windings.

The distribution windings begin at the common feed-in position.

17.1.5.1 **System requirements**

Hardware:

- PC with Pentium or equivalent processor
- 16 MB RAM or larger
- CD-ROM drive
- Minimum 3 MB hard disk memory available
- Printer: HP Laserjet or similar type, HP Deskjet or similar type, Kyocera laser printer or similar type

Note: The program does not support mouse control.

System software:

- Windows 95, Windows 98 or Windows NT

17.1.5.2 **Installation under Windows**

- Start Windows
- Insert CD-ROM in drive
- Call File Manager and start the Setup.exe file from CD-ROM
- The required hard disk memory capacity is shown and the directories C:\KUBSPLUS. 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 SETUP program for KUBS plus is started from the installation program. You can the start KUBS plus.

Note: KUBS plus is an MS-DOS application. During installation, the program groups KUBS plus 1.2 and the link KUBS plus 1.2 (for starting the program) are automatically set up.

17.1.5.3 **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, the following presettings are defined:

1. Dialog language
   The dialog language for the main KUBS plus program can be selected in the Setup program:
   - German
   - English
   - French
   - Dutch

   Selection is made with the cursor keys, followed by *RETURN*.
   Note: This selection has no effect on the dialog language for the SETUP.
2. Printer driver
   A selection menu is displayed on the screen with the available printer drivers. The existing or a similar printer driver is selected. The following choices are possible:
   - HP Deskjet
   - HP Laserjet
   - Kyocera

   Note: Most printers have the possibility to select an emulation. This often makes it possible to emulate a printer which can be operated with one of the printer drivers offered.
3. Reserve/overdimensioning KUBS plus could, for example, determine a conductor of 3×240 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 small tolerance results in very few (or no) selection
4. Consideration of the touch voltage Checking of the touch voltage can be switched on or off. Following the last input, a new configuration file is generated on the hard disk: SETUP.CFG and KUBS plus are started.

Note: The values entered in SETUP can be changed at any time by calling SETUP again at a later time.

17.1.5.4 Using KUBS plus

To start the program click on: Start – Programs – KUBS plus 1.2

17.1.6

NEPLAN: Planning and information system for electrical networks

Introduction

NEPLAN is a very user friendly planning and information system for electrical-, gas- and water-networks. All menu options and calculation modules are described in details in the manuals. This is a demo-version which you can use up to 30 nodes.

To get to know NEPLAN in a quick and easy way, it is recommended to follow the tutorials.

All programs are explained by examples and it is shown how to start a new project and how to build a small power system. That means, that the user will learn how to enter the elements graphically, how to enter data, how to use libraries, how to run calculations and how to present the results in a manner adapted to the objectives of the analysis.

As mentioned, the Tutorial is a first step to get used to the NEPLAN software. For details about models of elements, data input or calculation inputs, please consult the respective chapters of the User's Guide or use the context sensitive Online Help.

In this section some of the important modules are explained briefly.

Load Flow Analysis

- Computation procedures: Current Iteration, Newton Raphson, Extended Newton Raphson, Voltage Drop
- Limit check and appropriate automatic conversion of the node type.
- Voltage and flow control with phase-shifting transformers, controllable three windings transformers.
- FACTS devices: SVC, STATCOM, TCSC, UPFC
- Node types: slack, PQ, PV, PC, SC, PI, IC. More than one slack node possible.
- Power interchange between area / zones (area interchange control).
- Asymmetrical network elements and loads
- Predefined and user defined scaling factors for fast load and generation variations
- Distributed slack node
- Load balancing
- Calculation of loss sensitivities
- Step length convergence control
- Initialisation file input / output

Short Circuit Analysis

- Computations: IEC 909/VDE 0102, ANSI/IEEE, IEC 60909, superposition method
- Consideration of prefault voltages from a load flow computation.
- Computation of single-, two- (with and without earth connection) and three-phase faults.
- Option for computing user-defined fault types (e.g. double earth fault, fault between two voltage levels).
- Library with special faults is available (can be extended by user).
- Option for computing line faults (fault location on line user-selectable).
- Computable fault current types: initial symmetrical short-circuit current and power, peak, breaking, sustained short-circuit current, thermal and asymmetrical breaking current, plus DC component.
- Computation of minimum/maximum short-circuit current.
- Precise model for transformer earthing connection.
- Asymmetrical network structure are allowed for (asymmetrical short circuit)
- Current limiting due to circuit breakers

Voltage Stability Analysis

As an integral part of NEPLAN software, the Voltage Stability module provides 4 approaches for static voltage stability analysis of power systems: V-Q curves, P-V curves, V-Q sensitivity analysis and Q-V eigenvalue analysis (modal analysis). This module allows examination of a wide range of system conditions. It is an ideal tool to provide much insight into the nature of voltage stability problems.

Harmonic Analysis

- Module is fully integrated, and works independently of the type and size of the network concerned.
- Planning of ripple control systems, dimensioning of compensators (SVC) and harmonic filters, plus determination of network impedance for sub-synchronous resonances.
- Option for simulating frequency response of intermeshed networks.
- Harmonic generators (current and voltage sources) are entered directly in the single line diagram. Libraries available.
- Unrestricted number of harmonic generators can be computed with each harmonic.
- Computation of network impedance, and the harmonic level for each frequency and for each node.
- Frequency-dependence of elements is allowed for.
- Libraries for frequency-dependence are available (can be extended by the user).
- Length of computation steps for impedance computation is automatically adjusted to resonance proximity.
- Harmonic load flow

Filter Dimensioning

- Filter elements are transferred directly into the single line diagram.
- Filter elements: filters (normal, HP, C-filter), series RLC-circuits with or without earth connection, ripple control traps.
- Filters are dimensioned directly by the program.
- Filter data are listed or saved in a text file.
- Result lists can be saved in text files.
- Results can be saved in result files for evaluation by means of spreadsheet programs (like MS-Excel).

Over- current Protection

- All types of protective devices with an over-current time characteristic can be entered: fuse gear, circuit-breakers, definite-time over-current relays and inverse-time relays, electronic relays.
- Up to 6 protective functions (blocking of directional and non-directional over-current protection) can be assigned to each protective device.
- Extensive libraries with protective devices from a variety of manufacturers are available, and can be extended at will.
- Option for entering user-defined characteristics for simulating motor start-ups or thermal loadability of conductors, transformers, etc.
- Characteristic can be shifted using a k-factor (inverse-time relay).
- Entry options for characteristics: point-by-point or formula in conformity with BS142 or the American ASA standard.

Selectivity Diagram

- Relays and current transformers are positioned in the network plan graphically.
- Transformation ratios of current transformers incorporated in the network plan are allowed for in the selectivity diagrams.
- A maximum of 6 characteristics can be incorporated in one diagram.
- Unrestricted number of diagrams can be processed simultaneously.
- Selectivity analysis over more than one voltage level, and independently of the network type and size involved.
- Two reference voltages for diagrams can be user-defined.
- Individualized coloring of the characteristics.
- No limit on number of diagrams and protective numbers for management.

Network Reduction

This module is designed to reduce the size of a network model by replacing sets of buses and the network elements (lines, transformers,...) that connect them with a smaller but exact, numerically equivalent network. For a properly chosen set of buses, this equivalent network will have fewer buses and branches than the original, yet still provide the correct response to faults or load flow calculations in the unreduced portion. The network can be reduced for

- symmetrical or asymmetrical short circuit calculations according to IEC909, IEC60909, ANSI/IEEE or superposition method and
- load flow calculation.

The reduced network gives the same short circuit or load flow results as the original network. Giving the nodes to be reduced, the program determines the boundary nodes automatically.

Optimal Power Flow

- Control variables: active / reactive power generation, schedule voltages of generators and ULTC-transformers, reference values of HVDC systems and FACTS (UPFC, STATCOM, SVC, TCSC,...)
- Variable limits for bus voltages, branch loadings, active and reactive power of generators
- Individual or general limits, 'consider/not consider' limits function
- Objective function: apply to whole network / to a certain area or zone, minimize / maximize MW losses, MVAR losses, generation costs, MW import or MVAR import
- Multi objective function is possible (use of weight factors)

Motor Starting Analysis

- Simulation of motor start-up in unlimited networks.
- Simultaneous or time-delayed start-up for any desired number of motors.
- Identification of motor parameters using the least square of error method.
- Different motor models, depending on the motor data entered.
- Saturation and eddy-current losses in the motor allowed for (linear or point-by-point).
- Libraries for standard motor data, plus additional libraries for Me(s), I(s) and cosj(s) are available (can be extended by the user).
- Operating point computation for all non-starting motors in accordance with their load characteristics (Newton-Raphson).
- Automatic tap changing transformers are allowed for after a user-defined time-delay.
- Load torque entered as a characteristic or as a linear or quadratic load torque curve.
- Libraries for load torques are available (can be extended by the user).
- Start-up devices are allowed for, such as star-delta starter, series resistor, transformer.

Voltage Drop

- Computation of voltage drop to the moment t = 0.
- Reduced data entry for motors and computation parameters.
- Non-starting motors can be simulated by a user-defined load PQ (constant power) or shunt.
- Overloaded elements, measuring instruments and protective devices or nodes with voltages outside a defined range are highlighted.
- Results of the voltage drop computation are displayed in the single line diagram.
- The motor data entered and the motor parameters computed can be accessed by clicking on the motor concerned in the single line diagram.

17.2
Aids for Installation

1. To install the individual programs, insert the CD accompanying this book in the CD-ROM drive.
2. Click the corresponding drive and confirm with Return. The programs are then displayed on the screen.
3. Select the program with which you wish to work.
4. Before every installation, carefully read the **Read-me** file.
5. Proceed according to the instructions given.
6. Never try to start from the CD-ROM.
7. Following successful installation, make backup copies.

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