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Control in Electrical Power Engineering

Waldemar Dołęga

ADVANCED SUBSTATIONS AND ELECTRICAL EQUIPMENT

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Reviewer: Marek Szuba

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CONTENTS

From Author

I have dealt with the subject matter of electrical installations designing for many years of my teaching activity in the Electrical Faculty of Wroclaw University of Technology. I have used my teaching experience in a compiled book.

The book *Advanced substations and electrical equipment* is a knowledge compendium from a field of electrical installations planning and designing in industrial plants. It is composed of ten chapters, the titles of which reflect brought up problems. Distribution systems for industrial plants, power demand, power factor correction, power transformers, power substations, selecting cables, low-voltage protective devices, low-voltage switchgears and lighting in an industrial building are among them. Moreover, a subject matter of short-circuit currents, important for overcurrents protection of equipment, is described.

A limited volume of the book enforces omitting some design problems and concentration on the most essential design elements. That's why a reader who is interested in a complement and deepening information contained in the book should use the literature given in there.

The book *Advanced substations and electrical equipment* is intended for students of electrical departments of technical universities, as well as, workers of the electrical power sector and design offices who desire to broaden their knowledge in the field of electrical installations designing in industrial plants.

The book will be especially useful for students of English language speciality of the Electrical Faculty of Wroclaw University of Technology. The problems discussed are presented at cources in form of lectures and projects:

- *Advanced substations and electrical equipment (lecture)* – for the students of the Master full-time studies of the programme: *Control in Electrical Power Engineering*,
- *Advanced substations and electrical equipment (project)* – for the students of the Master full-time studies of the programme: *Control in Electrical Power Engineering.*

The book can successfully represent basic literature or a complement literature for these courses.

The problems in the book will be helpful, among other things, in design calculations, successive stages of design process of electrical installations in industrial plants, including:

- Design of the main indoor lighting for industrial halls.
- Calculation of the power requirement for individual divisions and the whole industrial plant.
- Calculation of reactive power compensation.
- Design of capacitor bank for required power factor correction.

- Design of power transformers.
- Selection of the main transformer substation.
- Selection of the main high-voltage switchgear.
- Selection of the main low-voltage switchgear.
- Design of the main supplied for division switchgear.
- Calculation of electrical installation.
- Calculation of electrical lighting installation.
- Design of wiring system.
- Design of the main switching apparatus and overcurrent protection.
- Design of conductors.
- Design of fault protection.
- Design of low-voltage switchgear for industrial hall.

Specification, description and analysis of selected design problems are performed on a background of concrete design issues presented in the chapters of the book.

Full understanding of the book contents requires possession of basic knowledge in the field of electrical and electrical power engineering concerned, among other things, with devices, apparatus and installations.

Waldemar Dołęga

1. INTRODUCTION TO PROJECT

1.1. Some aspects of planning and designing

Economic efficiency, flexibility, safety and reliability are key requirements for modern industrial services systems. These requirements must be fulfilled by: switchboards for power supply and distribution, devices, equipment etc.

Technical installations and equipment in industrial plants require an adequate source of power which is available on a continuous basis. Changing operational requirements, e. g. changes to required motor outputs or the connection of new loads, mean that low-voltage switchboards must be able to provide a high degree of flexibility.

Electrical installation engineering is concerned, first and foremost, with the erection of electrical installations in low-voltage power systems. For this reason, system protection focuses primarily on low-voltage systems.

The purpose of system protection in low-voltage industrial systems is to protect the equipment against impermissible loads caused by overload and short-circuit currents and to disconnect defective equipment selectively.

Necessary constructional measures

When the plans for a building are being drawn up, it is essential to ensure that the required electrical system components, their space requirements, and installation locations as well as possible transport routes are clarified with the architect.

The necessary constructional measures (including supply routes, openings for large system components, etc.) must be planned very early on in order to avoid costly alterations at a later stage. It must be possible to access the electrical operating areas for transformers and switchgear assemblies easily and safely. In the event of an emergency, it must also be possible to leave the operating areas without hindrance. When the required dimensions of the area are determined, the minimum clearances for walkway widths, walkway lengths, and passage heights must be taken into consideration with respect to the erection of the switchgear assemblies and distribution boards.

The number of riser ducts and their arrangement is based on the concept selected for the power supply system. The shape and size of the riser ducts depend on the type and number of the cables or busbar trunking systems used for the main power supply lines. Busbar trunking systems are being used to an increasing extent instead of cables or conductors with large cross sections or parallel cables.

Transport routes must be planned to allow transformers, switchgear assemblies, generating sets, etc. to be replaced at a future if it will be necessary.

When the building foundations are laid, the necessary grounding ring conductors can be installed around the building or in the peripheral foundations without additional excavation costs being incurred. A wide-meshed grounding grid in the base foundation is welded to the grounding ring conductors. In addition to this, the grounding ring conductors are connected to the conductive piping that leads into the building; conductive load-bearing supports, concrete-reinforcing iron, etc. are connected to the grounding grid in the base foundation or to the grounding ring conductor.

1.2. Some information about project

Designing concerns the electricity supply for industrial building. It is connected with designing of high- and low-voltage installation in industrial building. Correct process of designing requires among other things knowledge about project assumptions.

Project assumptions are divided into five groups:
A. Profile of industrial building.
B. Conditions of electricity supply for industrial building.
C. Profile of power substation.
D. Project documentation.

Profile of industrial building contains all necessary data for planner both general and detailed.

General data are among other things: name of building, branch of industrial plant (mechanical engineering and metalworking, chemical, glassworks, etc.), category of supply, construction of building, dimensions of building, plan of building, etc.

The branch of industrial plant is necessary information for the selection of the proper parameters in the calculations of the power demand and main lighting in the building.

Category of supply determines the requirements of the electricity supply for industrial plants. It is very important for designing of supply for factory and solution of industrial substations and installations.

Detailed data are among other things: data of receivers (motors, sockets, etc.) and data about low-voltage system (type of ground connection, switchgears, required overcurrents protection of the switchgear and the receivers, required fault protection for equipment, required cable installation method for equipment etc.).

Standard data of motors in industrial hall are the following:

- name of receivers,
- kind of motor,
- P_n – nominal power of motor (rated output),
- I_n – nominal current (rated current),
- η - efficiency,

- $\cos\varphi$ - power factor,
- I_r/I_n – starting current/rated current,
- T_r/T_n – starting torque/rated torque,
- U_n – nominal voltage,
- n – rated speed (turns/min),
- insulation class,
- degree of protection,
- number of receivers.

Standard data of sockets in industrial hall are the following:

- name of receivers,
- I_n – nominal current (rated current),
- U_n – nominal voltage,
- number of receivers.

Majority of these parameters are necessary for project calculation. They are taken from proper catalogues.

Motors are used for devices of different machines such as: turning-lathes, hammer drills, hammers, presses, jacks, conveyor belts, pumps, etc. Motors are often flange-mounted induction motors. Sockets are used mainly for portable receivers.

For sockets, planners standard assume that $\cos\varphi = 0,8$. Nominal power of sockets are calculated according to formulas:

for one-phase socket

$$P_n = U_n \cdot I_n \cdot \cos\varphi \qquad (1.1)$$

for three-phase socket

$$P_n = \sqrt{3} \cdot U_n \cdot I_n \cdot \cos\varphi \qquad (1.2)$$

Conditions of the electricity supply for industrial building contains all necessary data involved low-voltage basic and reserved supplied cables (parameters, length, cable installation method, number of loaded cores, spacing between cores, etc.).

Profile of power substation contains all necessary data involved supplied power substation of the industrial plant. These data concern among other things: transformer substation, main high-voltage switchgear, main low-voltage switchgear. Moreover these data must concern the required power factor ($\cos\varphi$) in the substation, power requirements for objects which are supplied from the substation, power factors for these objects, categories of supply for these objects, etc.

The required power factor is necessary for calculation of compensation of reactive power in the substation and selection of capacitor bank.

Project documentation consists of: the title page, contents, project assumptions, technical description, project calculations, technical drawings, literature and attachments.

Suitable elements of the project are:

- Planning of the supplied network and structure of the installation.
- Design of the main lighting in the building.
- Calculation of the power demand.
- Compensation of reactive power.
- Design of capacitor bank for compensation of reactive power.
- Design of power transformers.
- Selection of the main transformer station.
- Selection of the main high-voltage switchgear.
- Selection of the main low-voltage switchgear.
- Design of the main circuits in the installation.
- Design of load in normal operation conditions.
- Design of wiring system.
- Calculation of short-circuit currents.
- Design of the main switching apparatus and overcurrent protection.
- Design of conductors.
- Design of low-voltage switchgear for industrial building.
- Design of fault protection.
- The final proof of all conditions of wiring, overcurrent protection and its selectivity.
- Preparing of project documentation.

2. DISTRIBUTION SYSTEMS FOR INDUSTRIAL PLANTS

2.1. Introduction

The structure of electrical power supply systems in industrial plants is largely determined by the type of manufacturing involved, as is the selection of the electrical equipment.

Maximum possible security of supply is very important when designing the electrical distribution system for industrial plants. It is the basis requirement from the point of view of avoiding interruptions to production. The so-called “(n-l)-criterion” is often specified as the minimum requirement for preventing production stoppages caused by interruptions to the power supply. It specifies that the total supply capacity must be ensured for the production facilities, even if one system component associated with power supply fails. This means that two independent infeeds are necessary for connection to the public power supply system in order to avoid interruptions to production in the event of a fault.

In the event of a sudden failure of the entire public power supply a standby power supply system ensures that the supply is maintained to important loads, such as IT systems for production control, and that critical production facilities or production processes are shut down in an orderly manner.

2.2. High-voltage system

Large-sized industrial plants are usually connected to the public 110 kV network of the public utility responsible (distribution system operator). However, medium-sized industrial plants are usually connected to the public 15 kV or 20 kV network. Smaller-sized plants must also be connected to these voltage levels if the system perturbations caused by the industrial plant (when connected to the low-voltage system) have an adverse effect on the public loads. Examples of supply solutions for industrial plant are shown in Fig. 2.1 and Fig. 2.2.

Generally, power is transmitted to the load centers of industrial plant using a high-voltage and not a low-voltage current. Level of supplied voltage depends upon the considerable size of the production areas and the high load density.

The high-voltage connection of the transformer load-center substations is established via: radial cables or ring cables. In both cases, the high-voltage switching station is installed at a suitable location in a closed electrical operating area.

In the case of ring cables, the ring cable load transfer switch panels are set up locally as part of the transformer load-center substation, directly in the manufacturing area.

A high-voltage radial cable connection via load transfer switches or switch-disconnectors with fuses is the preferred solution here.

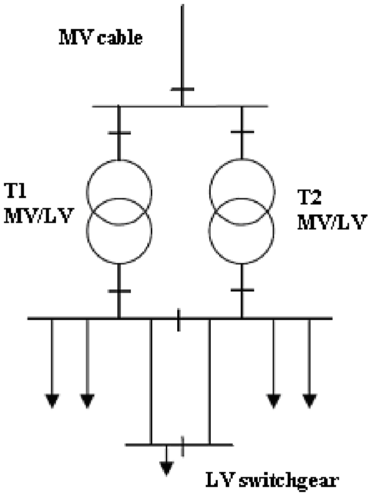


Fig.2.1. The example of electric power supply of industrial plant on MV level

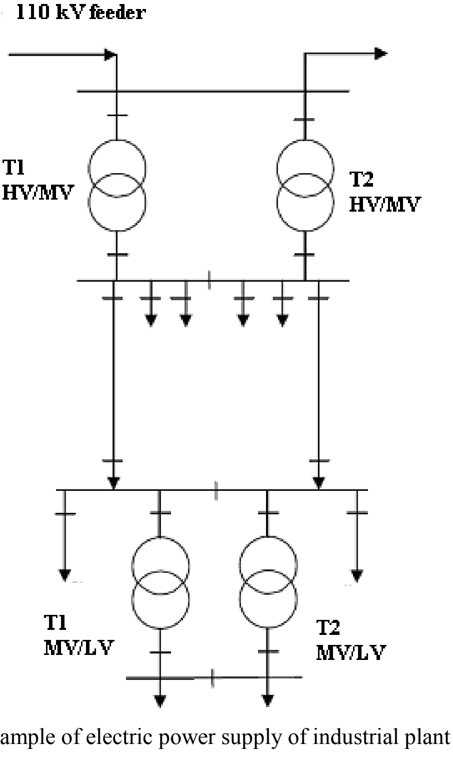


Fig.2.2. The example of electric power supply of industrial plant on HV level

2.3. Low-voltage system

The configuration of low-voltage distribution systems in an industrial building depends on the following factors and requirements:

- Level of power demand,
- Structure of supply area,
- Data of load centers,
- Possible arrangements of main supplied station,
- Possible routing for the main distribution system,
- General and special requirements of the investor.

Level of power demand determines the voltage level for the power supplied by the energy enterprise.

Structure of supply area concerns: density (low and/or high), industrial building type (low-profile, high-rise, etc.), purpose, etc.

Data of load centers involve: size, number, and physical location of the load centers in individual supply areas of the plant.

Possible arrangements of the main supplied station concern, among other things, arrangements of the transformers and associated low-voltage main distribution boards

General and special requirements of the investor involve mainly: supply reliability, supply quality, low investment costs, high cost-effectiveness during operation, etc.

The basic principle, when configuring distribution systems for industrial building, is to find the best possible overall solution — both from a technical and cost-related point of view — not only for the point in time at which the building is erected but also for the total service life of the building.

Following configurations are used in low-voltage systems:

- Radial system,
- Radial system with part-load or full-load reserve,
- Interconnected radial systems,
- Closed meshed systems.

Examples of low-voltage systems are shown in Fig. 2.3, Fig. 2.4 and Fig.2.5.

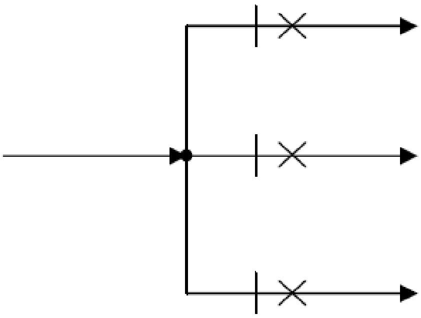


Fig. 2.3. One-stage radial system

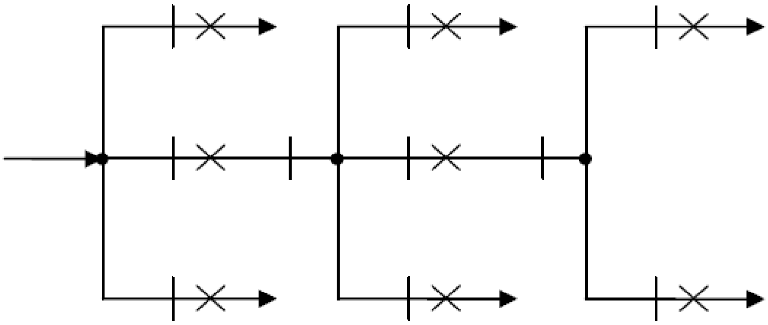


Fig. 2.4. Multi-stage radial system

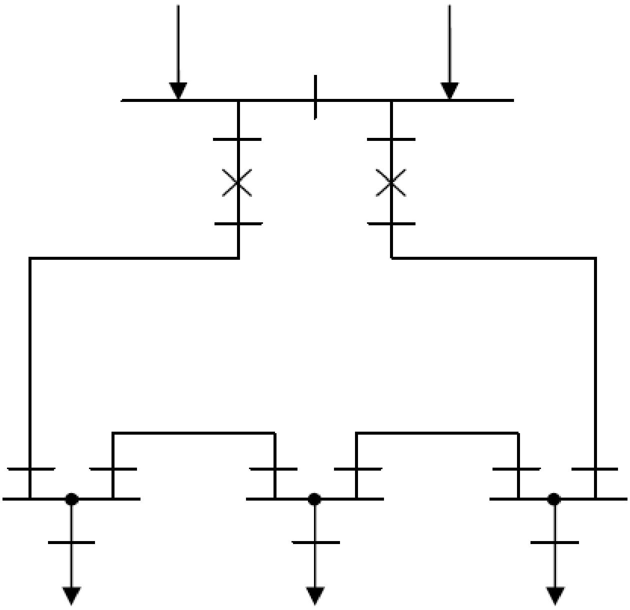


Fig.2.5. Interconnected radial system

Radial system is a simple system design, transparent and easy to manage. Such system has no special requirements with regard to security of supply, voltage stability or flexibility.

Radial system with part-load or full-load reserve characterises high security of supply. It results in additional switched reserve capacity, usually corresponding to a fairly large proportion of the load, depending on the design of the transformers and connecting cables. It is a system with transfer reserve.

Interconnected radial systems is a solution which is a more effective utilization of investment costs through continuous parallel operation of transformers in an interconnected system. It is a system with instantaneous reserve.

As a result of the stringent requirements with regard to security of supply and voltage stability in large industrial installations, the only system that represents a viable option, at present, is the interconnected radial system. The costs for radial systems in closed interconnected systems and radial systems with transfer reserve are approximately the same.

Interconnected radial systems have the following distinct advantages:

- better voltage stability due to the higher fault level,
- the regulations for preventing electric shock by means of automatic disconnection and for the selective behaviour of power system protection equipment, can be adhered to more easily,
- more balanced utilization of the transformers,
- lower transmission losses,
- lower system simultaneity factor as a result of a larger integrated system, and hence lower transformer ratings [15].

Interconnected radial systems are nowadays the preferred solution. Only radial systems may be designed as TN-S systems (separate PE and N-conductors).

Closed meshed systems are used if still greater security of supply to the loads is required. In comparison to the interconnected radial system, it offers following advantages:

- greater flexibility if loads in the system are redistributed,
- lower voltage drops as far as the ultimate consumers,
- instantaneous reserve capacity as far as the sub-distribution boards or important loads.

Closed systems can only be constructed as TN-C systems with combined equipment grounding and neutral conductors (PEN).

The type of power supply system depends on the size of the premises, the length of the supply cables, and the types of load. During the project planning stage, a distinction is made between:

- main power supply,
- load power supply.

The main power supply transports the power from the main low-voltage switchgear to the distribution boards via cables and rising main busbars, while the load power supply transports power in the individual supply sections to the ultimate consumers.

The distribution boards contain the protective devices, such as fuses and miniature circuit-breakers, required for the load power supply of a certain supply section (e.g. part of industrial plant division) as well as any necessary control devices. The size of the distribution boards primarily depends on the size of the supply section concerned, the type of distribution (central or decentralized), the type of current-using equipment to be supplied and controlled, and the required control equipment.

During the project planning stage, a distinction is made between two types of load power supply:

- central distribution,
- decentralized distribution.

In the case of central distribution, all protective devices and a number of control devices for the current-using equipment in a supply section are installed in a central distribution board (e.g. division distribution board). In the past, this type of distribution was generally adequate for simple wiring systems with a relatively small number of loads and a few, mainly decentralized control units. Now, widespread use of electrical equipment, the rise in the number of electric circuits to provide a sufficiently high level of supply security and the rise in the number of control devices in industrial plant means that central distribution boards have to be extremely versatile. This often results in very large distribution boards as well as complex masses of conductors. It often leads to problems with exploitation such distribution board.

Nowadays, large industrial buildings are often fitted with decentralized distribution systems in which several, mostly identical sub-distribution boards installed at regular intervals along corridors or rooms are fed by one central distribution board.

The advantages of decentralized distribution type with sub-distribution boards are the following:

- transparent system structure,
- short outgoing cables to the loads,
- lower fire load,
- straightforward troubleshooting,
- only a small section of the system is disconnected in the event of a fault [15].

Decentralized distribution systems allow the horizontal power supply to be adapted relatively easily to changes in the layout of the room.

An independent safety power supply is required to supply important safety equipment, e.g. safety lighting, sprinkler systems, fire service elevators, etc. An independent power supply system, which must be installed separately from the general power supply, must be provided for this purpose.

Star-type system configurations are normally used for industrial power systems. A number of switchgear stations and distribution boards are required for distributing power from the infeed to the load. High power density, high individual power outputs, and the relatively short distances in industrial power systems mean that low-voltage and high-voltage systems are closely linked. Activities in the low-voltage system (short circuits, starting current) have an effect on the high-voltage system and the other way around.

3. POWER DEMAND

3.1. Introduction

Medium-voltage and low-voltage installations in industry plants are usually near the consumer (industry plant) and generally accessible, so they can be particularly dangerous if not installed properly.

The forecast of a predictable load, as power requirements, is the basis for the installation project in an industrial building.

Estimating the future power demand accurately for industrial hall, influences the expenditure for electrical equipment.

It is important to take into calculation the proper value of the load.

The adoption of too small values of the load can lead to a small load network, excessive device unreliability, and excessive energy losses. It also leads to cost increases, as a result of additional losses in supplied lines, cables and busbars in conditions of exceed of economic current density and decreasing of insulation durability. It also leads to additional load losses in transformers, increase of current redecoration number, additional economic expenditures for devices conversion and considerable decreasing of power system flexibility.

The adoption too large load value can lead to considerable economic expenditures as a result of partial freezing of investment expenditures. It also leads to additional no load losses in transformers (use of too large of a unit) and too significant dimension of devices.

Consequences of a wrong power demand estimate, reduce the investment effectiveness considerably.

Many methods for power demand calculation are used throughout the world. Some of them give results which are different from reality. It is often independent of applied calculation methods. The main contribution to this situation gives imperfection of applied calculation methods and inappropriate values of indicators taken to calculation.

The values of these indicators depend on: technology of production, set of machines, level of adoption of set of machines to technology, organisation of production, work discipline and qualifications of production staff and different technical and human factors [11].

Determining industry network parameters (supplied and indoor) requires calculation of predictable power demand on different levels of the project industry plant. The calculation should be realised on the busbar level – the main supplied transformer station, division transformer station and division switchgear.

Calculation methods of power demand are fundamentally varied in range of the application and precision of the obtained results.

Calculation methods are divided into three groups:

- Simplified methods,

- Universal methods,
- Special methods.

Simplified methods are not dependent on the ratio of power requirements (calculated power) to installed power from number of receivers.

Universal methods have more considerable possibilities to use for power demand calculation than simplified methods. The ratio of power requirements to installed power is dependent on the number of receivers. These methods are used for power requirements calculation in divisions, plants, factories, etc. with any number of receivers. These receivers must have mutually independent characteristics.

Special methods rest on the analysis of technological graphs and diagrams and the individual characteristics of receivers. This analysis is very detailed and time-consuming.

In the project, the following practices are used:

- specific surface-area loading method,
- method of coincidence factor,
- method of requirement factor,
- two parts method (Liwszyc method),
- method of a surrogate number of receivers (n_z method),
- method of power demand rate (k_z method),
- statistical method,
- method of individual load determining.

In many European countries, workers of project offices use simplified methods for power demand calculation like the following:

- specific surface-area loading method,
- method of coincidence factor,
- method of requirement factor,
- method of power demand rate (k_z method).

Generally, the rated output (apparent power S in kVA) of the required infeed power for an industrial plant must be determined from the maximum power requirement $P_{\max}$ while taking account of the mean power factor $\cos\varphi$ a reactive power compensation device that may be installed, and the required redundancy [e.g. (n—1)-principle].

3.2. Specific surface-area loading method

Industrial loads can be roughly divided into groups, which differ according to the type, area the scale and the degree of automation of the manufacturing processes, as well as the effect on the power supply system and the power requirements.

For planning purposes, values for the expected average load per unit area P_m in W/m^2 for the entire power demand, including approximately $17 \div 22$ W/m^2 for lighting, are shown in Table 3.1.

Table 3.1 Average load per unit area [15]

Type of production facility	Examples	Average load per unit area P_m	
		W/m^2	at $\cos\varphi$
Production facilities with low to medium power requirements. Loads that are distributed more or less uniformly over the production area. Power requirements that do not vary very much with time. Relatively low level of automation.	Repair workshops, automatic lathe shops, spinning and weaving mills, precision-engineering production	50 to 100	0.6
Loads that are distributed more or less uniformly over the production area. Considerable differences in the connected loads of the individual consumers. Non-coincident power requirements to momentary rhythmic impulse loads. Medium to high level of automation.	Toolmakers'shops, mechanical. workshops, weldings plants	70 to 100 170 to 500 150 to 300	0.6 0.6 0.7
Very high power loads (e.g. concentrated loads, such as ovens, presses or other large machines). Small loads that are insignificant in terms of the total supply.	Press shops, hardening shops, metallurgical plants, rolling mills	200 to 450 200 to 500	0.5 0.9

Power requirement is calculated according to the formula:

$$P_{\max} = P_m \cdot F \tag{3.1}$$

$P_{\max}$ - power requirement in W,

P_m - average load per unit area in W/m^2,

F – surface of shop, plant in m^2.

3.3. Method of requirement factor

Method of requirement factor is used by planners with the aim of obtaining simply and fast information about power requirement. Generally, the total power is derived from the sum of the installed individual power consumers multiplied by the requirement factor with the formula:

$$P_{\max} = \sum_{i=1}^{n} P_i g \qquad (3.2)$$

P_{max} – power requirement in W,
P_i – individual rated output (installed) in W,
n – number of receivers (loads),
g – requirement factor (sometimes determined as demand factor).

The power requirement is usually derived from the sum of individual rated outputs (P_i) for all installed loads, multiplied by the requirement factor (demand factor).

The requirement factor, also frequently referred to as the demand factor, allows for the fact that not all of the loads in an installation are switched on at the same time. It is, therefore, always less than 1 and decreases with a growing number of loads in installation.

Values of demand factors for German conditions are shown in Table 3.2.

Table 3.2. Requirement factor (demand factor) g for main infeed of different installations /German conditions/ [1]

Type of installation in building	Demand factor g for main infeed	Remarks
Residential building		
Houses	0,4	Apply g to average use per dwelling Total demand=heating+a.c.+general.
Block of flats		
- general demand (exclude electrical heating)	0,6 typical	
- electric heating and air-conditioning	0,8 to 1,0	
Public buildings		
Hotels etc	0,6 to 0,8	Power demand strongly influenced by climate e.g. - in tropics high demand for air-conditioning, - in arctic high heating demand
Small offices	0,5 to 0,7	
Large offices (banks, insurance companies, public administration)	0,7 to 0,8	
Shops	0,5 to 0,7	
Department stores	0,7 to 0,9	
Schools etc.	0,6 to 0,7	
Hospitals	0,5 to 0,75	
Places of assembly (stadiums, theatres, restaurants, churches)	0,6 to 0,8	
Railway stations, airports, etc	no general figure	Power demand strongly influenced by facilities
Mechanical engineering		
Metalworking	0,25	Electrical drives often generously sized
Car manufacture	0,25	
Pulp and paper mills	0,5 to 0,7	Factor g depends very much on standby drives
Textile industry		
Spinning mills	0,75	

Weaving mills, finishing	0,6 to 0,7	
Miscellaneous industries Timber industry Rubber industry Leather industry	 0,6 to 0,7 0,6 to 0,7 0,6 to 0,7	
Chemical industry Petroleum industry	0,5 to 0,7	Infeed must be generously sized owing to sensitivity of chemical production processes to power failures
Glassworks	0,5 to 0,7	
Cement works	0,8 to 0,9	Output about 3500 t/day with 500 motors (large mills with h.v. motor drives)
Food industry silos	0,7 to 0,9 0,8 to 0,9	
Mining Hard coal Underground working Processing Brown coal General Underground working	 1 0,8 to 1 0,7 0,8	
Iron and steel industry (blast furnaces, convertors) blowers auxiliary drivers	 0,8 to 0,9 0,5	

3.4. Method of power demand rate (k_z method)

The method of power demand rate (k_z method) is the most popular method of power demand calculation in Poland. The power requirement is derived from the sum of individual rated outputs in division (plant) multiplied by the power demand factor (k_z).

Power demand factor (k_z) is determined for individual groups of load or for divisions of an industrial plant or industrial plants.

First step of power demand calculation is the calculation of the sum of individual rated outputs (P_{nij}) for all *(j)* installed loads in *(i)* a homogeneous group.

The next step is the calculation of power requirements for *(i)* a homogeneous group with the formulas:

Active power requirement for *(i)* homogeneous group (P_{maxi}):

$$P_{\max i} = k_{zi} \cdot \sum_{j=1}^{n} P_{nij} \tag{3.3}$$

P_{maxi} – power requirement for *(i)* homogeneous group,
P_{nij} – individual rated output (installed) for all *(j)* installed loads in *(i)* homogeneous group,

n – number of receivers (loads) in *(i)* homogeneous group,
k_{zi} – power demand factor for *(i)* homogeneous group.

Reactive power requirement for *(i)* homogeneous group (Q_{maxi}):

$$Q_{maxi} = P_{maxi} \cdot tg\varphi_{zi} \tag{3.4}$$

$tg\varphi_{zi}$ – reactive power factor for *(i)* homogeneous group.

The power requirements for the division of plants including *(m)* different groups of load on the busbar level of division switchgear is determined according to the formula:

$$P_{\max} = \sum_{i=1}^{m} P_{\max i} \tag{3.5}$$

$$Q_{\max} = \sum_{i=1}^{m} Q_{\max i} \tag{3.6}$$

P_{max} – active power requirement,
Q_{max}– reactive power requirement,
P_{maxi} – active power requirement for *(i)* homogeneous group,
Q_{maxi} – reactive power requirement for *(i)* homogeneous group,
m – number of homogeneous group of loads.

Total power requirements for industrial plant including *(l)* divisions on the busbar division transformer station is determined according to the formula:

$$P_{\max} = k_{jc} \cdot \sum_{k=1}^{l} P_{\max k} \tag{3.7}$$

$$Q_{\max} = k_{jb} \cdot \sum_{k=1}^{l} Q_{\max k} \tag{3.8}$$

P_{max} – total active power requirement for industrial plant,
Q_{max}– total reactive power requirement for industrial plant,
P_{maxk} – active power requirement for *(k)*division of industrial plant,
Q_{maxk} – reactive power requirement for *(k)* division of industrial plant,
l – number of divisions of industrial plant,
k_{jc} – factor of simultaneous load of active power,
k_{jb} – factor of simultaneous load of reactive power.

Factors of simultaneous load are dependent on power requirements for industrial plants (Table 3.3).

Table 3.3. Factors of simultaneous load of active power and reactive power [4]

Power requirement P_{max} kW	k_{jp}	k_{jq}
$P_{max} \leq 500$	1,0	0,9
$500 < P_{max} \leq 1000$	0,9	0,97
$1000 < P_{max} \leq 2500$	0,85	0,95
$2500 < P_{max} \leq 7000$	0,8	0,93
$P_{max} > 7000$	0,7	0,9

Total apparent power requirements for an industrial plant is determined according to the formula:

$$S_{\max} = \sqrt{P_{\max}^2 + Q_{\max}^2} \qquad (3.9)$$

P_{max} – total active power requirement for an industrial plant,
Q_{max}– total reactive power requirement for an industrial plant.

Power factor ($cos\varphi_{max}$) for an industrial plant is determined according to the formula:

$$\cos\varphi_{\max} = \frac{P_{\max}}{S_{\max}} \qquad (3.10)$$

Power demand factors (k_z) and power factors ($\cos\varphi$) for selected branches: mechanical engineering and metalworking, glassworks and lighting are shown in Tables: 3.4, 3.5 and 3.6.

Table 3.4. Power demand factors (k_z) and power factors ($\cos\varphi$) for branches of mechanical engineering and metalworking [4]

No.	Kind of receivers	k_z	$cos\varphi$
1	Lathes (machine tools) for small series production	0,15	0,45
2	Lathes (machine tools) for big series production	0,20	0,55
3	Lathes (machine tools) for unit production	0,15	0,50
4	Lathes (machine tools) with heavy program of work	0,25	0,65
5	Lathes (machine tools) with very heavy program of work	0,37	0,65
6	Lathes (machine tools) working in automatic lines	0,40	0,70
7	Sockets	0,10	0,50
8	Ventilators	0,67	0,80
9	Pumps, compressors	0,75	0,85
10	Transformers and collective drives	0,67	0,80
11	Elevators, jacks with work: 25%	0,10	0,50
12	Elevators, jacks with work: 40%	0,20	0,50
13	Hoisters, conveyors, roll conveyors without blockade	0,50	0,75
14	Hoisters, conveyors, roll conveyors with blockade	0,65	0,75
15	Rectifiers	0,70	0,85
16	Radiator tunnels	0,65	0,95
17	Transformer welders for arched weld	0,30	0,40
18	Transformer welders	0,33	0,50
19	One-unit special transformers welders	0,35	0,60
20	Some-unit special transformers	0,70	0,70
21	Point welders	0,23	0,65
22	Stitch welders	0,33	0,70
23	Small-frequency stoves	0,80	0,35
24	Arched stoves	0,85	0,85
25	Large-frequency transformers for arched stoves	0,80	0,80
26	Generators for large-frequency arched stoves	0,80	0,65

Table 3.5. Power demand factors (k_z) and power factors ($\cos\varphi$) for branch – glassworks [4]

No	Kind of receivers	k_z	$cos\varphi$
1	Water pumps	0,80	0,83
2	Water pumps supplied furnaces	0,95	0,90
3	Ventilators	0,80	0,83
4	Ventilators of forced air blow	0,70	0,75
5	Compressors	0,70	0,70
6	Scissors for cold cut	0,50	0,65
7	Jacks	0,35	0,70
8	Elevators	0,50	0,70
9	Furnaces for constant work	0,85	1,00
10	Furnaces for period work	0,70	1,00
11	Resistance furnaces for glass	0,78	0,75
12	Small stove devices	0,70	1,00
13	Transformers	0,30	0,40
14	Sort tables	0,16	0,80

Table 3.6. Power demand factors (k_z) and power factors ($\cos\varphi$) for lighting [4]

No.	Kind of receivers	k_z	$cos\varphi$
1	Industrial objects (large halls)	0,90	0,98
2	Allowed rooms in industrial halls	0,70	0,97
3	Small industrial buildings	0,90	0,98
4	Administrative and social buildings	0,75	0,95
5	Hospitals	0,65	0,95
6	Warehouses, power substations	0,45	0,95
7	Hotels	0,65	0,95
8	Emergency lighting	1,00	0,98
9	Incandescent (light bulb) lighting	0,80	1,00

4. POWER-FACTOR CORRECTION

4.1. Introduction

Depending on the nature of the loads involved in industrial plants, allowances have to be made for a relatively high lagging reactive-power demand.

Majority of the receivers in an industrial plant, for example motors in a plant of the metal-working industry, work with inductive power factor ($\cos\varphi$). Besides active power *P*, they also take inductive reactive power from network, according to the formula:

$$Q = P \cdot tg\varphi \tag{4.1}$$

Q - inductive reactive power,
P - active power,
$\tan\varphi$ - tangens of an angle φ, correspond to inductive power factor $\cos\varphi$.

Motors and transformers are receivers which are characterized by large reactive power consumption. Motors have about 70% of reactive power consumption and transformers about 20%. Other devices with large reactive power consumption are: reactors, induction furnaces, etc.

Large number of motors and other devices cause a large reactive power consumption. It is very disadvantageous phenomenon from a technical and cost-related point of view. It is beneficial to compensate for reactive power as closely as possible to the loads themselves.

This means that:

- transmission losses in cables and electric lines are reduced, as are losses in the transformers as of the correction point ($P_v \approx I^2 \cdot R$),
- investment costs for this equipment are lower because the rated capacity of the equipment can usually be reduced,
- energy costs are reduced.

In many cases, it is necessary to compensate the reactive power in main power substation of the plant. It is applied almost invariably on the low-voltage side.

For the improvement of the power factor and compensation of the reactive power, a capacitor bank is often used.

4.2. Power factor correction units

In most cases, fundamental-frequency reactive power is corrected by means of capacitors. These can be associated with individual loads, or groups of loads, or may be installed centrally to correct a complete system.

Capacitors are manufactured for single-phase or three-phase circuit. Three-phase capacitor elements can be connected internally in star or delta (Fig. 4.1).

Fig.4.1. Connection of capacitors: a) star connection, b) delta connection

The capacitor rating is calculated according to the formulas:

for star connection
$$Q_C = 3 \cdot \left(\frac{U}{\sqrt{3}} \right)^2 \cdot \omega \cdot C_Y \cdot 10^{-3} \qquad (4.2)$$

for delta connection
$$Q_C = 3 \cdot U^2 \cdot \omega \cdot C_\Delta \cdot 10^{-3} \qquad (4.3)$$

The capacitor current is calculated according to the formula:

$$I_C = \frac{Q_C}{\sqrt{3} \cdot U} \qquad (4.4)$$

Capacitors having a rated frequency of 50 Hz which compensate the reactive power at points of heavy demand in industrial and public networks are often described as power capacitors.

Power-factor correction units consist of a controller and a power section including:

- capacitors,
- contractors for capacitor switching,
- fuses for capacitor circuits,
- elements for discharging the capacitors when they are disconnected from the system.

A power-factor correction unit is characterized by its power rating, which comprises the sum of the output values of the branch circuits, its step function ratio and number of steps.

Table 4.1 shows standard data of low-voltage capacitor banks manufactured by OLMEX [4,82]. Fig 4.2 shows one example solution of capacitor banks.

Table 4.1 Selected parameters of capacitor bank with automatic regulation on voltage: 400 V, 525 V and 690 V and nominal power 100 ÷ 600 kvar (OLMEX production) [4,82]

Type of capacitor bank	Rated reactive power kvar	Control step kvar	Number of units	Number of control steps	Control series	Dimensions		
						L mm	H mm	G mm
BK-360 120/20	120	20	6	6	1:1:1	750	2000	500
BK-360 140/20	140	20	4	7	1:2:2	750	2000	500
BK-360 160/20	160	20	5	8	1:1:2	750	2000	500
BK-360 180/20	180	20	5	9	1:2:2	750	2000	500
BK-360 190/10	190	10	6	19	1:2:4	750	2000	500
BK-360 200/20	200	20	6	10	1:1:2	750	2000	500
BK-360 210/10	210	10	8	21	1:2:3	750	2000	500
BK-360 220/20	220	20	6	11	1:2:2	750	2000	500
BK-360 225/25	225	25	5	9	1:2:2	750	2000	500
BK-360 230/10	230	10	7	23	1:2:4	750	2000	500
BK-360 240/20	240	20	7	12	1:2:2	750	2000	500
BK-360 250/25	250	25	6	10	1:1:2	750	2000	500
BK-360 260/20	260	20	7	13	1:2:2	750	2000	500
BK-360 270/10	270	10	8	27	1:2:4	750	2000	500
BK-360 275/25	270	25	6	11	1:2:2	750	2000	500
BK-360 280/20	280	20	8	14	1:1:2	750	2000	500
BK-360 300/20	300	20	8	15	1:2:2	750	2000	500
BK-360 300/25	300	25	7	12	1:1:2	750	2000	500
BK-360 310/10	310	10	9	31	1:2:4	750	2000	500
BK-360 320/20	320	20	9	16	1:1:2	750	2000	500
BK-360 320/20	320	20	9	16	1:1:2	750	2000	500

BK-360 325/25	325	25	7	13	1:2:2	750	2000	500
BK-360 340/20	340	20	9	17	1:2:2	750	2000	500
BK-360 360/40	360	40	9	9	1:1:1	750	2000	500
BK-360 375/25	375	25	8	15	1:2:2	750	2000	500
BK-360 380/20	380	20	10	19	1:2:2	2x750	2000	500
BK-360 400/20	400	20	11	20	1:1:2	2x750	2000	500
BK-360 400/25	400	25	9	16	1:1:2	750	2000	500
BK-360 400/40	400	40	10	10	1:1:1	2x750	2000	500
BK-360 420/20	420	20	11	21	1:2:2	2x750	2000	500
BK-360 425/25	425	25	9	17	1:2:2	2x750	2000	500
BK-360 440/20	440	20	12	22	1:1:2	2x750	2000	500
BK-360 440/40	440	40	11	11	1:1:1	2x750	2000	500
BK-360 450/25	450	25	10	18	1:1:2	2x750	2000	500
BK-360 450/50	450	50	9	9	1:1:1	750	2000	500
BK-360 460/20	460	20	12	23	1:2:2	2x750	2000	500
BK-360 475/25	475	25	10	19	1:2:2	2x750	2000	500
BK-360 480/40	480	40	12	12	1:1:1	2x750	2000	500
BK-360 500/25	500	25	11	20	1:1:2	2x750	2000	500
BK-360 500/50	500	50	10	10	1:1:1	2x750	2000	500
BK-360 525/25	525	25	11	21	1:2:2	2x750	2000	500
BK-360 550/25	550	25	12	22	1:1:2	2x750	2000	500
BK-360 550/50	550	50	11	11	1:1:1	2x750	2000	500
BK-360 575/25	575	25	12	23	1:2:2	2x750	2000	500
BK-360 600/50	600	50	12	12	1:2:2	2x750	2000	500

L – width, H – height, G – depth

Fig.4.2. Capacitor bank BK 360 325/25 (OLMEX production) [99]

4.3. Power-factor correction configurations

Loads can be corrected: individually, in groups or centrally. The choice of configuration must be considered from both an economic and technical point of view. Solutions of power-factor correction configurations are shown in Fig. 4.3.

- Individual correction,
- group correction,
- central correction.

are used in project and exploitation practice for power-factor correction.

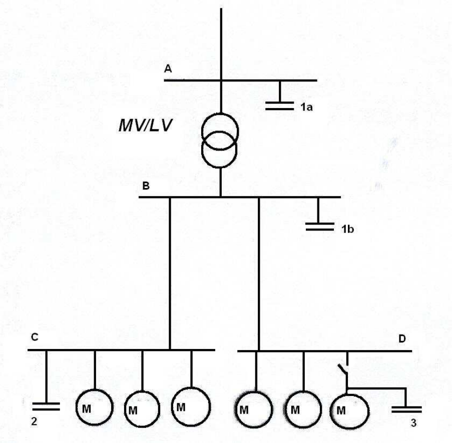


Fig. 4.3. Localisation of power-factor correction units in network: la – central correction (MV (high – voltage) side/, lb – central correction /LV (low-voltage) side/, 2 – group correction, 3 – individual correction [4]

Individual correction is recommended when large loads with constant power factors switched on for long periods have to be corrected.

One advantage of this type of correction is that the load on the supply cable to the loads is reduced. In many cases, the capacitors can be connected directly to the terminals of the individual loads and activated and deactivated with a common switchgear.

There are also some disadvantages. Care must be taken when using individual correction for motors. In the case of pole-changing motors, or motors that are connected via star-delta starters, the correction capacitor must not be momentarily disconnected from the supply system (danger of phase opposition). This also applies to motors that are operated intermittently. In this case, the capacitor must always be discharged sufficiently before the motor is started (less than 10% of its rated voltage). In order to prevent dangerous self-excitation, the capacitor rating connected directly to the motor terminals should be less than 90% of the no-load reactive-power consumption. One solution here is to connect the capacitor via a separate contractor which is integrated in the motor controller.

Power-factor correction of individual loads in industrial plant is hardly ever used nowadays, because of the large number of loads with different ratings and work periods. It is also very expensive, since each load has to be compensated for its maximum reactive-power demand.

Predominantly, individual correction is used in industrial buildings, for lighting systems and for compensating the no-load reactive power in motors.

In a group correction system, one correction unit is associated with each load group. This may consist of motors or fluorescent lamps connected to the system via a common contractor or switch. In this arrangement, as with individual correction, separate switchgear is often not necessary for switching capacitors.

The power factor can be adjusted satisfactorily by means of group correction in the transformer load-center substations with automatic power-factor correction units.

Central correction system is very often used in the industrial plants. Power-factor correction units are used for it. These are directly associated with the main or sub-distribution board.

This type of correction is particularly suitable when a large number of loads with different power requirements switched on for varying periods are connected to the system.

Further advantages of central correction:

- the correction equipment can be easily checked because of its centralized arrangement,
- retro-installation or extension is relatively simple,
- the capacitor rating is always matched to the reactive power requirements of the loads,
- with regard to the coincidence factor, a lower capacitor rating than would be required for individual load correction is often sufficient.

4.4. Selection of capacitor bank

Correct selection of capacitor bank for power-factor correction require to check conditions connected with: required capacitor power, desired power factor ($\cos\varphi_2$), overcorrection, voltage and frequency.

In order to correct a given power factor ($\cos\varphi_1$) to an improved power factor ($\cos\varphi_2$), a capacity rating Q_C of

$$Q_C = P \cdot (\tan\varphi_1 - \tan\varphi_2) \tag{4.5}$$

is required.

The power diagram for an uncorrected and a corrected system is shown in Fig. 4.4.

For desired ($\cos\varphi_2$), a lagging power factor of between 0,9 and 0,98 should be used for a connected system, if it is possible. Public utilities frequently stipulate a power factor greater than 0,9.

Overcorrection $Q_C \geq Q_1$ should, on the whole, be avoided in order to prevent the transmission of capacitive reactive power, which can result in an increase in the system voltage.

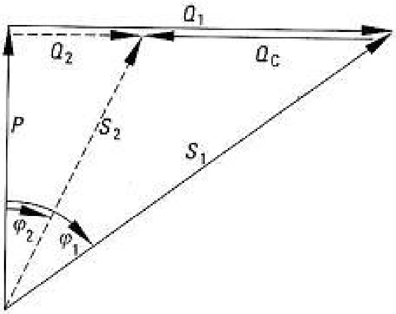


Fig.4.4. Power diagram for an uncorrected (index 1) and a corrected (index 2) system: P- active power, Q_1 – uncorrected reactive power, Q_C – capacitor rating, Q_2 – residual reactive power, S – apparent power, φ - phase angle

It is important to ensure that the rated voltage of the capacitor corresponds to the operating voltage of the system at the point of installation. If the operating voltage and frequency differ from the rated voltage and frequency of the capacitor, the power output by the capacitor changes.

The following formula applies:

$$Q_2 = Q_1 \cdot \left(\frac{U_2}{U_1}\right)^2 \cdot \frac{f_2}{f_1} \qquad (4.6)$$

Index 1- Capacitor rating,
Index 2- Power output by the capacitor for different operating values.

The nominal system voltage should never exceed the rated voltage of the capacitors at the point at which they are installed.

Total apparent power requirement for the industrial plant after power-factor correction is determined according to the formula:

$$S = \sqrt{P^2 + (Q - Q_C)^2} \qquad (4.7)$$

P – total active power before power-factor correction,
Q– total reactive power before power-factor correction,
Q_C - capacity rating.

The increase in the use of regulated drives in the industrial plants leads to a rise in the levels of harmonic interference in industrial systems.

When power capacitors are used to compensate for this, parallel resonance phenomena can occur in the system (anti-resonant circuit capacitors/power transformers). If the natural frequency of this oscillating circuit coincides with the frequency of a current harmonic, the harmonic interference is amplified and the equipment is subjected to the increase in thermal stress. In individual cases, this can lead to overloading or cause overcurrent protective devices to be triggered.

By using reactor-connected capacitor control units (series resonant circuit with $f_r \prec f_n$ of the smallest line current harmonic), amplified points of resonance are avoided in the system, and, depending on the level of imbalance, some of the harmonic current is filtered. Filter circuits must be used if a high level of harmonics is generated.

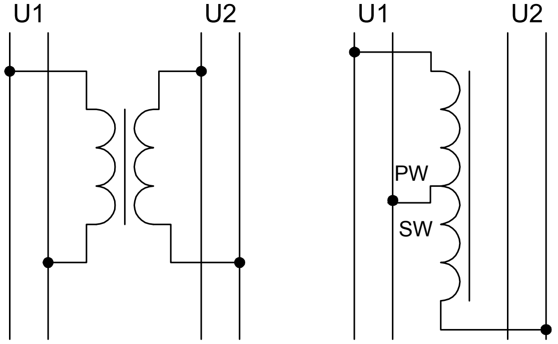
5. POWER TRANSFORMERS

5.1. Introduction

The purpose of transformers is to transfer electrical energy from systems of one voltage U_1 to systems of another voltage U_2.

Transformers can be differentiated according to their manner of operation:

- *Power transformers,* the windings of which are in parallel with the associated systems (Fig. 5.1). The systems are electrically independent. The transfer of power is made solely by induction.
- *Autotransformers,* the windings of which are connected in line (series winding RW and parallel winding PW) (Fig. 5.1). The throughput power is transferred partly by conduction and partly by induction.
- *Booster transformers;* their windings are electrically independent, one winding being connected in series with one system in order to alter its voltage. The other winding is connected in parallel with its associated system (excitation winding EW). The additional power is transferred purely inductively.



Fig, 5.1.Transformer windings and autotransformer windings: PW – parallel winding, SW – series winding

The majority of power transformers are two-winding transformers, for example 110/20 kV, 20/0,4 kV. Sometimes also three-winding transformers, are used, for example: 110kV/20kV/6kV.

The following distinctions are made according to applications:

- Transformers for the power supply such as: distribution or main transformers, machine transformers and system-tie transformers,
- Industrial transformers, such as: welding transformers, furnace transformers, starting transformers and converter transformers,

- Transformers for traction systems,
- Special transformers, e.g. for testing, protection and control purposes.

Transformers are divided into the following categories:

1. *Class* A: dry-type transformers (e.g. cast-resin transformers) (Fig. 5.2).

Core and windings are not contained in an insulating liquid. Heat losses are dissipated directly to the ambient air, hence a large surface area and low current density, up to approx. 20 MVA and a maximum of 36 kV.

ABB resin-encapsulated transformers of the RESIBLOC type are characterized by extremely high mechanical resistance of the windings because of fiber-glass-reinforced resin insulation and a very high resistance to fluctuations in temperature.

2. *Class O:* oil-immersed transformers (Fig. 5.3).

Core and windings are contained in mineral oil or similarly flammable synthetic liquid with a fire point more than 300°C which is simultaneously a coolant and insulating medium.

3. *Class K*

Core and windings are contained in a synthetic liquid having a fire point more than 300°C, which is also a coolant and insulating medium. In construction, they are much like oil-immersed transformers.

Fig, 5.2. Dry-type transformer

Oil power transformers are divided into the three following groups:

- Distribution transformers,
- Medium power transformers,
- Large power transformers.

Fig, 5.3. Oil-immersed transformer

The distribution transformers are characterized by:

- rated power ≤ 2,5 MVA,
- rated voltage of upper side ≤ 33 kV,
- cooling with natural oil circulation,
- taps changed in no-load state;
- main application in MV substations.

The medium power transformers are used in load-centre substations and their rated power is 2,5÷100 MVA. However, the large power transformers are used in main transformer stations and their rated power > 100 MVA.

The main parameters of a transformer are the following:

- Ratio (U_{NHT} / U_{NLT}),
- Rated power (S_{NT}),
- Load losses (P_{Cu}),
- No-load losses (P_0),
- Rated impedance losses (P_{Kn}),
- Impedance voltage drop (u_Z),
- Efficiency (η),
- Connections and voltage groups,
- Cooling system,
- Construction – indoor, outdoor.

Load losses of a transformer, sometimes described as copper losses, are necessary for calculation of windings resistance. No-load losses are composed of the hysteresis losses and eddy-current losses in the iron and leakage losses in the dielectrics. Rated impedance losses are the sum of load losses and additional losses.

5.2. Selection of transformers

Industry power substations are mainly substations with one transformer or two transformers. Main substation is HV/MV station for large plants and MV/LV station for medium and small plant. It is 20/0,4 kV or 15/0,4 kV in Polish conditions.

The main and key information which is necessary for the selection of transformers in industry power substation is the total apparent power requirement, calculated according to the formula 4.4.

Selection of transformers in power substation MV/LV depends on determining:

- nominal power (rated power),
- number of transformers,
- type and kind of design,
- nominal voltages (high voltage, low voltage),
- required regulation range,
- vector group,
- impedance voltage,
- type of cooling,
- thermal and dynamic short-circuit capacity,
- overload capacity,
- parallel operation.

Mainly, the selection of transformers depends on determining the nominal power of the transformer and number of transformers.

For one-transformer station, nominal apparent power for transformer is determined according to formula:

$$S_{NT} \geq S \qquad (5.1)$$

S_{NT} - nominal (rated) apparent power for a transformer,

S - total apparent power after power-factor correction.

Sometimes, it is necessary to calculate total apparent power requirement for receivers of category of supply II. This condition should be considered if you have information about it. Category of supply II means the division of the plant (or factory) requires an additional spare supply from independent sources. Mostly in this case, the definite percentage of receivers requires a spare supply. It is the necessary information for the proper selection of transformers in electrical power substations.

The total apparent power requirement for receivers of category of supply II is determined according to the formula:

$$S_{res} = \sum_{k=1}^{l} p_k \cdot S_k \qquad (5.2)$$

S_{res} - total apparent power for receivers with requirement of absolute continuity of supply,
p_k – percentage shares for receivers of supply category II from *(k)* division of industrial plant,
S_k – total apparent power for *(k)* division of industrial plant,
l – number of divisions of industrial plant.

For two-transformer station, nominal apparent power for transformers (S_{NT1}, S_{NT2}) is determined according to the formulas:

$$S_{NT1} + S_{NT2} \geq S \qquad (5.3)$$

$$S_{NT2} \geq S_{res} \qquad (5.4)$$

S_{NT1} - nominal (rated) apparent power for transformer 1 $S_{NT1} \geq S_{NT2}$),
S_{NT2} - nominal (rated) apparent power for transformer 2 ($S_{NT1} \geq S_{NT2}$),
S - total apparent power after power-factor correction,
S_{res} - total apparent power for receivers with requirement of absolute continuity of supply.

Rated power of transformers are normalized in a range of values from 0,03 kVA to 63000 kVA. Nominal apparent powers of power transformers form series: 16, 25, 40, 63, 100, 160, 250, 400, 630, 800, 1000, 1600, 2500, 3150, 4000, 5000, 6300, 8000, 12500, 16000, 20000, 25000, 31500, 40000, 50000 i 63000 kVA [4,63].

Transformers with a rated power of between 400 kVA and 1000 kVA are usually selected for the surface-area loads encountered nowadays, among other things, in many medium industrial plants. More powerful transformers of up to 2,5 MVA are used in industrial buildings with a particularly high load density or large individual loads. Depending on the required level of supply reliability (partial or full reserve, instantaneous reserve), the necessary transformer output is divided into several smaller units which can be operated either in parallel or individually. The required reserve power increases with the rated power of the transformers. It results in a lower capacity utilization of the transformers under normal operating conditions.

The type of transformers, which are used in industry power substation, are distribution transformers.

The design of the transformers is defined by the class of transformers (oil-immersed transformers, dry-type transformers).

Nominal voltages are defined for industry power substation.

Transformer voltage regulation is an important aspect of operating power transformers. Sometimes it is necessary to change level of voltage to match the voltage if the load fluctuates, to distribute load, to adjust active and reactive currents in interconnected systems. To obtain specified voltages on the output side, the transformer's high-voltage winding is provided with tappings (main and control windings) which are connected in different sequences according to the load. The respective winding sections are selected by means of off-load or on-load tap changers.

Off-load regulation is applied in relatively small transformers, up to about 1 MVA, usually in the substations MV/LV. Such solution is used in network with little load fluctuations. The switching operation is made usually two times during the year, according to the change of seasons. Transformer must be disconnected from the network in this time.

Off-load tap charger covers a band of ±5% or + 2,5% and – 7,5% or ±2,5% of guaranteed operating voltage. In first case, the typical ratio is 3-level regulation: ±5% and 0 or 5-level regulation ±5%, ±2,5% and 0. In second case the typical ratio is 5-level regulation + 2,5%, 0, - 2,5%, - 5% and -7,5 %. In third case the typical ratio is 3-level regulation: ±2,5% and 0. For majority of these solutions a stage of regulation is equal 2,5%.

On-load tap charger is applied in medium and large transformers, usually in the substations UHV/HV or HV/MV. Such solution is used in network with frequent brief load fluctuations. The on-load tap charger selects the winding sections while under voltage and load.

The required regulation range for distribution transformers in industry power substation should have three levels: - 2,5 %, 0 and +2,5 %. It should be an off-load regulation.

The vector group denotes the way in which the windings are connected and the phase position of their respective voltage vectors. It consists of letters identifying the configuration of the phase windings and a number indicating the phase angle between the voltages of the windings.

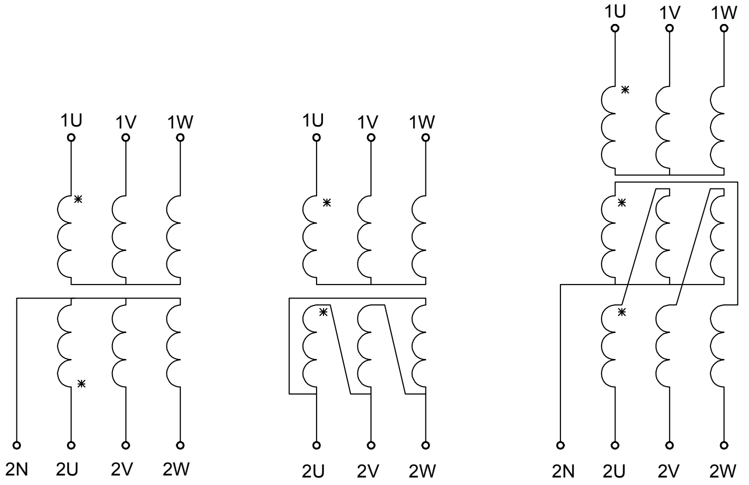
With three-phase a.c. the winding connections are categorized as follows:

- Delta (D, d),
- Star (Y, y),
- Interconnected star (Z, z),
- Open (III, iii).

Capital letters relate to the high-voltage windings, lower-case letters to the medium and low-voltage windings. The vector group begins with the capital letter. In the case of more than one winding with the same rated voltage, the capital letter is assigned to the winding with the highest rated power; if the power ratings are the same the capital letter is assigned, to the winding which comes first in the order of connections listed above. If the neutral of a winding in star or interconnected star is brought out, the letter symbols are YN or ZN, or yn or zn, respectively.

To identify the phase angle, the vector of the high-voltage winding is taken as a reference. The number, multiplied by 30° denotes the angle by which the vector of the LV winding lags that of the HV winding. With multi-winding transformers, the vector of the HV winding remains the reference; the symbol for this winding comes first, the other symbols follow in descending order according to the winding's rated voltages.

Examples of typical transformer winding connections are shown in Fig, 5.4.



Yyn 0 Yd 5 Yzn 5

Fig, 5.4. Examples of typical transformer winding connections

Preferred connections:

- Yyn0 - for distribution transformers. The neutral point can be loaded continuously with up to 10% of the rated current, or with up to 25 % of the rated current for a maximum of 1,5 hours. Example: for connecting arc suppression coils.
- Yzn 5 - for distribution transformers, used up to approx. 250 kVA for local distribution systems. The neutral point can be loaded with the rated current.
- Dyn 5 for distribution transformers above approx. 315 kVA, for local and industrial distribution systems. The neutral point can be loaded with the rated current.

Impedance voltage for distribution transformers equals 4% for transformers with rated power up to 630 kVA and 6% for transformers with rated power more than 630 kVA. This information is determined from the catalogue of transformers.

Cooling is very important for transformers. The method of cooling is stated by manufacturer in the form of four capital letters, the first two letters denoting the coolant and the manner of circulation for the winding, and the last two letters indicating the coolant and manner of circulation for cooling the outside of the transformer. These code letters are explained in Tables 5.1 and 5.2. For example, AN means "dry-type transformer with natural air circulation" and ONAN – "oil-immersed self-cooled transformer".

Table 5.1. Key to cooling systems – COOLANT [7]

Coolant	Symbol
Mineral oil or equivalent synthetical liquid with fire point no more than 300° C	O
Other synthetical liquids	K
Gas with fire point more than 300° C	G
Air (dry-type transformers)	A
Water	W

Table 5.2. Key to cooling systems – COOLANT CIRCULATION [7]

Coolant circulation	Symbol
Natural circulation	N
Forced circulation (non – directed)	F
Forced circulation (directed)	D

Parallel operation is referred to min. two transformers in industry power substation. Transformers are in parallel operation if they are connected in parallel on at least two sides. A distinction is made between busbar interconnection and network interconnection.

The following conditions must be satisfied in order to avoid dangerous transient currents:

- vector groups should have the same phase angle number; terminals of the same designation must be connected together on the HV and LV sides; (exception: phase angle numbers 5 and 11);
- the ratios should be as similar as possible, i.e. the same rated voltages on the HV and LV sides;
- approx. the same impedance voltages U_k maximum permissible discrepancies between – 10 % and + 10 %. In the event of differences, an inductance (vector) can be connected ahead of the transformer with the lower impedance voltage.
- rated output ratio smaller than 3:1.

Table 5.3 shows standard data of transformers manufactured by ABB ELTA [4,71].

The physical location of the load centers, the size, number, and arrangement of the transformers (centralized or distributed) as well as their operating modes (individual or parallel) play a decisive role in determining the configuration of the power system and the subsequent operating costs.

Transformers are usually protected or monitored for overcurrents and internal short circuits.

Table 5.3. Selected parameters of 15,75 / 0,4 kV and 21 / 0,4 kV transformers for nominal power 630 ÷ 2000 kVA (production ABB ELTA) [4,71]

Type	Rated Pow., kVA	Vol. MV, kV	Vol. LV, kV	Vec. group	Imp. vol. %	No-load losses W	Load losses W	Dimensions AxBxH (mm)	Regulation	Remarks
TNOSCT630/15	630	15,75	0,4	Dyn5	6	900	6250	1520x920x1570	+2,5/-3x2,5 off-voltage	ON-AN, corrugated steel tank
TZE630/15	630	15,75	0,4	Dyn5	6	1800	7000	1560x810x1820	+2,5/-3x2,5 off-voltage	Cast-resin, RESIBLOC
TZE630/15	630	15,75	0,4	Yyn0	6	1800	7000	1560x810x1820	+2,5/-3x2,5 off-voltage	Cast-resin, RESIBLOC
TNOSCT630/20	630	21	0,4	Dyn5	6	900	6300	1520x920x1570	+2,5/-3x2,5 off-voltage	ON-AN, corrugated steel tank
TZE630/20	630	21	0,4	Dyn5	6	1800	7000	1560x810x1820	+2,5/-3x2,5 off-voltage	Cast-resin, RESIBLOC
TZE630/20	630	21	0,4	Yyn0	6	1800	7000	1560x810x1820	+2,5/-3x2,5 off-voltage	Cast-resin, RESIBLOC
TNOSCT1000/15	1000	15,75	0,4	Dyn5	6	1450	11000	1890x1105x2040	+2,5/-3x2,5 off-voltage	ON-AN, corrugated steel tank
TNOSLH1000/15PN	1000	15,75	0,4	Dyn5	6	1400	9800	2050x1120x2000	+2,5/-3x2,5 off-voltage	ON-AN, corrugated steel tank with conservator
TZE1000/15	1000	15,75	0,4	Dyn5	6	2500	9800	1740x980x1930	+2,5/-3x2,5 off-voltage	Cast-resin, RESIBLOC
TZE1000/15	1000	15,75	0,4	Yyn0	6	2500	9800	1740x980x1930	+2,5/-3x2,5 off-voltage	Cast-resin, RESIBLOC
TNOSCT1000/20	1000	21	0,4	Dyn5	6	1450	11000	1890x1105x2040	+2,5/-3x2,5 off-voltage	ON-AN, corrugated steel tank
TNOSLH1000/20PN	1000	21	0,4	Dyn5	6	1400	9800	2050x1120x2000	+2,5/-3x2,5 off-voltage	ON-AN, corrugated steel tank with conservator
TZE1000/20	1000	21	0,4	Dyn5	6	2500	9800	1740x980x1930	+2,5/-3x2,5 off-voltage	Cast-resin, RESIBLOC
TZE1000/20	1000	21	0,4	Yyn0	6	2500	9800	1740x980x1930	+2,5/-3x2,5 off-voltage	Cast-resin, RESIBLOC
TNOSCT1600/15	1600	15,75	0,4	Dyn5	6	1850	15200	2050x1140x2240	+2,5/-3x2,5 off-voltage	ON-AN, corrugated steel tank
TNOSLH1600/15PN	1600	15,75	0,4	Dyn5	6	1850	16000	2100x1140x2300	+2,5/-3x2,5 off-voltage	ON-AN, corrugated steel tank with conservator
TZE1600/15	1600	15,75	0,4	Dyn5	6	3600	14000	1920x980x2150	+2,5/-3x2,5 off-voltage	Cast-resin, RESIBLOC
TZE1600/15	1600	15,75	0,4	Yyn0	6	3600	14000	1920x980x2150	+2,5/-3x2,5 off-voltage	Cast-resin, RESIBLOC
TNOSCT1600/20	1600	21	0,4	Dyn5	6	1850	15200	2050x1140x2240	+2,5/-3x2,5 off-voltage	ON-AN, corrugated steel tank

TNOSLH1600/20PN	1600	21	0,4	Dyn5	6	1850	16000	2100x1140x2300	+2,5/-3x2,5 off-voltage	ON-AN, corrugated steel tank with conservator
TZE1600/20	1600	21	0,4	Dyn5	6	3600	14000	1920x980x2150	+2,5/-3x2,5 off-voltage	Cast-resin, RESIBLOC
TZE1600/20	1600	21	0,4	Yyn0	6	3600	14000	1920x980x2150	+2,5/-3x2,5 off-voltage	Cast-resin, RESIBLOC
TNOSAA2000/20PN	2000	15,75	0,4	Dyn5	6	2500	19000	2330x1770x2470	+/-2x2,5 off-voltage	ON-AN, corrugated steel tank with conservator
TNOSCT2000/15	2000	15,75	0,4	Dyn5	6	2200	19500	2240x1360x2360	+2,5/-3x2,5 off-voltage	ON-AN, corrugated steel tank
TNOSAA2000/20PN	2000	21	0,4	Dyn5	6	2500	19000	2330x1770x2470	+/-2x2,5 off-voltage	ON-AN, corrugated steel tank with conservator
TNOSCT2000/20	2000	21	0,4	Dyn5	6	2200	19500	2240x1360x2360	+2,5/-3x2,5 off-voltage	ON-AN, corrugated steel tank

Rated power – rated power, vol. MV – voltage MV, vol. LV – voltage LV, Vec. group – vector group, Imp.vol. – impedance voltage

The rated values specified in the standards usually apply for continuous operation at defined limit values for the temperature of the coolant and for a normal service life. When industrial buildings are supplied, however, the time-related loading of the transformers changes in relation to the production type and cycle. In addition, the coolant temperature often deviates from the values specified in the regulations.

The constructional requirements specify the permissible loads for oil-immersed transformers for normal daily use of life for load cycles (previous load/overload for limited period), for continuous operation at different coolant temperatures and normal use of life, and for overloading with increased use of life for emergency loading.

Overcurrents occur in the range of 1 to 1,5 times the rated transformer current, and can be detected by means of the thermal release of the circuit-breaker on the low-voltage side of the transformer.

5.3. Environmental aspects

Suitable selection of power transformers requires often analysis and assessment of the negative aspects of technology on people and the environment. The potentially disturbing or hazardous aspects of transformers include:

- Noise pollution.
- Land pollution, due to escaping oil caused by leaks and explosions.
- The use of PCBs (polychlorinated biphenyls)- very toxic chemicals – in cooling liquids.

- Electromagnetic fields: the effects of such fields on human beings and instruments are not yet fully understood.
- Energy losses. Even though transformers are generally highly efficient, some energy is lost in the transforming process.

Transformers in service can produce a humming noise in the range of 100 Hz with harmonics up to 2000 Hz, which in the long run may cause serious nuisance or discomfort for people in the environment. In many countries of the Europe, there are strict limits on the noise levels which may be generated by transformers in both urban and rural locations. The primary source of the noise produced is the alternating magnetization of the core steel, while the current-carrying windings contribute only a limited amount. The noise of transformers is defined as the A-weighted sound pressure level measured in dB (A) at a specified measuring surface with the sound level meter, and then converted to a sound power level. A-weighted sound power level for transformers with rated power of 250 kVA, 630 kVA and 1600 kVA equals 65 dB, 70 dB and 76 dB respectively [1].

Manufacturers of transformers use a variety of techniques to limit noise levels drastically, the most important being to reduce the induction in the core, producing an appropriate core shape (e.g. the step-lap method), a special clamping construction and the use of low-resonance tanks, etc. This enables to build transformers with extremely low noise levels (below 30 dB (A)), which called low-noise transformers.

An escape of coolant from the tank can cause land pollution and possibly lead to the danger of fire when a spark or flame is present at the same time. The WGK (water pollution class) of a liquid provides a measure of the threat posed by the liquid to underground and surface water. This classification is based on the biodegradability of the liquid. Most mineral oils and all silicone liquids are in category 1 while esters are more biodegradable and classified as category 0. A WGK of 0 is normally specified only when the transformer is located in the vicinity of a water extraction area. Fire regulations conditions often also lead to the choice of these somewhat more expensive coolants. Their higher flash points and ignition temperatures enable the transformer to be operated without excessively stringent stipulations in respect of sprinkler installations or drip pans to catch leakages thus yielding significant reductions in installation costs.

Many manufacturers of transformers operate a consistent, stringent PCB monitoring policy: the test certificate delivered with each power transformer certifies that its PCB content is less than 1 ppm (part per million). Oil deliveries or transformers returned for overhaul or servicing are never accepted before an oil sample analysis has provided conclusive proof that the liquid is PCB-free. The collection and treatment of transformers filled or contaminated with harmful PCB are made by officially accredited specialist waste disposal companies.

All current-carrying conductors and machines create an electromagnetic field which can have an interfering effect on sensitive (e.g. electronic) equipment. Therefore all products must be made with the highest possible electromagnetic compatibility (EMC): they must not produce a disruptive field or be affected by other fields in their vicinity. Transformers are often good in this respect: their tank acts as a natural electromagnetic screen, reducing the effect of external fields to negligible values.

The use of transformers with low losses has influence on lower consumption of primary energy sources. Electricity utilities using low-loss transformers will clearly need to generate less electricity to satisfy the same energy demand. Generating less electricity involves lower consumption of primary energy sources (coal, gas and oil), thus reducing emissions of the harmful combustion gases which cause phenomena such as acid rain and depletion of the atmospheric ozone layer [83].

6. POWER SUBSTATIONS

6.1. Introduction

Prefabricated electrical substations (often determine as transformer container stations or prefabricated transformer substation) are commonly used as distribution stations in power system.

Prefabricated transformer substations are designed to provide electric power for administrative, residential, industrial and agricultural buildings. They receive electric power of MV, transformed it to LV and distribute it to the consumers. These substations are power supplied by ring networks MV. In Poland, they are commonly used as MV/LV substation, for example 20/0,4 kV or 15/0,4 kV.

Prefabricated transformer substations are often applied as ready-made standard products. Various modifications have been designed - with one or more transformers, terminal or transition type, MV switchgear type, LV switchgear type, with cable or air input and outputs etc.

The construction of prefabricated transformer substations is durable and strong.

Transformer container stations have long operation term, small volume and short installation time. They ensure safe and stable work in various atmospheric conditions. These stations have excellent appearance and are well consistent with the environment.

The equipment of low and middle voltage can be produced by different companies, for example: ABB, Siemens, Schneider, Alstom, GE Power Controls, etc. The necessary electrical and mechanical block systems are provided to ensure the unit proper working.

Prefabricated transformer substations are delivered completely equipped to the site and are mounted on foundation, which is prepared in advance.

The enclosure of transformer container station is a concrete panel construction with two modules: main body (base) and roof.

These substations have three functional sections:

- section Transformer (or transformers),
- section Middle Voltage with input, output and transformer protection cells,
- section Low Voltage.

6.2. Review of transformer container stations

Transformer stations for the purpose of housings are manufactured in:

- Concrete,
- Metal,
- Aluminium.

Transformer stations are:

- with External Service Access,
- with Internal Service Access.

Transformer stations are designed as:

- Poster-Pillar,
- Double Floor,
- Underground Stations.

Technical options of transformer station:

- Distribution Transformers up to 2,5 MVA,
- MV Switchgear up to 36 kV (air or SF_6 isolation),
- LV Switchgear up to 6300 A.

The types of standard transformer container stations manufactured by the main Polish producer - ZPUE Wloszczowa are:

- MRw-b - Concrete Transformer Station with Walk-In Service, up to 1 MVA, with medium voltage switchgear in air insulation or SF_6 insulation,
- Minibox 20/630 - Concrete Transformer Station with External Service with medium voltage switchgear in SF_6 insulation,
- WST 20/630 - Concrete "Poster Pillar" Transformer Station,
- PST 20/630 - Concrete Underground Transformer Station designed for areas where there are unique architectural and/or spatial concerns,
- MRw - Special Aluminium Transformer Stations designed to individual client's requirements,
- ZK-SN/TPM 24-3(4) - Medium Voltage Cable Box in Concrete Case with medium voltage switchgear in SF_6 insulation [76,104].

For the mentioned solutions some examples of data are described.

MRw-b (5,4 × 2,6) 20/1000 is a container transformer station in concrete case with transformer with internal service (Fig. 6.1). Parameters are following:

- dimensions: 5400 × 2600 × 2450 mm (W × D × H) + roof /W – width, D – depth, H – high/,
- building area: 12,48 m^2,
- foundation: 7500 kg,
- main body: 10500 kg,
- concrete roof: 5500 kg,
- metal roof: 650 ÷ 800 kg,
- service: internal,
- number of transformers: 1,
- max. transformer's power: 1000 kVA,
- casing class: 10,
- MV switchgear (typical solution): Rotoblok, Rotoblok SF in air insulation, max. 6 quantity,

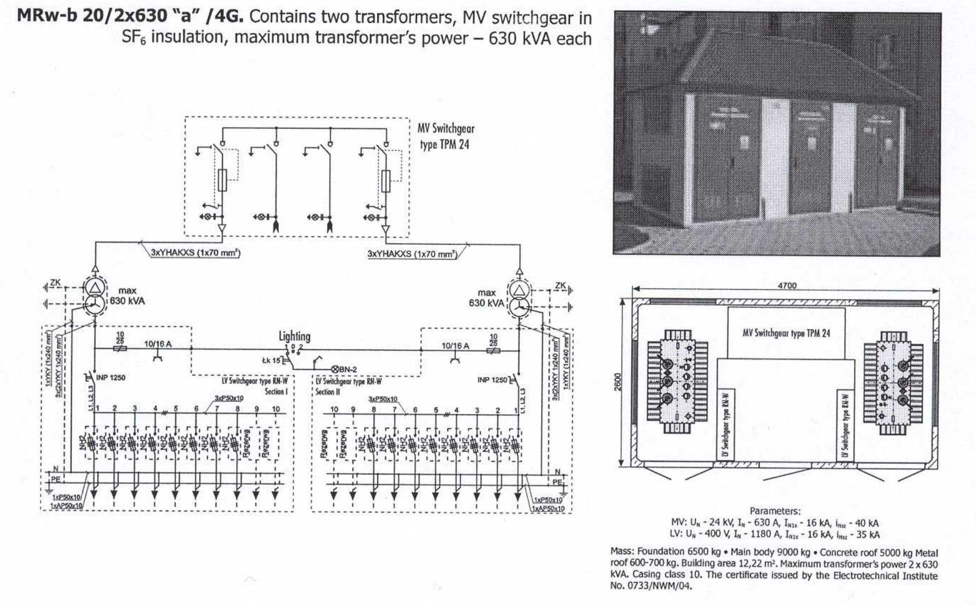
- LV switchgear (typical solution): RN-W, RT-W, PRW max. 10 quantity outgoings [76,104].

Fig, 6.1.Transformer container station in concrete case type MRw-b1 20/630 [2]

MRw-b $(6{,}1\times3)$ $20/2\times630$ is a container transformer station in concrete case with double transformer with internal service (Fig. 6.2). The parameters are the following:

- dimensions: 6100 × 3000 × 2450 mm (W × D × H) + roof /W – width, D – depth, H – high/,
- building area: 16,52 m^2,
- foundation: 8500 kg,
- main body: 12000 kg,
- concrete roof: 6000 kg,
- metal roof: $700 \div 900$ kg,
- service: internal,
- number of transformers: 2,
- max. transformer's power: 630 kVA,
- casing class: 10,
- MV switchgear (typical solution): Rotoblok, Rotoblok SF, max. 7 quantity of MV sections,
- LV switchgear (typical solution): RN-W, RT-W, PRW, max. 2 × 12 quantity of LV outgoings [76,104].

Fig, 6.2.Transformer container station in concrete case type MRw-b (6,1 × 3) 20/2 × 630 [104]



MRw-b 20/2x630 "a" /4G. Contains two transformers, MV switchgear in SF_6 insulation, maximum transformer's power – 630 kVA each

Parameters:
MV: U_N - 24 kV, I_N - 630 A, I_{N1s} - 16 kA, i_{Nsz} - 40 kA
LV: U_N - 400 V, I_N - 1180 A, I_{N1s} - 16 kA, i_{Nsz} - 35 kA

Mass: Foundation 6500 kg • Main body 9000 kg • Concrete roof 5000 kg Metal roof 600-700 kg. Building area 12,22 m². Maximum transformer's power 2 x 630 kVA. Casing class 10. The certificate issued by the Electrotechnical Institute No. 0733/NWM/04.

Fig, 6.3.Transformer container station in concrete case type MRw-b (6,1 × 3) 20/2 × 630 [76,104]

6.3. Review of medium-voltage switchgears in container transformer stations

Typical solutions of MV (medium voltage) switchgears which are used in container transformer stations produced by ZPUE Wloszczowa are Rotoblok and Rotoblok SF.

Rotoblok is a medium voltage metal-enclosed air-insulated switchgear (Fig. 6.4). It is a compact structure with separate modules (bays), the width of which equals 700 mm. It is a switchgear mainly up to 24 kV**.** This switchgear is used in medium voltage secondary power distribution. In particular, it can be used for transformer substations and for control and protection of feeders and power distribution transformers.

The switchgear is constructed by placing the standardized units side by side in a coordinated way. It is possible to obtain the required set from the wide variety of panels: feeders, line panels, bus-sections, measuring panels, etc.

The small size of the Rotoblok switchgear was made possible through the use of a modern rotary disconnector switch manufactured from the best of materials and using the latest technology. The unique mechanical interlock system is a key safety device ensuring that the power is disconnected and the earthing system is simultaneously closed before the door opens.

Each bay is of a closed metal construction, which means that the main on-load switch shaft makes a mechanical and electrical barrier between the lower part of the switchgear and the main bus bars.

The switchgear Rotoblok characterizes such advantages as: long life, reliability and most of all very high levels of safety.

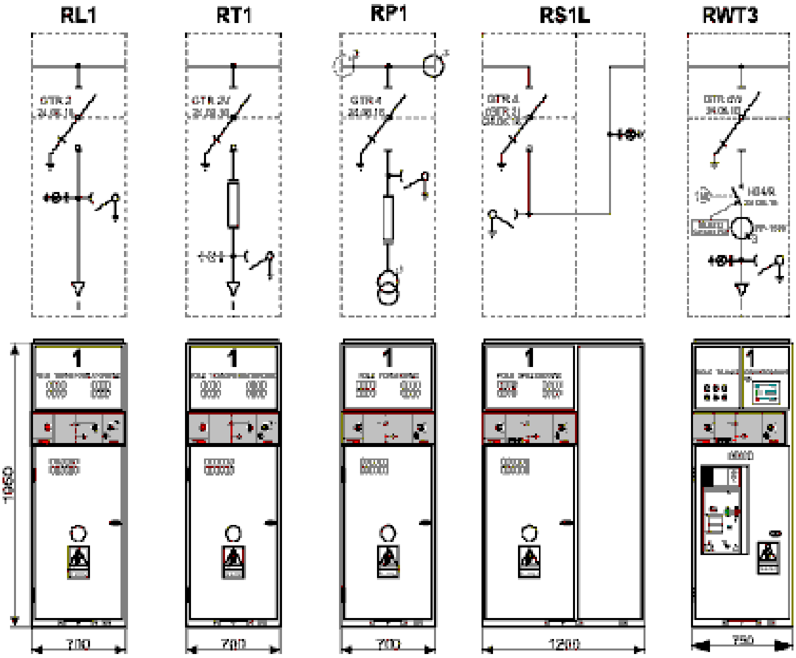
Depending on end-user requirements, the switchgear can be switched off by pressing the control button or through a relay.

Each switchgear bay may be additionally equipped with a motor drive unit. Rotoblok series includes: line bays, transformer bays, metering bays, couplers etc. as well as bays equipped with MV circuit breakers (Fig. 6.5).

Parameters of switchgear are the following:

- nominal (max.) voltage - 24 kV,
- rated continuous nominal current - 630 A,
- rated short-time withstand current - 16 kA (1s),
- rated peak withstand current - 40 kA,
- bay’s dimensions: height - 1950 mm, width - 700 (750, 1200) mm, depth - 1150 mm [76,104].

Fig, 6.4. MV switchgear type Rotoblok [76,104]



Fig, 6.5. Examples of electric diagrams and elevation switchgears Rotoblok type [76,104]: RL1-line bay, RT1-transformer bay, RP1-measurement bay, RS1L-coupling bay, RWT3-transformer bay with circuit breaker

Rotoblok SF is a medium voltage metal-enclosed air-insulated switchgear with an SF_6 insulated load isolator (Fig. 6.6). It is a compact structure with bay width which equals 500 mm or 375 mm. It is a switchgear mainly up to 24 kV. This switchgear is used in medium voltage secondary power distribution. In particular, it can be used for transformer substations and for control and protection of feeders and power distribution transformers.

Rotoblok SF switchgear consists of separate modules (bays). Each bay contains a gas filled SF_6 stainless steel tank. It is within this SF_6 inert gas that the load isolator is housed. Cables enter through the lower section of the bays (air insulation) and are connected through the cable-heads. All the electric bars are connected together in the busbar compartment.

A typical system includes the following bays: line, transformer, metering, coupler, voltage limiter, MV circuit breakers etc. (Fig. 6.7). The line bays can be equipped with a motor drive unit and remote signalling contacts. Further, the transformer bay can be equipped with a tripping coil that can be controlled remotely.

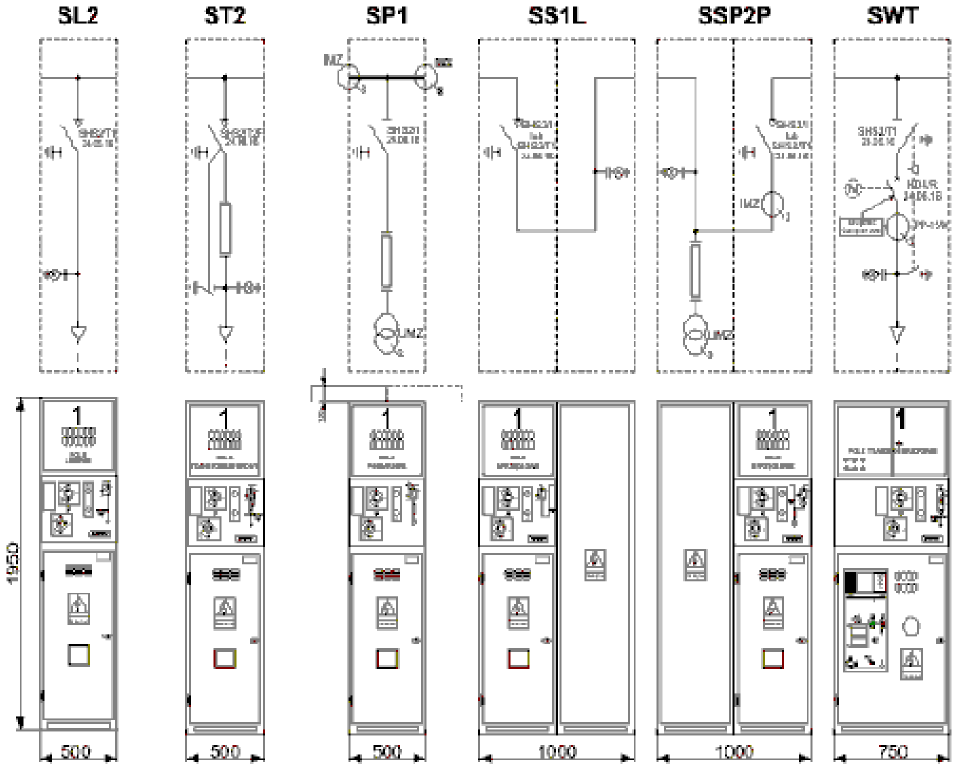
The switchgear Rotoblok SF has the following advantages: long life, reliability, simply and easy exploitation and most of all very high levels of safety.

Stringent quality control during the production of these bays ensures that the rated performance parameters of the Rotoblok SF can be achieved reliably and repeatedly under varying atmospheric conditions.

Parameters of switchgear are the following:

- nominal (max.) voltage - 24 kV,
- rated continuous nominal current – 400 (630) A,
- rated short-time withstand current – 12,5 (16) kA (1s),
- rated peak withstand current – 31,5 (40) kA,
- bay's dimensions: height - 1950, width 500 (375, 750, 1000), depth - 950 (1000) [76,104].

Fig, 6.6. MV switchgear type Rotoblok SF [76,104]



Fig, 6.7. Examples of electric diagrams and elevation switchgears Rotoblok SF type [76,104]: SL2-line bay, ST2-transformer bay, SP1-measurement bay, SS1L-coupling bay, SSP2P- couple measurement bay, SWT-transformer bay with circuit breaker

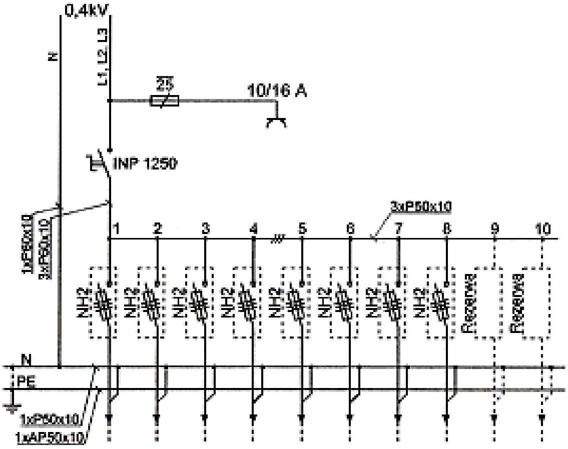
6.4. Review of low-voltage switchgears in container transformer stations

Typical solutions of LV (low voltage) switchgears which are used in container transformer stations produced by ZPUE Wloszczowa are: RN-W, RT-W and PRW.

RN-W is a low voltage metal-enclosed air-insulated switchgear incorporating fuse load switch. It has a modular structure with bay width which equals 100 mm. It is a switchgear for 400 V. The switchgear consists of a set of independent modules (Input, Output, Meter), which facilitates modular system expansion. In the Input unit it is possible to use differing types of load switches or circuit breakers. The Output bays can be equipped with any type of fuse load switches. RN-W switchgear's one line diagram is shown in Fig. 6.8.

Parameters of switchgear are the following:

- nominal voltage – 400 V,
- rated continuous nominal current – 1180 (1600) A,
- rated short-time withstand current – 16 (20) kA (1s),
- rated peak withstand current – 35 (40) kA,
- switchgear's dimensions: height - 1950 (support frame 1990) mm, width - 550 ÷ 1300 mm, depth - 400 (320) mm [76,104].



Fig, 6.8. Example of RN-W switchgear's one line diagram [76,104]

RT-W is a low voltage metal-enclosed air-insulated switchgear equipped with the SLMB fuse load switch. It is a switchgear for 400 V. The low voltage switchgear, equipped with the SLBM fuse load switch consists of a set of independent components (Input, Output, Metering), which allows easy expansion of the switchgear to facilitate the design to a customer's specific requirements.

The Input unit can be equipped with a variety of load-switches of BSL-1600, R-1250 or INP-1250(1600) type. The Output panels are equipped with the SLBM type load switch.

Parameters of switchgear are the following:

- nominal voltage – 400 V,
- rated continuous nominal current – 1180 (1600) A,
- rated short-time withstand current – 16 kA (1s),
- rated peak withstand current – 35 kA,
- switchgear's dimensions: height - 1950 (support frame 1990) mm, width - 550 ÷ 1180 mm, depth - 400 (320) mm [76,104].

PRW is a low voltage metal-enclosed air-insulated switchgear equipped with load switch RB-2 or RB-25. It is a switchgear for 400 V. The switchgear is composed of various sets and with differing number of outlets. It is possible to assemble systems from a minimum of four fused load switches. Measuring current transformers can be placed on the top of the switchgear as an external component. The supply unit can be equipped with load-switches R-1250 or INP-1250 types. While the outlet panels are equipped with the fuse-load-switches of RB-2 or RB2S types.

Parameters of switchgear are the following:

- nominal voltage – 400 V,
- rated continuous nominal current – 1180 A,
- rated short-time withstand current – 16 kA,
- rated peak withstand current – 35 kA,
- switchgear's dimensions: height - 2100 (support frame 2140) mm, width - 625 ÷ 1175 mm, depth - 400 mm [76,104].

6.5. Simplified selection of transformer container station

Simplified selection of transformer container station:

1.Type of housing (Concrete, Metal, Aluminium)

A transformer substation in concrete enclosure is preferred.

2. Access service in transformer container station

A transformer container station with internal service access is required.

3.Number of transformers (1 or 2)

Transformer container station should be adapted to the required number of transformers.

4. Nominal power of transformers

Nominal power of transformers should be equal or less than permissible maximum transformer's power in transformer container station.

5. Nominal voltages of transformer container station

Medium voltage should be equal or less than permissible upper voltage of transformer container station.

6. Current conditions

Current conditions should be taken as standard for selected transformer container station.

7.Type of MV switchgear

It is determined by selected transformer container station.

8. Kind and number of quantities (branches) in MV switchgear

For one transformer station, it should be minimum 5 quantities (two line bays, one transformer bay, one measurement bay and one line bay (reserved)).

For two transformer stations, it should be minimum 7 quantities (two line bays, two transformer bays, one measurement bay, one coupling bay and one line bay (reserved)).

9. Current conditions

Current conditions should be taken as standard for selected MV switchgear.

10.Type of LV switchgear

It is determined by selected transformer container station.

11. Kind and number of quantities (branches) in LV switchgear

For one transformer station, it should be minimum 10 quantities (seven line bays, one measurement bay and two line bays (reserved)).

For two transformer stations, it should be minimum 12 quantities (eight line bays, one measurement bay, one coupling bay and two line bays (reserved)).

12. Current conditions

Current conditions should be taken as standard for selected LV switchgear.

7. SELECTING CABLES

7.1. Introduction

One of very important project tasks for planners is selection of cables for electrical installations. Insulated wires and flexible cables that conform to IEC standards are mostly used in wiring systems for electrical installations. These standards stipulate cable types for fixed installation and portable electrical equipment and contain specifications regarding cable construction, characteristics, tests, and information for users and planners.

Guidelines for selecting cables:

- selecting the rated voltage,
- selecting conductor cross-sectional areas.

The types of cables specified in these standards for electrical installations are:

- PVC-insulated cables,
- XLPE-insulated cables,
- rubber-insulated cables.

7.2. Selecting the rated voltage of cables

The rated voltage of an insulated cable is the key parameter of cables. It is the voltage on which its construction and testing of its electrical characteristics are based.

The rated voltage is expressed by two a.c. voltage values U_0/U where: U_0 means the r.m.s. value between an external conductor and ground in non-insulating environment and U means the r.m.s. value between any two phase conductors in a multi-core cable or a system of single-core cables.

Cables for low-voltage installations are built on values U_0/U: 100/100 V, 300/300 V, 300/500 V, 450/750 V oraz 0,6/1 kV.

In systems with a.c. voltage, the rated voltage of an insulated cable (U_{ni}) must be at least equal to the nominal voltage of the system in which it is used (U_n).

$$U_{ni} \geq U_n \tag{7.1}$$

This also applies to the values U_0 and U:

$$U_0 \geq U_n \text{ or} \tag{7.2}$$

$$U \geq U_n \tag{7.3}$$

The operating voltage is the voltage present between the conductors or between a conductor and ground in a power installation under normal conditions.

Cables with rated voltages $U_0/U \leq 0.6/1$ kV are suitable for use in three-phase and single-phase a.c. systems with an effectivly grounded neutral point or where the neutral point is not effectively grounded.

For standard low-voltage electrical installation (400/230V), cables with rated voltages: 300/500 V, 450/750 V are most suitable for usage. Cable with rated voltages 0,6/1 kV are specially suitable for LV supply cable.

For medium-voltage cables the rated voltage of cables is specified by the voltages $U_0/U(U_m)$ where U_0 is the voltage between an external conductor and a metal sheath or ground, U is the voltage between the external conductors of a three phase system: $U = \sqrt{3}U_0$, U_m is the maximum voltage for equipment U_m. It is the r.m.s. value of the highest phase-to-phase voltage for which an item of equipment is rated. With cables, the voltage is $U_m = 1.2 \cdot U$.

Cables for medium-voltage installations are built among other things on values $U_0/U(U_m)$: 3,6/6(7,2) kV; 6/10(12) kV; 8,7/15(17,5) kV; 12/20(24) kV and 18/30(36) kV.

7.3. Current load

Load is the short designation for current load. Load designates the currents that a cable may be required to carry during a particular type of operation, or in the event of a fault. The nominal operating current I_B for receivers is calculated from the nominal voltage U_n in V and the nominal effective power P_n in W:
for receivers of single-phase alternating current:

$$I_B = \frac{P_n}{U_{nf} \cdot \eta \cdot \cos\varphi} \quad \text{in A} \qquad (7.4)$$

U_{nf} - nominal phase voltage in V (for standard low-voltage electrical installation – 230 V),
$\cos\varphi$ - power factor,
η - efficiency (mainly for motors),

for receivers of three-phase alternating current:

$$I_B = \frac{P_n}{\sqrt{3} \cdot U_n \cdot \eta \cdot \cos\varphi} \quad \text{in A} \qquad (7.5)$$

Nominal effective power P_n of receiver is nominal power of motor (rated output) or nominal power of socket, etc.

Sometimes especially for medium-voltage cables the operating current I_B is calculated from the maximum permissible operating voltage U_{bmax} in kV and the effective power P for transmission in kW:
for three-phase current:

$$I_B = \frac{P}{\sqrt{3}U_{b\max} \cdot \cos\varphi} \text{ in A} \qquad (7.6)$$

For calculating load current for switchgear, it is necessary to determine current requirement for considered switchgear I_S :

$$I_B = I_S = \frac{P_S}{\sqrt{3} \cdot U_n \cdot \cos\varphi_S} \quad \text{in A} \qquad (7.7)$$

P_S - active power requirement for considered switchgear in kW,
U_N - nominal voltage of supply installation of considered switchgear in kV,
$\cos\varphi_S$ - power factor for considered switchgear.

Current requirement for considered switchgear I_S can be calculated according to the correlation:

$$I_S = \frac{S_S}{\sqrt{3} \cdot U_N} \text{ in A} \qquad (7.8)$$

S_S - apparent power requirement for considered switchgear in kVA.

7.4. Selecting conductor cross-sectional areas of cables

Conductor cross-sectional area of a cable is the most important parameter of cables. The selected conductor cross-sectional area must ensure that the current load under normal operating conditions does not exceed the current-carrying capacity of the conductor, and that no part of the conductor is at any time heated above the maximum permissible operating temperature. The temperature rise or current-carrying capacity of a cable with a particular cross-sectional area depends on its construction, its material properties, and the particular operating conditions.

The following requirement must always be fulfilled, whatever the particular operating conditions:

$$I_Z \geq I_B \qquad (7.4)$$

I_B - current load,
I_Z - current- carrying capacity.

Types of installation

Norm IEC [39] is the main standard to specify comprehensive recommended values for the current-carrying capacity of cables for fixed installation and of flexible cables.

Basic types of installation are the following:

- Installation type A – Installation in thermally-insulated walls,
- Installation type B – Installation of cables in conduit or duct on or in a wall,
- Installation type C – Installation of cables directly on or in a wall/under plaster,
- Installation type E – Installation of cables in free air.

The main representative installation conditions for each type of installation are following:

✓ Installation type A1, A2

- Installation in thermally-insulated walls
  - single-core non-sheathed cables in conduit (A1)
  - multi-core cable in conduit (A2)
  - multi-core cable in wall (A2)

✓ Installation type B1, B2

- Installation in conduit or ducts
  - single-core non-sheathed cables in conduit on wall (B1) (conduits are installed on walls in such a way that the clearance between the conduit and wall is less than 0,3 × the diameter of the conduit)
  - single-core non-sheathed cables in conduit on wall (B1)
  - single-core non-sheathed cables, single-core light-sheathed cable, or multi-core cable in conduit in wall or under plaster (B1)
  - multi-core cable in conduit on wall or on floor (B2) (conduits are installed on walls in such a way that the clearance between the conduit and wall is less than 0,3 × the diameter of the conduit)
  - multi-core cable in conduit on wall or on floor (B2)

✓ Installation type C

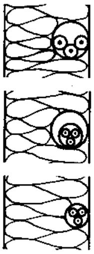
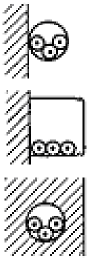
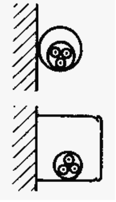
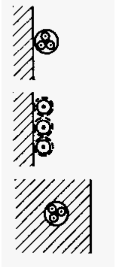
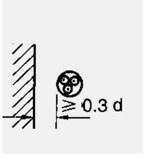
- Direct installation
  - multi-core cable on wall or floor
  - single-core light-sheathed cable on wall or floor
  - multi-core cable in wall or under plaster
  - flat webbed cables under plaster

✓ Installation type E

- installation in free air, i.e. unhindered heat dissipation is ensured by:
  - clearance from wall
  - clearance ($\geq 2 \times$ cable diameter) between cables installed side by side
  - clearance ($\geq 2 \times$ cable diameter) between cable runs above one another

Selected examples of methods of cable laying are shown in Table 7.1.

Table 7.1. Methods of cable laying [39,56]

Installation type				
A	B1	B2	C	E
				

A representative selection of additional installation types can be found in Table 7.2, together with references to the installation types that specify the current-carrying capacity.

Table 7.2. Common fixed installations and corrensponding installation types [15,39,56]

Description of installations	Installation type for determining current-carrying capacity
Single-core non-sheathed cables in conduit in thermally insulated wall	A1
Multi-core cable or multi-core light-sheathed cable in conduit in thermally-insulated wall	A2
Multi-core cable or multi-core light-sheathed cable installed directly in thermally-insulated wall	A2
Single-core non-sheathed cables, single-core cables or light sheathed cables in conduit on (wooden) wall, or with clearance of less than 0,3 × outer diameter of conduit	B1
Multi-core cable or multi-core light-sheathed cable in conduit on (wooden) wall, or with clearance of less than 0,3 × outer diameter of conduit	B2
Single-core non-sheathed cables, single-core cables, or light-sheathed cables in enclosed conduit on (wooden) wall	B1
Multi-core cable or multi-core light-sheathed cable in enclosed conduit on (wooden) wall	B2
Single-core non-sheathed cables, single-core cables, or light-sheathed cables in conduit in masonry/concrete	B1
Multi-core cable or multi-core light-sheathed cable in conduit in masonry/concrete	B2
Single-core or multi-core cable(s) or light-sheathed cable installed on (wooden) wall or with clearance less than 0,3 × outer diameter of cable between cable and wall	C
Single-core or multi-core cable(s) or light-sheathed cable installed under (wooden) ceiling	C

Single-core or multi-core cable(s) or light-sheathed cable installed with clearance more than 0,3 × outer diameter of cable between cable and ceiling	E
Single-core or multi-core cable(s) or light-sheathed cable on cable tray (blank)	C or E
Single-core or multi-core cable(s) or light-sheathed cable on cable tray (perforated), horizontal or vertical	E
Single-core or multi-core cable(s) or light-sheathed cable on cable consoles	E
Single-core or multi-core cable(s) or light-sheathed cable on cable ladder	E
Single-core or multi-core cable(s) or light-sheathed cable in conduit in building cavity building cavity 1) 2)	B2 $1.5d \le V < 5d$ B1 $5d \le V < 50d$
Single-core non-sheathed cables in conduit in building cavity 1) 2)	B2 $1.5d \le V < 20d$ B1 $20d \le V$
Single-core or multi-core cable(s), or light-sheathed cable in conduit in building cavity	B2
Single-core non-sheathed cables in enclosed conduit in building cavity 1) 2)	B2 $1.5d \le V < 20d$ B1 $20d \le V$
Single-core or multi-core cable(s), or light-sheathed cable in enclosed conduit in building cavity	B2
Single-core non-sheathed cables in enclosed conduit in masonry/concrete	B2 $1.5d \le V < 5d$ B1 $5d \le V < 50d$
Single-core or multi-core cable(s) or light-sheathed cable in enclosed conduit in masonry/concrete	B2
Single-core or multi-core cable(s) or light-sheathed cable in ceiling cavity 1) 2) or in raised floor 1) 2)	B2 $1.5d \le V < 5d$ B1 $5d \le V < 50d$
Single-core non-sheathed cables, single-core cable or light-sheathed cable in conduit on wooden wall - horizontal installation	B1
Single-core non-sheathed cables, single-core cable or light-sheathed cable in conduit on wooden wall – vertical installation	B1
Multi-core cable(s) or light-sheathed cable in conduit on wooden wall – horizontal installation	B2
Multi-core cable(s) or light-sheathed cable in conduit on wooden wall – vertical installation	B2
Single-core non-sheathed cables in duct for underfloor installation	B1
Multi-core cable(s) or light-sheathed cable in conduit for underfloor installation	B2
Single-core non-sheathed cables in suspended conduit	B1
Multi-core cable(s) or light-sheathed cable in suspended conduit	B2
Single-core non-sheathed cables in conduit with non-ventilated duct (horizontal or vertical installation) 1) 2)	B2 $1.5d \le V < 5d$ B1 $5d \le V < 50d$
Single-core non-sheathed cables in conduit with ventilated duct in floor	B1
Single-core or multi-core cable or light-sheathed cable in an open or ventilated duct (horizontal or vertical installation)	B1
Single-core or multi-core cable(s) or light-sheathed cable installed directly in masonry/concrete without additional mechanical protection	C
Single-core or multi-core cable(s) or light-sheathed cable installed directly in masonry/concrete with additional mechanical protection	C

1) V is the smaller measurement or the diameter of a building duct /cavity; or the internal height of a rectangular, enclosed conduit, floor or ceiling cavity.
2) d is the outer diameter of a multi-core cable or a multi-core light-shealted cable.
D is 2,2 × the outer diameter if three single-core cables or single-core light-shealted cables are grouped in a trefoil arrangement
d is 3 × the outer diameter if single-core cables or single-core light-shealted cables are installed flat in one plane.

Cable installation methods

Cables in industrial buildings are installed following standard methods:

- Surface installation,
- Flush installation,
- Cable raceways,
- Cable ducts for walls and ceilings.

With surface installation, the incoming cables to the loads as well as switches and socket-outlets of power installations and communication systems are secured directly to the wall of the building using spacing saddles, in plastic/high strength steel conduits or in duct systems.

With flush installation, the incoming cables are installed directly in the unfinished wall or in conduits and duct systems to protect them against damage and then plastered over.

Cables, which frequently have to be relaid or installed at a later stage in electrical systems in industrial plants, can be installed conveniently in cable raceways, cable ladders, cable troughs, gridways, and cable routes made of hot-dip galvanized steel or plastic. These cable routes are usually laid in cable ducts, under ceilings in corridors, or in suspended ceilings. The cables are, generally, only inserted in the raceways from above. The cable raceways can be mounted on wall brackets or are suspended from the ceiling using hangers and clamping brackets. Cable raceways have a modular design and consist of cable troughs, connectors, and accessories.

The cable ducts made of impact-resistant plastic or metal, or a combination of the two materials, are used to install cables of power installations on walls and ceilings. They permit cables to be rearranged or new cables to be installed if the system is modified.

The ducts are available with:

- welded cross members,
- removable retaining clips.

Ducts with welded cross members are extremely stable and are, therefore, usually mounted on ceilings in premises used for industrial purposes.

Low-profile ducts with retaining clips are preferred for wall mounting in offices, laboratories, or workshops.

Ducts with welded cross members consist of a base and a clip-on cover. The welded cross members give the duct the stability of a rectangular pipe.

Short gudellines for laying cables

Cables must either be equipped with a convering or positioned to technical standards (IEC, others) to provide adequate protection against mechanical damage. Within normal arm's reach, a covering is always required to protect cables against mechanical damage.

At points subject to particular hazards, such as floor bushings, all cables must be provided with additional protection, e.g. by means of slip-over plastic or steel conduits, or other coverings, which must be fixed securely.

Cables in and under plaster, as well as behind wall paneling, must be routed vertically or horizontally or parallel to the edges of the room.

With single-core non-sheathed cables in conduits or ducts, only the conductors of one main circuit may be laid in the same conduit/duct. This requirement does not apply to closed electrical operating areas.

Several main circuits may be combined in one multi-core cable/flexible cable, provided this is not prohibited by other standards.

If auxiliary circuits are installed separately from the main circuits, several auxiliary circuits may be combined in a multi-core cable. The same applies to single-core non sheathed cables in a conduit or duct.

Flexible cables may only be laid directly in concrete that has been shaken or tamped if they are installed in conduits. Light-sheathed cables, however, may be installed in recesses and covered with concrete in a similar way to underplaster installation.

Flexible cables must not, under any circumstances, be laid in the ground or in inaccessible underground ducts on buildings.

Current-carrying capacities of cables

The current-carrying capacities are specified in norm [39,56] for PVC-insulated cables, XLPE-insulated cables and rubber-insulated cables etc. Values for current-carrying capacity are always based on clearly defined operating conditions and were determined on the basis of the most unfavourable installation conditions. For example, all the values specified for Installation Types B and C apply to installation on wooden walls. Sometimes, however, cables are installed on wall surfaces with more favourable heat dissipation than wood.

The current-carrying capacities of PVC-isulated copper cables with a permissible operating temperature of 70 °C for fixed installation in buildings are listed in Table 7.3 for installation types Al, A2, B1, B2, C, and E. The values specified here apply for a maximum ambient temperature of 30 °C, which is usual in Poland and other central European countries.

Tab 7.3. Current-carrying capacity. Cables for fixed installation. Installation types A1, A2, B1, B2, C, and E (Insulation PVC, Maximum permissible operating tempetature: 70 °C, Ambient temperature: 30 °C) [15,39,52]

Installation type	A1	A1	A2	A2	B1	B1	B2	B2	C	C	E	E
No. of loaded conductors	2	3	2	3	2	3	2	3	2	3	2	3
Rated cross-sectional area of copper conductor in mm	Current-carrying capacity in A											
1,5	15,5	13,5	15,5	13,0	17,5	15,5	16,5	15,0	19,5	17,5	22	18,5
2,5	19,5	18,0	18,5	17,5	24	21	23	20	27	24	30	25
4	26	24	25	23	32	28	30	27	36	32	40	34
6	34	31	32	29	41	36	38	34	46	41	51	43
10	46	42	43	39	57	50	52	46	63	57	70	60
16	61	56	57	52	76	68	69	62	85	76	94	80
25	80	73	75	68	101	89	90	80	112	96	119	101
35	99	89	92	83	125	110	111	99	138	119	148	126
50	119	108	110	99	151	134	133	118	168	144	180	153
70	151	136	139	125	192	171	168	149	213	184	232	196
95	182	164	167	150	232	207	201	179	258	223	282	238
120	210	188	192	172	269	239	232	206	299	259	328	276

The current-carrying capacities of XLPE–isulated copper cables with a permissible operating temperature of 90 °C for fixed installation in buildings are listed in Table 7.4 for installation types Al, A2, B1, B2, C, and E.

Tab 7.4. Current-carrying capacity. Cables for fixed installation. Installation types A1, A2, B1, B2, C, and E (Insulation XLPE, Maximum permissible operating tempetature: 90 °C, Ambient temperature: 30 °C) [15,39,52]

Installation type	A1	A1	A2	A2	B1	B1	B2	B2	C	C	E	E
No. of loaded conductors	2	3	2	3	2	3	2	3	2	3	2	3
Rated cross-sectional area of copper conductor in mm	Current-carrying capacity in A											
1.5	19,0	17,0	18,5	16,5	23	20	22	19,5	24	22	26	23
2.5	26	23	25	22	31	28	30	26	33	30	36	32
4	35	31	33	30	42	37	40	35	45	40	49	42
6	45	40	42	38	54	48	51	44	58	52	63	54
10	61	54	57	51	75	66	69	60	80	71	86	75
16	81	73	76	68	100	88	91	80	107	96	115	100
25	106	95	99	89	133	117	119	105	138	119	149	127
35	131	117	121	109	164	144	146	128	171	147	185	158
50	158	141	145	130	198	175	175	154	209	179	225	192
70	200	179	183	164	253	222	221	194	269	229	289	246
95	241	216	220	197	306	269	265	233	328	278	352	298
120	278	249	253	227	354	312	305	268	382	322	410	346

The current-carrying capacities for cables installed in buildings or in air apply, for example, to individually installed single-core and multi-core cables operated in three-phase a.c. systems (if three conductors are loaded), or in single-phase a.c. systems (if two conductors are loaded). These operating conditions presuppose that no other non-loaded conductors are involved.

The current-carrying capacities for cables are connected with the reference values (e.g. ambient temperature, grouping). When cables are actually installed, the appropriate conversion factors may have to be used to take account of site operating conditions deviating from the reference values (e.g. different ambient temperatures, grouping). In this situation, it is necessary to use: conversion factors for site ambient temperatures, conversion factors for grouping or for multi-core cables.

The current-carrying capacity I'_Z for the actual operating conditions is calculated by multiplying the rated value I_Z (Tables 7.3, 7.4) by the product of all the relevant conversion factors (Tables 7.5 to 7.8) using the following equation:

$$I'_Z = I_Z \cdot k_g \cdot k_t \tag{7.5}$$

k_g – conversion factor for grouping,
k_t – conversion factor for site ambient temperatures.

In this situation the following requirement must always be fulfilled, whatever the particular operating conditions:

$$I'_Z \geq I_B \tag{7.6}$$

I_B - current load,
I'_Z - current- carrying capacity for the actual operating conditions.

Then, the following correlation must be taken into consideration:

$$I_Z \cdot k_g \cdot k_t \geq I_B \tag{7.7}$$

and

$$I_Z \geq \frac{I_B}{k_g \cdot k_t} \tag{7.8}$$

The current-carrying capacity must be determined for:

- normal operating conditions,

Permissible operating temperature

The permissibbe operating temperature is the maximum permissible temperature of the conductor during normal operation. This temperature is used to calculate the current-carrying capacity during normal operation, and is specified in accordance with the service life in the relevant construction specifications.

The temperature rise of a cable depends on its construction, material properties, and the specific operating conditions. Additional temperature rises (caused by grouping with other cables, heating lines, etc.) must be taken into account. Impermissibly high operating temperatures and temperature rises cause cables to age more rapidly.

The permissible temperature rise of a cable is determined by means of the permissible operating temperature and the ambient temperature.

The perrnissible operating temperature is mainly determined by the insulation of a cable. For PVC-insulated cable, the permissible operating temperature is 70°C, however, for XLPE-insulated cable – 90°C.

Ambient conditions

Standard ambient temperature for Poland and other central European countries is 30°C. But sometimes for central European conditions the ambient temperatures are different. For cables installed in free air the ambient temperature is 20 °C (unheated cellars) or 25°C (rooms without air-conditioning (not heated in summer)). For cables installed in the ground with installation depth 0,7 m to 1,0 m, the ambient temperature is 20 °C. Ambient temperatures over 30 °C occur, for example: where there is insufficient protection against direct solar radiation or in poorly ventilated rooms or with machines or installations with high heat dissipation.

Conversion factors for site ambient temperatures for PVC-isulated copper cables for fixed installation in buildings are listed in Table 7.5.

Conversion factors for site ambient temperatures for XLPE-isulated copper cables for fixed installation in buildings are listed in Table 7.6.

Table 7.5. Conversion factors for ambient temperatures other than 30°C (Insulation PVC, Maximum permissible operating temperature 70°C) [15,39,52]

Ambient temperature in °C	Conversion factor
10	1,22
15	1,17
20	1,12
25	1,06
30	1,00
35	0,94
40	0,87
45	0,79
50	0,71
55	0,61
60	0,50
65	0,35

Table 7.6. Conversion factors for ambient temperatures other than 30°C (Insulation XLPE, Maximum permissible operating temperature 90°C) [15,39,52]

Ambient temperature in °C	Conversion factor
10	1,15
15	1,12
20	1,08
25	1,04
30	1,00
35	0,96
40	0,91
45	0,87
50	0,82

Conditions for grouping cables

Conversion factors for multi-core cables for PVC-isulated copper cables for fixed installation in buildings are listed in Table 7.7.

Table 7.7. Conversion factors for multi-core cables with rated cross-sectional area less or equal 10 mm^2 [15]

Number of loaded cores	Conversion factor
5	0,75
7	0,65
10	0,55
14	0,50
19	0,45
24	0,40
40	0,35
61	0,30

Conversion factors for grouping for different arrangement of installation in buildings are listed in Table 7.8. When these conversion factors are applied to the values in Table 7.8 the number of loaded cores, type of cable, and installation type must conform. When multi-core cables and two or three loaded cores are grouped together, the conversion factor of total number of grouped cables must be selected and applied to the current-carrying capacity for cables with two or three loaded cores.

Table 7.8 Conversion factors, for grouping [15,39,52]

Number *	Arrangement								
	Trefoil arrangement directly on wall, on floor, in conduit or duct on or in wall (installation types A to E)	One layer on wall or on floor, touching (installation type C)	One layer on wall or on floor, with spacing equal to outer diameter of cable *d* (installation type C)	One layer under ceiling, touching (installation type C)	One layer under ceiling, with spacing equal to outer diameter of cable *d* (installation type C)	One layer on cable tray (perforated), horizontal or vertically, touching (installation type E) I $\geq 20mm$	One layer on cable tray (perforated), horizontal or vertically, touching (installation type E) II	One layer on cable tray (perforated), horizontal or vertically, touching (installation type E) III $\geq 225mm$	One layer on cable rack or on cable clamps etc. touching (installation type E)
1	1,00	1,00	1,00	0,95	0,95	1,00	1,00	1,00	1,00
2	0,80	0,85	0,94	0,81	0,85	0,88	0,88	0,88	0,87
3	0,70	0,79	0,90	0,72	0,85	0,82	0,82	0,81	0,82
4	0,65	0,75	0,90	0,68	0,85	0,79	0,78	0,76	0,80
5	0,60	0,73	0,90	0,66	0,85	0,77	0,75	0,73	0,80
6	0,57	0,72	0,90	0,64	0,85	0,76	0,73	0,71	0,79
7	0,54	0,71	0,90	0,63	0,85	0,76	0,73	0,71	0,79
8	0,52	0,70	0,90	0,62	0,85	0,73	0,73	0,71	0,78
9	0,50	0,70	0,90	0,61	0,85	0,73	0,72	0,70	0,78
10	0,48	0,70	0,90	0,61	0,85	0,73	0,72	0,70	0,78
12	0,45	0,70	0,90	0,61	0,85	0,73	0,72	0,70	0,78
14	0,43	0,70	0,90	0,61	0,85	0,73	0,72	0,70	0,78
16	0,41	0,70	0,90	0,61	0,85	0,73	0,72	0,70	0,78
18	0,39	0,70	0,90	0,61	0,85	0,73	0,72	0,70	0,78
20	0,38	0,70	0,90	0,61	0,85	0,73	0,72	0,70	0,78

Number* - Number of multi-core cables or number of single-phase or three-phase a.c. electric circuits comprising single-core cables (2 or 3 current-carrying conductors)

7.5. Specified voltage drop

A constant service voltage is essential for proper functioning of much equipment. For this reason, cables must be rated to ensure that the permissible voltage drop is not exceeded. This case also requires maximum values for the lengths of cables, based on the expected load current.

The following requirement must always be fulfilled, whatever the particular operating conditions:

$$\Delta U_{\%} \leq \Delta U_{\%\max} \tag{7.8}$$

$\Delta U_{\%}$ - percentage voltage drop in cable,

$\Delta U_{\%\max}$ - permissible percentage voltage drop.

The percentage voltage drop $\Delta U_{\%}$ relative to the nominal system voltage U_n is calculated according to the formula:

$$\Delta U_{\%} = \frac{\Delta U}{U_n} \cdot 100\% \tag{7.9}$$

ΔU - voltage drop in cable in V.

When a low-voltage distribution system is dimensioned, a permissible voltage drop of approx. 8% is possible. If lower voltage tolerances are required by the loads used, they must be allowed for when the distribution system is being dimensioned.

At present, the standards do not contain generally applicable international reference values for the partial voltage drops of a supply concept. Different references in the European countries recommend a voltage drop of 4% between the distribution system and electrical equipment. For Polish conditions, recommendations for maximum permissible percentage voltage drop in industry distribution network are shown in Fig. 7.1.

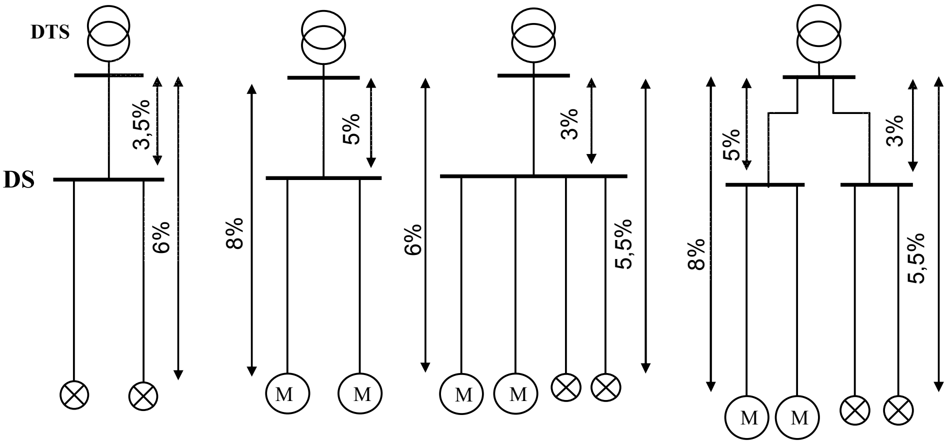


Fig. 7.1. Values of maximum permissible percentage voltage drops in industry distribution network supplied from own transformer substations: MV/LV: DTS – division transformer substation MV/LV, DS – division switchgear [4]

Percentage voltage drop $\Delta U_{\%}$ is calculated according to suitable formulas:
for one-phase circuit alternating current:

$$\Delta U_{\%} = \frac{200}{U_{nf}} I_B \left(R\cos\varphi + X\sin\varphi \right) \tag{7.10}$$

for three phase circuit alternating current:

$$\Delta U_{\%} = \frac{100\sqrt{3}}{U_n} I_B \left(R\cos\varphi + X\sin\varphi \right) \tag{7.11}$$

U_{nf} - nominal phase voltage in V (for standard low-voltage electrical installation – 230 V),
U_n - nominal voltage in V,
I_B - current load in A,
R – resistance of supplied cable in Ω (calculated according formula 7.12 or 7.13),
X – reactance of supplied cable in Ω, (calculated according formula 7.14),
$\cos\varphi$ - power factor (φ is the phase angle between the voltage U and the load current I_B that lags behind it (inductive load)),

$$R = \frac{l}{\gamma \cdot S} \tag{7.12}$$

$$R = r' \cdot l \cdot 10^{-3} \tag{7.13}$$

$$X = x' \cdot l \cdot 10^{-3} \tag{7.14}$$

l – lengh of considered cable in m,
γ – conductivity of conductor material in $\frac{\mathrm{m}}{\Omega \cdot \mathrm{mm}^2}$ (for copper $\gamma_{cu} = 56\ \frac{\mathrm{m}}{\Omega \cdot \mathrm{mm}^2}$, for aluminium $\gamma_{Al} = 33\ \frac{\mathrm{m}}{\Omega \cdot \mathrm{mm}^2}$),
S – conductor cross-sectional area of a cable in mm^2,
r' – resistance of cable per unit length in $\frac{\mathrm{m\Omega}}{\mathrm{m}}$,
x' – reactance of cable per unit length in $\frac{\mathrm{m\Omega}}{\mathrm{m}}$ (for cables standard values: $0{,}07 \div 0.08\ \frac{\mathrm{m\Omega}}{\mathrm{m}}$).

The resistances per unit length can be taken directly from catalogues of cables, the reactances per unit length can be calculated using the inductance specifications in catalogues of cables or different references.

When the voltage drop in cables with a conductor cross-sectional area of up to 16 mm^2 in single-phase and three-phase a.c. systems is calculated, only the resistance per unit length of the cable at operating temperature has to be taken into account. For cables with conductor cross-sectional areas greater than 16 mm^2 in single-phase a.c. and three-phase a.c. systems, however, the resistance and reactance must be considered. With non-armored cables and especially with insulated wiring cables and flexible cables, the limit is considerably higher. In Poland, it is suitably 50 mm^2 for copper cables and 70 mm^2 for aluminium cables.

In this situation, percentage voltage drop $\Delta U_{\%}$ is calculated according to suitable formulas:
for one-phase circuit alternating current:

$$\Delta U_{\%} = \frac{200 \cdot P \cdot l}{\gamma \cdot S \cdot U_{nf}^2} \tag{7.15}$$

for three-phase circuit alternating current:

$$\Delta U_{\%} = \frac{100 \cdot P \cdot l}{\gamma \cdot S \cdot U_{n}^2} \tag{7.16}$$

P - effective power P for cable transmission in W (e.g. nominal power of receiver /rated output/).

Sometimes planners use transformed formulas: 7.15 and 7.16, which let calculate required minimum values for the conductor cross-sectional area of cables, based on the permissible percentage voltage drop $\Delta U_{\%\max}$.

These formulas are the following:
for one-phase circuit alternating current:

$$S \geq \frac{200 \cdot P \cdot l}{\gamma \cdot \Delta U_{\%\max} \cdot U_{nf}^2} \tag{7.17}$$

for three-phase circuit alternating current:

$$S \geq \frac{100 \cdot P \cdot l}{\gamma \cdot \Delta U_{\%\max} \cdot U_{n}^2} \tag{7.18}$$

In low-voltage systems in particular, checks must be carried out to determine whether the conductor cross-sectional area selected with regard to the current-carrying capacity fulfills the requirements relating to the voltage drop.

In medium-voltage systems, it is also advisable to carry out this type of check.

One-stage radial system or multi-stage radial system are often used in low voltage systems of industrial plants (Fig. 2.3, Fig 2.4). Such systems have loads in many nodal points (Fig. 7.2). The voltage drop between determined network points (switchboards) requires adding up voltage drops for individual lengths of current circuit. In this situation, the voltage drop ΔU_{1n} between switchboards S1 and Sn is calculated according to the formula:

$$\Delta U_{1n} = \sum_{i=1}^{n\text{-}1} \Delta U_{i(i+1)} \tag{7.19}$$

$\Delta U_{i(i+1)}$ - voltage drop between network points *(i)* and *(i+1)* in V,
n – number of network points.

For calculating voltage drop at radial current circuit, it is necessary to allow for value of transmitted power by analysed circuit and its length. For example from Fig. 7.2, the voltage drop between points S1 and S3 is $\Delta U_{13} = \Delta U_{12} + \Delta U_{23}$, however, between points S1 and S4 - $\Delta U_{14} = \Delta U_{12} + \Delta U_{24}$.

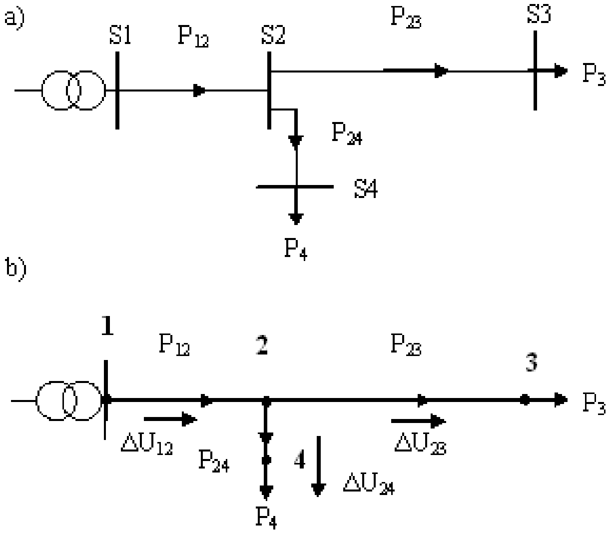


Fig. 7.2. The principle for determining voltage drop in multi-stage radial system: a) diagram of supplied system: S1, S2, S3, S4 – successive switchboards, P_i – effective power of load, P_{ij} – effective power of transmission b) equivalent diagram for calculating the voltage drops: ΔU_{ij} – voltage drop between points *(i)* and *(j)*

7.6. Protection against overcurrents

Overload protection

Overcurrents include overload currents as well as short-circuit currents. Over a limited period of time, these give rise to conductor temperatures that exceed the permissible operating temperatures.

Overload currents are caused by overloading during normal operation of fault-free circuits. The permissible temperatures for conditions of this type depend on the duration/number of overloads, which, in turn, depend on the heat/pressure performance characteristics of cables, and the effects of accelerated aging.

Short-circuit currents are caused by faults between live conductors with negligible impedance, which have different potentials during normal operation. The permissible short circuit temperatures are restricted in the extreme accident to a maximum short-circuit duration of 5 seconds.

Overcurrent protection devices must be used to protect cables against excessive temperature rises. It may be necessary to dimension the conductor cross-sectional area in accordance with the specifications for thermal short-circuit ratings of the short-circuit load as well.

Depending on the type selected, overcurrent protective devices provide protection against overloads and short circuits, or one of these conditions only.

Overcurrent protective devices for providing protection against overloads and/or short circuits must be installed at the origin of each electric circuit, as well as at points in the circuit where the current-carrying capacity or short-circuit rating is reduced. This can occur, for example, with reduced conductor cross-sectional areas, or when cable installation conditions are changed and the upstream protective device can no longer provide adequate protection.

The following conditions must be fulfilled for suitable protection of cables against excessive temperature rises in the event of an overload:

$$I_B \leq I_n \leq I'_Z \tag{7.20}$$

$$I_2 \leq 1.45 \cdot I'_Z \tag{7.21}$$

I_B - prospective operating current of electric circuit,

I_n - rated current of overcurrent protective device (for settable overcurrent protective devices, I_n corresponds to the setting value),

I'_z – corrected current-carrying capacity (for the actual operating conditions – formula 7.5),

I_2 - current that causes the overcurrent protective device to trip under the conditions defined in the device specifications (conventional tripping current).

Conditions (7.20) and (7.21) define protection against overload. They are often determined as coordination of protection. When one of these conditions is not fulfilled, it is necessary to increase the rated conductor cross-sectional area of cable. It results in an increase of the value of current-carrying capacity. This procedure should be introduced until all two conditions are fulfilled.

The applicable value of current-carrying capacity of the cable in formulas: (7.20) and (7.21) concerns the conditions for the cables which are protected differ from nominal. These differences can be connected with: other environmental conditions, other ambient temperatures, grouped cables or installation of cables in the ground. For nominal conditions, value I'_z should be replaced with the value of current-carrying capacity I_z.

The rated current I_n may equal the current-carrying capacity I_z when overload protection equipment is used, to which $I_2 \leq 1.45 \cdot I_n$ applies. This property is included in miniature circuit-breakers, circuit-breakers and fuses as these overcurrent protective devices have a maximum conventional tripping current of 1,45 × their rated current.

The rated current I_n depends on kind of applicable overcurrent protective device for protection of receiver and cable. For fuse, it is a nominal curent of fuse I_{NF} (Fig.7.3a). For thermistor-type motor protection, it is a nominal curent of thermistor setting I_{NTh} (Fig.7.3b).

With overcurrent protective devices equipped with settable overcurent releases (such as circuit-breakers), I_n corresponds to the setting value of the release.

The conventional tripping current I_2 depends on kind of applicable overcurrent protective device for protection of receiver and cable. For fuse, it is a large test current of fuse I_f (Fig.7.3a). The interrupting behaviour of the fuse links is characterized by the small test current I_{nf} (no fusing during the test period) and the large test current I_f (interruption during the test period), The value of the large test current of fuse depends on: time/current characteristics, test period and rated current of fuse (Table 7.9).

For thermistor-type motor protection, I_2 equals 1,45$\cdot I_{NTh}$ (Fig.7.3b).

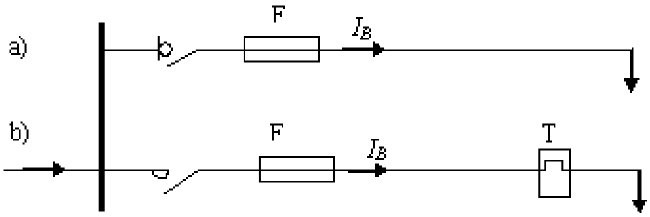


Fig. 7.3. Selected means of protection against overload: F – fuse, T – thermistor-type motor protection, I_B – current load [4]

In the following cases, it is permissible, to dispense with an overload protective device:

- in cable joints, in which the occurrence of overcurrents does not have to be taken into account,
- in connecting cables between electrical machines, starters, transformers, rectifiers, batteries, switchgear or similar parts of systems,
- in auxiliary circuits,
- in public utility networks comprising cables installed in the ground or overhead lines [15].

Table 7.9. Values of test current for gG and gL fuse links [1]

Type of fuse links	Rated current I_{NF} A	test period h	test current I_{nf}	test current I_f
gG	$I_{NF} \leq 4$	1	$1.50 \cdot I_{NF}$	$2.10 \cdot I_{NF}$
	$4 < I_{NF} \leq 16$	1	$1.50 \cdot I_{NF}$	$1.90 \cdot I_{NF}$
	$16 < I_{NF} \leq 63$	1	$1.25 \cdot I_{NF}$	$1.60 \cdot I_{NF}$
	$63 < I_{NF} \leq 160$	2	$1.25 \cdot I_{NF}$	$1.60 \cdot I_{NF}$
	$160 < I_{NF} \leq 400$	3	$1.25 \cdot I_{NF}$	$1.60 \cdot I_{NF}$
	$400 < I_{NF}$	4	$1.25 \cdot I_{NF}$	$1.60 \cdot I_{NF}$
gL	$I_{NF} = 4$	1	$1.50 \cdot I_{NF}$	$2.10 \cdot I_{NF}$
	$4 < I_{NF} \leq 10$	1	$1.50 \cdot I_{NF}$	$1.90 \cdot I_{NF}$
	$10 < I_{NF} \leq 25$	1	$1.40 \cdot I_{NF}$	$1.75 \cdot I_{NF}$
	$25 < I_{NF} \leq 63$	1	$1.30 \cdot I_{NF}$	$1.60 \cdot I_{NF}$
	$63 < I_{NF} \leq 160$	2	$1.30 \cdot I_{NF}$	$1.60 \cdot I_{NF}$
	$160 < I_{NF} \leq 400$	3	$1.30 \cdot I_{NF}$	$1.60 \cdot I_{NF}$
	$400 < I_{NF}$	4	$1.30 \cdot I_{NF}$	$1.60 \cdot I_{NF}$

Overload like short-circuit protective devices should not be used if interrupting the electric circuit could give rise to a hazardous situation, e.g.

- in the field circuits of rotating machines,
- in the supply circuits of solenoids,
- in the secondary circuits of current transformers,
- in electric circuits used for safety purposes, such as fire-extinguishing, safety lighting, smoke and heat extraction systems, etc.

The cable runs in these electric circuits should be designed so that damaging temperature rises due to overload currents do not have to be taken into account.

Short-circuit protection

Short-circuit protective devices are designed to interrupt the short-circuit currents in the conductors of an electric circuit, before they can cause a temperature rise that would endanger the conductor insulation, connecting points and junctions, as well as the surroundings of the cables.

The breaking capacity of the protective device must be at least equal to the highest current in the event of a dead short circuit at the point of installation. However, a lower breaking capacity is permissible if the device is backed up by another which has the necessary capacity. In this case, the characteristics of the two devices must be coordinated so that the downstream device and the protected cable cannot be damaged (energy throughput, weld resistance, dynamic strength of current paths).

If overload protection is not required for a particular electric circuit, or if, for special reasons, a shared overcurrent protective device is not necessary, the short-circuit protective device is selected in accordance with the conductor cross-sectional area to be protected, the circuit length, and the loop impedance of the system on the supply side.

The following condition must be fulfilled for suitable protection of cables against excessive temperature rises in the event of short-circuit current:

$$t_s \le t_{km} \tag{7.22}$$

t_s - break-time for short-circuit protective device in the event of a short circuit in s,
t_{km} - permissible break-time in the event of a short circuit in s.

The following relationship applies for the permissible time until the required disconnection of short-circuit current at any point of an electric circuit:

$$t_{km} = \left[k \frac{S}{I_k''} \right]^2 \tag{7.23}$$

I_k'' - r.m.s. value of the current with an assumed dead short-circuit in A (initial symmetrical short-circuit current),
S – conductor cross-sectional area of a cable in mm^2,
k - material coefficient of the conductor material in $[\frac{A}{\sqrt{\Omega} \cdot mm^2}]$ (with values of 115 for PVC-insulated copper conductor; 76 for PVC-insulated aluminium conductor; 141 for rubber-insulated copper conductor; 87 – for rubber-insulated aluminium conductor; 115 for soft solder joints in copper conductor).

Sometimes planners use transformed formulas: 7.22 and 7.23, which allow to calculate required minimum value for the conductor cross-sectional area of cables, based on the break-time for short-circuit protective device in the event of a short circuit t_s.

This formula is the following:

$$S \geq \frac{I''_k}{k}\sqrt{t_s} \qquad (7.24)$$

Condition (7.22) define protection in the event of short-circuit. It is often determined as third condition for coordination of protection. When condition is not fulfilled, it is necessary to increase the rated conductor cross-sectional area of cable. This procedure should be introduced until the condition is fulfilled.

Break-time t_s depends on the kind of applicable overcurrent protective device for protection of receiver and cable, their time/current characteristics and the value of current on dead short-circuit. Generally, it is taken from the time/current characteristics for applicable overcurrent protective device for maximum expected current on dead short-circuit. For fuse, it is the time response of fuse (time of current switching off by fuse). It is taken from the time/current characteristics for fuse link (about a nominal curent of fuse- I_{NF}) of applicable duty class (e.g. gG), for current I''_k.

If the permissible break time are very short (< 0,01 s), the product $k^2 \cdot S^2$ obtained from the equation (7.23) must be greater than the value $I''_k \cdot t_{km}$. In such a case, it is necessary to use a characteristics of Joule integral $\int_t I^2 dt$ for applicable overcurrent protective device, stated by the manufacturer of the device.

In general, a permissible break-time t_{km} of 5 s can be assumed for short circuits.

The current in the event of a dead short circuit (point at which dead short circuit occurred) or the loop impedance of the short circuit loop can be determined by means of: calculation and/or simulations using system models and/or system measurements.

The prerequisite for effective protection in the event of a short circuit is that the fault current reaches the trip value of the short-circuit protection device. This means that the resistance of the cable, i.e. its length, must not exceed a specified limit value. The upstream loop impedance between the power source and the protection device must be taken into account here. Planners in some European countries for checking the protection use value of permissible maximum lengths for short-circuit protection with applicable protective devices (ensuring the permitted break times t_{km}) [15].

In a practical solution, for short-circuit current remote from generator terminals, value of initial symmetrical short-circuit current for three-phase short circuit $I''_{k3\max}$ is taken to calculation of permissible break-time in the event of a short circuit.

The following relationship applies for initial symmetrical short-circuit current:

$$I''_{k3\max} = \frac{c_{\max} \cdot U_n}{\sqrt{3} \cdot |\underline{Z}_{K3}|} \qquad (7.25)$$

$I''_{k3\max}$ – maximum initial symmetrical short-circuit current in A,

$c_{\max}$ –voltage factor for maximum short-circuit current (for MV $c = 1{,}1$, for LV $c = 1{,}0$),

U_n - nominal voltage in V,

$|\underline{Z}_{K3}|$ – module of equivalent impedance for three-phase short circuit loop in Ω.

The value of equivalent impedance for three-phase short circuit loop depends on the protected cable and components of supplied system.

The principle for determining the equivalent impedance for three-phase short circuit loop for cables of received installation supplied from a switchgear is shown in Fig. 7.4.

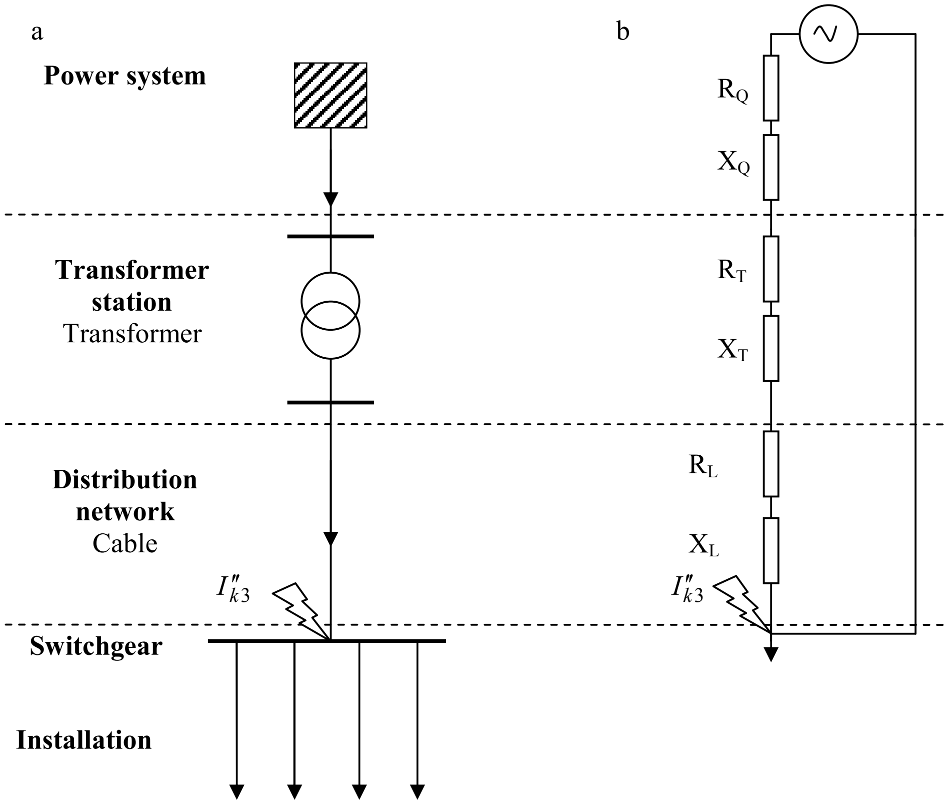


Fig. 7.4. The principle for determining equivalent impedance for three-phase short circuit loop for cables of received installation supplied from a switchgear: a) diagram of supplied system, b) equivalent three-phase short circuit loop [4]

Equivalent impedance for three-phase short circuit loop $\underline{Z}_K$ for example from Fig. 7.4 is determined according to the following relationship:

$$\underline{Z}_{K3} = \underline{Z}_Q + \underline{Z}_T + \underline{Z}_{WLZ} = R_{K3} + jX_{K3} \tag{7.26}$$

where equivalent resistance for three-phase short circuit loop is:

$$R_{K3} = R_Q + R_T + R_L \tag{7.27}$$

and equivalent reactance for three-phase short circuit loop is:

$$X_{K3} = X_Q + X_T + X_L \tag{7.28}$$

R_{K3}, - equivalent resistance for three-phase short circuit loop in Ω,
X_{K3} - equivalent reactance for three-phase short circuit loop in Ω,
R_Q - equivalent resistance of the system infeed in Ω,
X_Q - equivalent reactance of the system infeed in Ω,
R_T - equivalent resistance of transformer in Ω,
X_T - equivalent reactance of transformer in Ω,
R_L - resistance of cable in Ω,
X_L - reactance of cable in Ω.

The impedance values of the individual items of equipment must be known before the short-circuit currents can be calculated. The impedance values can be determined from the equipment data which is provided by the respective manufacturer.

Short-circuits calculation concerns low-voltage electrical installations supplied from transformer stations MV/LV.

In such a case, equivalent resistances and equivalent reactances of selected basic system elements are calculated according to the following formulas:

System:

Effective impedance of system infeed for short-circuit calculation for MV voltage busbars (HV side of transformer)

$$Z_Q = \frac{c \cdot U_{NQ}^2}{S_{kQ}^{"}} \tag{7.29}$$

Effective impedance of system infeed for LV voltage busbars (LV side of transformer)

$$Z_Q^{(LV)} = Z_Q \cdot \left(\frac{U_{NLT}}{U_{NHT}} \right)^2 \tag{7.30}$$

Equivalent reactance of the system infeed

$$X_Q = 0.995 \cdot Z_Q \tag{7.31}$$

Equivalent resistance of the system infeed

$$R_Q = 0.1 \cdot X_Q \tag{7.32}$$

Z_Q - effective impedance of system infeed for short-circuit calculation for MV voltage busbars (HV side of transformer) in Ω,

$Z_Q^{(LV)}$ - effective impedance of system infeed for LV voltage busbars (LV side of transformer) in Ω,

$S_{kQ}^{''}$ - initial symmetrical short-circuit power at MV (medium-voltage) busbars in MVA,

U_{NQ} - nominal voltage of system in kV,

c – voltage factor (for MV c = 1,1 , for LV c = 1,0),

U_{NHT} - nominal high voltage of transformer in kV,

U_{NLT} - nominal low voltage of transformer in kV,

X_Q - equivalent reactance of the system infeed in Ω,

R_Q - equivalent resistance of the system infeed in Ω.

Two-winding transformer:

Ohmic voltage drop

$$u_R = \frac{P_{Cu}}{S_{NT}} \cdot 100\% \tag{7.33}$$

Reactance voltage drop

$$u_X = \sqrt{u_Z^2 - u_R^2} \tag{7.34}$$

Equivalent resistance of transformer

$$R_T = \frac{u_R \cdot U_{NLT}^2}{100 \cdot S_{NT}} \tag{7.35}$$

Equivalent reactance of transformer

$$X_T = \frac{u_X \cdot U_{NLT}^2}{100 \cdot S_{NT}} \tag{7.36}$$

S_{NT} - nominal (rated) apparent power of transformer in kVA,

U_{NHT} - nominal high voltage of transformer in kV,

U_{NLT} - nominal low voltage of transformer in kV,

u_R - ohmic voltage drop,

u_X - reactance voltage drop,

u_Z - impedance voltage drop,

P_{Cu} - load losses of transformer in kW,
R_T - equivalent resistance of transformer in Ω,
X_T - equivalent reactance of transformer in Ω,

Overhead line and cable
Resistance of overhead line (cable)

$$R_L = \frac{l}{\gamma \cdot S} \qquad (7.37)$$

or

$$R_L = r' \cdot l \cdot 10^{-3} \qquad (7.38)$$

Reactance of overhead line (cable)

$$X_L = x' \cdot l \cdot 10^{-3} \qquad (7.39)$$

R_L - resistance of overhead line (cable) in Ω,
l – lengh of considered overhead line (cable) in m,
γ – conductivity of conductor material in $\frac{\mathrm{m}}{\Omega \cdot \mathrm{mm}^2}$,
S – conductor cross-sectional area of a cable in mm^2,
r' – resistance of overhead line (cable) per unit length in $\frac{\mathrm{m}\Omega}{\mathrm{m}}$,
X_L - reactance of overhead line (cable) in Ω,
x' – reactance of overhead line (cable) per unit length in $\frac{\mathrm{m}\Omega}{\mathrm{m}}$.

7.7. Protection against indirect contact

Protection against indirect contact is now often described as protection against electric shock under fault conditions or simply as fault protection.

Each electrical equipment must be provided with protection in the event of indirect contact or protected by means of measures.

The fault protective measure “protection by automatic disconnection of the power supply” must always be applied. Its basic principle is that the power supply of the circuit or equipment to be protected must be disconnected as quickly as possible in order to minimize the risk of physical injury to personnel.

The power supply must be disconnected automatically by means of:

- overcurrent protective devices (fuses, circuit-breakers, miniature circuit-breakers),

- RCDs (residual-current protective devices).

The protection device must disconnect the protected component of an installation from the system within the period defined in the standard (e.g. 0,2 s, 0,4 s, 5 s) to prevent excessively high touch voltages from occuring.

Protection by automatic disconnection of the power supply must be coordinated with respect to the type of ground connection and the properties of the equipment grounding conductors and protective devices.

Standard value of limit for permissible continuous touch voltage (with alternating current voltage) is 50 V.

The disconnecting times are specified in the norm lEC [29]. For standard conditions, the time is equal 0,4 s for circuits about nominal alternating current voltage (r.m.s. value) with respect to ground on level 230 V, and 0,2 s on level 400 V. Under certain circumstances, a disconnecting time of 5 seconds is permitted depending on the type of ground connection.

For suitable fault protection, it is also necessary to connect the exposed conductive parts of the electrical equipment to equipment grounding conductors under the conditions specified for each system according to the type of ground connection. Exposed conductive parts, which are accessible simuitaneously, must be connected to the same grounding system (equipment grounding conductor system with common grounding).

The following condition must be fulfilled for suitable protection of the circuit or equipment of cables against electric shock under fault conditions:

$$t_s \le t_d \tag{7.40}$$

t_s - break-time for protective device in the event of one-phase short circuit in s,
t_d – maximum permissible disconnecting time in s.

Often planners use transformed formula 7.40, which allows to compare short-circuit current for one-phase fault and nominal current of circuit switched off by protective device.

This relationship is the following:

$$Z_{K1} \cdot I_a \le U_0 \tag{7.41}$$

and after transformation:

$$I_{k1} \ge I_a \tag{7.42}$$

Z_{K1} – equivalent impedance for one-phase short circuit loop in Ω,
I_a – nominal current of circuit switching off by protective device in A,
U_0 – nominal alternating current voltage (r.m.s. value) with respect to ground in V,
I_{k1} – short-circuit current for one-phase fault in A.

For the fuse as fault protection, the nominal current of circuit switched off by fuse I_a can be calculated according to the formula:

$$I_a = k \cdot I_{NF} \tag{7.43}$$

I_{NF} – nominal current (rated current) of fuse in A,
k – coefficient for current of circuit switched off by fuse (according to Table 7.10).

Table. 7.10. Values of coefficient k for different types of fuses for permissible disconnecting time: 0,2 s, 0,4 s and 5 s [77,95]

Nominal current of fuse in A	WTN 00, 00C Gg, gL			WTN 1C Gg, gL			WTN 1 Gg, gL		
	0,2 s	0,4 s	5 s	0,2 s	0,4 s	5 s	0,2 s	0,4 s	5 s
6	6,6	5,8	4,0	7,9	6,7	4,2	6,5	5,8	3,9
10	7,7	6,5	4,0	7,1	6,3	4,1	7,7	6,4	3,9
16	6,9	5,8	3,6	6,7	5,8	3,7	6,8	5,8	3,6
20	7,7	6,5	3,7	7,4	6,3	3,8	7,7	6,5	3,7
25	8,7	7,2	4,1	6,8	5,9	3,6	8,6	7,2	4,1
32	8,8	7,3	4,0	8,3	7,2	4,4	8,7	7,3	4,0
40	9,5	8,0	4,4	7,8	6,8	4,2	9,4	7,9	4,3
50	9,5	8,1	4,5	8,0	7,0	4,2	9,5	8,1	4,4
63	9,5	8,0	4,5	8,6	7,4	4,5	9,4	8,0	4,4
80	1,2	9,6	5,1	11,0	9,6	5,1	11,1	9,5	5,1
100	1,5	9,5	5,0	11,0	9,5	5,0	11,5	9,5	4,9
125	1,5	9,7	5,3	11,1	9,4	4,7	11,4	9,7	5,3
160	0,5	9,0	5,2	11,4	9,8	5,1	10,4	9,0	5,1

In the practical solution, value of minimum initial short-circuit current for one-phase short circuit I_{k1} is taken to calculation.

The following relationship applies for initial short-circuit current:

$$I_{k1} \approx \frac{c_{\min} \cdot U_{nf}}{\left|\underline{Z}_{k1}\right|} \tag{7.44}$$

I_{k1} – maximum initial short-circuit current for one-phase fault in A,
$c_{\min}$ –voltage factor for minimum short-circuit current (for MV $c = 1{,}0$, for LV $c = 0{,}95$),
U_{nf} - nominal phase voltage in V (for standard low-voltage electrical installation – 230 V),
$\left|\underline{Z}_{K1}\right|$ – module of equivalent impedance for one-phase short circuit loop in Ω.

Allowing for voltage factor for minimum short-circuit current for low-voltage installation, the formula (7.44) is the following:

$$I_{k1} \approx \frac{0.95 \cdot U_{nf}}{\left|\underline{Z}_{K1}\right|} \tag{7.45}$$

The value of equivalent impedance for one-phase short circuit loop depends on the protected circuit and components of supplied system.

The principle for determining equivalent impedance for one-phase short circuit loop for cables of received installation supplied from a switchgear is shown in Fig. 7.5.

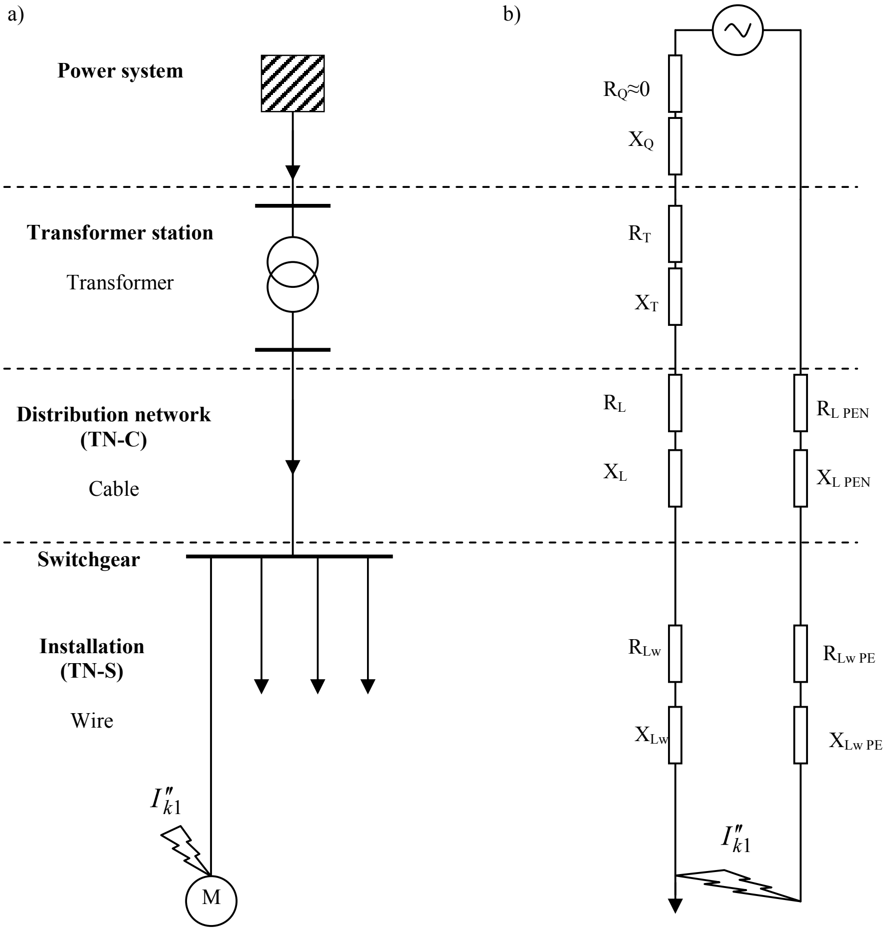


Fig. 7.5. The principle for determining equivalent impedance for one-phase short circuit loop for protection by automatic disconnection of the power supply in TN system: a) diagram of supplied system, b) equivalent one-phase short circuit loop [4]

The equivalent impedance for one-phase short circuit loop $\underline{Z}_{K1}$ for example from Fig. 7.5 is determined according to the following relationship:

$$\underline{Z}_{K1} = \underline{Z}_{Q} + \underline{Z}_{T} + \underline{Z}_{L} + \underline{Z}_{Lw} + \underline{Z}_{L\,PEN} + \underline{Z}_{Lw\,PE} = R_{K1} + \mathrm{j}X_{K1} \qquad (7.46)$$

where the equivalent resistance for one-phase short circuit loop is:

$$R_{K1} = R_{T} + R_{L} + R_{Lw} + R_{L\,PEN} + R_{Lw\,PE} \qquad (7.47)$$

and the equivalent reactance for three-phase short circuit loop is:

$$X_{K1} = X_{Q} + X_{T} + X_{L} + X_{Lw} + X_{L\,PEN} + X_{Lw\,PE} \qquad (7.48)$$

R_{K1} - equivalent resistance for one-phase short circuit loop in Ω,
X_{K1} - equivalent reactance for one-phase short circuit loop in Ω,
R_{Q} - equivalent resistance of the system infeed in Ω,
X_{Q} - equivalent reactance of the system infeed in Ω,
R_{T} - equivalent resistance of transformer in Ω,
X_{T} - equivalent reactance of transformer in Ω,
R_{L} - resistance of associated external conductor for cable in Ω,
X_{L} - reactance of associated external conductor for cable in Ω,
$R_{L\,PEN}$ - resistance of PEN conductor for cable in Ω,
$X_{L\,\mathrm{PEN}}$ - reactance of PEN conductor for cable in Ω,
R_{Lw} - resistance of associated external conductor for wire in Ω,
X_{Lw} - reactance of associated external conductor for wire in Ω,
$R_{Lw\,PE}$ - resistance of PE conductor for wire in Ω,
$X_{Lw\,\mathrm{PE}}$ - reactance of PE conductor for wire in Ω.

When cross sectional area of equipment grounding conductors (PEN, PE) equals cross-sectional area of associated external conductors, the formulas (7.47) and (7.48) are the following:

$$R_{K1} = R_{T} + 2R_{L} + 2R_{Lw} \qquad (7.49)$$

$$X_{K1} = X_{Q} + X_{T} + 2\mathrm{X}_{L} + 2X_{Lw} \qquad (7.50)$$

Furhermore, resistances of cables and wires must be calculated for average level of temperature which equals 80ºC. It means that values of the resistances of cables and wires must multiply by temperature factor of 1,24.

An important requirement for applying protection by automatic disconnection of the power supply is that the main equipotential bonding exists in every building.

Protection by tripping requires the main equipment grounding conductor, which connects all conductive parts in the building, such as the main protective conductor, the main grounding conductor, the main ground terminal or bus, the main water and gas metal pipes and other metallic pipes and metal reinforcement elements of a building construction. Furthermore, components such as: lightning protection grounding electrodes, outdoor antenna installations and surge arresters must also be included.

In such situations measures for protection in case of indirect contact are not required. It concerns among other things equipment that is not likely to come into contact with any part of the human body because of its small dimensions (e.g. 50 mm × 50 mm) or because of its configuration, metal enclosures for protection of total insulation equipment, etc.

Selection cross sectional area of equipment grounding conductors

Suitable protection against indirect contact requires proper selection of cross-sectional areas of all equipment grounding conductors.

Cross-sectional area of all equipment grounding conductors depends on the type of ground connection and cross-sectional area of associated external conductors.

The cross-sectional area of all equipment grounding conductors (irrespective of the system's grounding connection) must be selected according to Table 7.11 or formula (7.51).

Table 7.11. Cross-sectional areas of equipment grounding conductor in relation to cross-sectional area of external conductor [15]

Cross-sectional area S of external conductor in mm^2	Minimum cross-sectional area S_p of equipment grounding conductor in mm^2
$S \le 16$	S (i.e. the same as exernal conductor)
$16 < S \le 35$	16
$S > 35$	$S/2$ (i.e. $1/2$ exernal conductor)

The cross sectional area of all equipment grounding conductors can be calculated according to the following formula:

$$S_p \ge \frac{I_k}{k}\sqrt{t_s} \qquad (7.51)$$

S_p – cross-sectional area of equipment grounding conductor a cable in mm^2,

I_k - maximum possible fault current in A (at least the current which causes the protective device to disconnect within the required time, maximum 5 s),

t_s - operating time of protective device in s with maximum possible fault current,

k - material coefficient of the conductor material in $[\frac{A}{\sqrt{\Omega} \cdot mm^2}]$.

If the formula (7.51) or Table 7.11 yields a non-standard cross-sectional area of conductor, the next largest standard cross-sectional area of conductor must be selected.

Determining the cross-sectional areas of the equipment grounding conductor using some of these two methods does not mean that the conditions for protection by automatic disconnection of the power supply do not have to be checked. With PEN conductors, the current flowing through the neutral conductor must also be taken into consideration when dimensioning the cross-sectional areas.

Systems according to type of ground connection

Existing systems are classified according to the type of ground connection.

Systems are the following:

- IT system (Fig. 7.6),
- TT system (Fig. 7.7),
- TN system (Fig. 7.8).

The commonly used TN system has three variants:

- TN-C system,
- TN-C-S system,
- TN-S system.

The system marks contain the following information:

- The first letter (I or T) refers to the grounding characteristics of the power source (i.e. primarily to the grounding of the public utility power system or of an industrial system).
- The second letter (T or N) refers to the grounding characteristics of the exposed conductive parts.
- The supplementary letters in the TN system (C, C-S, S) refer to the combination or separation of the equipment grounding conductor and neutral conductor.

IT system is shown in Fig.7.6. Point in system is not directly grounded, conductive parts are not directly grounded and supplementary equipotential bonding may be necessary.

If neutral conductors are used, overcurrent detection is required in them. Overcurrent detection must disconnect all of the external conductors including the neutral conductor. The neutral conductor must not be disconnected before the external conductors or connected after the external conductors.

TN system is shown in Fig.7.7. Direct grounding of point in system required, exposed conductive parts are connected to grounded point in system via equipment grounding conductor PE and or PEN and supplementary equipotential bonding may be necessary. In TN-C system neutral and equipment grounding conductors are installed as PEN throughout. In TN-C-S system, neutral and equipment grounding conductors are partly installed together as PEN, partly installed separately. In TN-S, neutral and equipment grounding conductors are installed separately throughout.

TN-S system is possible with a grounded external conductor. In such a case, a grounded external conductor must not be used as a PEN conductor.

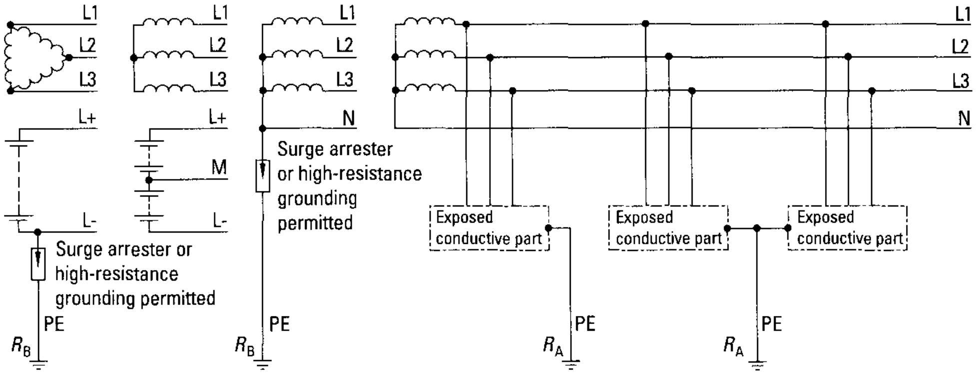


Fig. 7.6. IT system: R_A - contact resistance of frame ground, R_B - operational ground resistance [3,15]

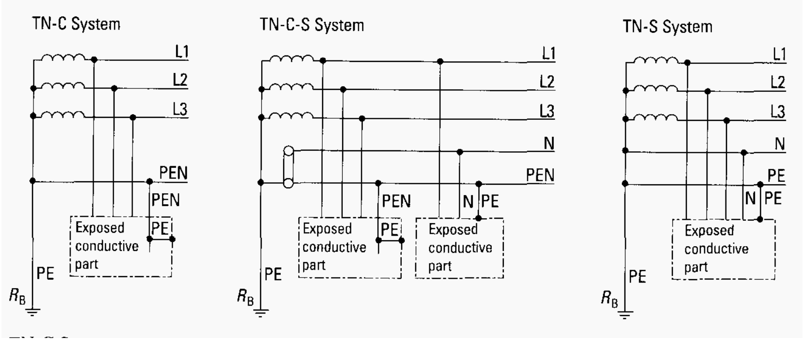


Fig. 7.7. TN system: R_B - operational ground resistance, no fixed value, recommendation for $R_B \leq 2\Omega$ [3,15]

The requirements for the three TN system variants are similar. All exposed conductive parts of the electrical installation must be connected to the grounded point (usually the neutral point or, if this is inaccessible, an external conductor) of the supply system. The grounding connection must be established at or near (i.e. ≤ 50 m) the associated transformer.

Sometimes the following condition must be fulfilled if an abnormal fault occurs between an external conductor and the ground:

$$\frac{R_B}{R_E} \leq \frac{50V}{U_0 - 50V} \tag{7.52}$$

R_B - total ground resistance of all parallel grounding electrodes (including those of the power supply system) in Ω,
R_E - lowest ground contact resistance of extraneous conductive parts not connected to an equipment grounding conductor via which a fault between the external conductor and ground can occur in Ω,
U_0 - nominal a.c. voltage (r.m.s. value) with respect to ground in V,
50 V - limit for permissible continuous touch voltage (with a.c. voltage).

In permanently installed cable systems, the equipment grounding conductor, which connects the exposed conductive parts to the neutral point of the power source, can also be used as the neutral conductor. A combined neutral conductor and equipment grounding conductor, which is referred to as a PEN conductor, can only be used for copper conductors with a cross sectional area $\geq$ 10 mm^2 and aluminum conductors $\geq$ 16 mm^2.

The same protective devices (RCDs and overcurrent protective devices) can be used for fault protection for all TN system variants, with one exeption for RCDs which must not be used in the TN-C section.

TT system is shown in Fig.7.8. Direct grounding of point in system is required, conductive parts are directly grounded and supplementary equipotential bonding may be necessary.

If neutral conductors are used: overcurrent detection is required in them in the case of “protection by disconnection” with overcurrent protective devices. The neutral conductor must not be disconnected or connected before the external conductors.

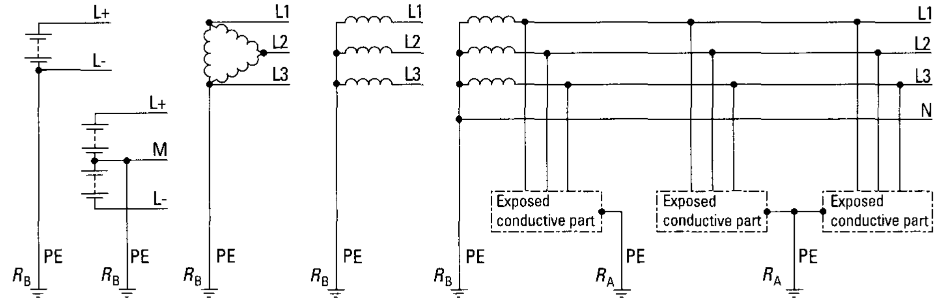


Fig. 7.8. TT system: R_A - contact resistance of frame ground, dependent on operating current of protective device, R_B - operational ground resistance, no fixed value, recommendation for $R_B \leq 2\Omega$ [3,15]

8. LOW-VOLTAGE PROTECTIVE DEVICES

8.1. Introduction

One of very important project tasks for planners is selection of protective devices. Electrical installations in a power system are protected by protection equipment allocated to the installation components or by combinations of these protective elements.

Protective devices are used in electrical installation for:

- protection in the event of short circuits,
- overload protection,
- protection against indirect contact.

The key parameter of protection device is the rated switching capacity. It is the maximum value of the short circuit that the protection device is able to clear correctly. The protection device may be used in power systems for rated switching capacities up to this value. If a short circuit, which is higher than the rated switching capacity of the protection device used, back-up protection must provide protection for the downstream installation component and for the protection device by means of an upstream protection device.

For suitable protection of equipment, its selectivity is important. It is advisable for series-connected protection devices to ensure the greatest possible level of supply reliability for the unaffected feeders. System protection is regarded as “selective” if only the protection device closest to the fault location (relative to the direction of power flow) is triggered.

8.2. Protection devices

Overcurrent protection in low-voltage electrical installations can be realised by using the following overcurrent protection devices:

- Low-voltage fuses,
- Circuit-breakers,
- Miniature circuit-breakers.

Depending on the type selected, overcurrent protective devices provide protection against overloads and short circuits, or one of these conditions only. Short overview of the protection equipment is shown in Table 8.1.

Fault protection in low-voltage electrical installations can be introduced by using the following protection devices:

- Overcurrent protection devices,
- RCDs (residual-current protective devices).

In industrial and commercial applications, residual-current-operated circuit breakers and miniature circuit-breakers with fault-current tripping are used as fault protection devices.

Table 8.1 Overview of conductor and cable overcurrent protection devices together with their protection ranges

Overcurrent protection devices	Overload protection	Short-circuit protection
Fuses gL	x	x
Miniature circuit- breakers	x	x
Circuit-breakers with overload and overcurrent releases	x	x
Switchgear fuse aM	-	x

x Protection provided, - No protection provided

8.3. Fuses

Fuses are overcurrent protection devices that open a current circuit by melting one or more fusible elements and break the current if it exceeds a specific value for a specific period.

Fuses are divided into two groups: low-voltage and high-voltage.

Low-voltage fuses are classified by their operating classes and designs. They are divided into functional and utilization categories in accordance with their type.

Duty class of fuse is described by two letters: small and then the capital letter (e.g. gG, gL). The first letters identify the breaking range:

g - General purpose fuses can continuously conduct currents up to their rated current and can disconnect currents from the smallest fusing current to the rated breaking capacity,

a - Back-up fuses can continuously conduct currents up to their rated current and can disconnect only the currents above a specific multiple of their rated current.

The second letter identifies the application:

G - for general application,
L - for protection of cables,
M - for the protection of motor current circuits and switchgear,
R - for protection of semiconductors,
Tr - transformer protection,
B - for protection of mining installations.

Second letter determines also the time/current characteristics.

Rated voltages of low-voltage fuse links are the following: 230, 400, 500, 690 V.

Nominal currents (rated currents) of fuse links are the following: 6, 10, 16, 25, 32, 40, 50, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630 A, etc [77,90].

The time response of fuse links depending on the breaking current that causes the fuse to melt and interrupt is shown in time/current characteristics (Fig. 8.2 and 8.3).

The interrupting behaviour of the fuse links is characterized by the small test current I_{nf} (no fusing during the test period) and the large test current I_f (interruption during the test period). The value of the large test current of fuse depend on: time/current characteristics, test period and rated current of fuse (Table 7.6).

Low-voltage fuses have high breaking capacity. They fuse quickly to restrict the peak short circuit current. The protective characteristics is determined by the selected utilization category of fuse (e.g. full-range fuse for overload and short-circuit protection, or partial range fuse for short-circuit protection only) and the rated current.

Functional category g applies to full-range fuses which can interrupt currents from the minimum fusing current up to the rated short-circuit breaking current.

This category includes fuses of utilization category gG or gL used to protect cables and conductors.

Functional category a applies to back-up fuses which can interrupt currents above a specified multiple of their rated current up to the rated short-circuit breaking current. This functional category applies to switchgear fuses of utilization category aM, the minimum breaking current of which is approximately four times the rated current. These fuses are thus only intended for short circuit protection. For this reason, fuses of functional category a must not be used above their rated current. Means of overload protection, e. g. thermal time-delay relay, must, therefore, always be provided.

In most cases in electrical installations, several fuses are connected in series between the current source and the apparatus to be protected in case of a short circuit. These devices must operate selectively to limit a fault to the place of its origin as far as possible. Fuses generally respond selectively when their time/current characteristics do not touch. This requirement is usually met when grading the fuse current ratings in the ratio 1:1,6.

Fuses are often used with circuit-breakers as upstream fuses. The upstream fuses are only responsible for short-circuit clearance with higher short-circuit currents than the rated short-circuit breaking capacity of the circuit-breaker.

Fuses are often used with load-break switch, disconnector or switch-disconnector as an assembled unit e.g. for switchgear (Table 8.1).

Table. 8.1. Kinds of fuse combination units [1]

Name of fuse combination unit	Description of fuse combination unit
Disconnector with fuses	Unit comprising disconnector and fuses, in which one fuse is switched in series with the disconnector in one or more phases.
Load-break switch with fuses	Unit comprising load-break switch and fuses, in which one fuse is switched in series with the load-break switch in one or more phases.
Fuse-disconnector	Disconnector in which a fuse link or a fuse holder with fuse link forms the movable contact piece.
Fuse-switch disconnector	Switch-disconnector in which a fuse link or a fuse holder with fuse link forms the movable contact piece.

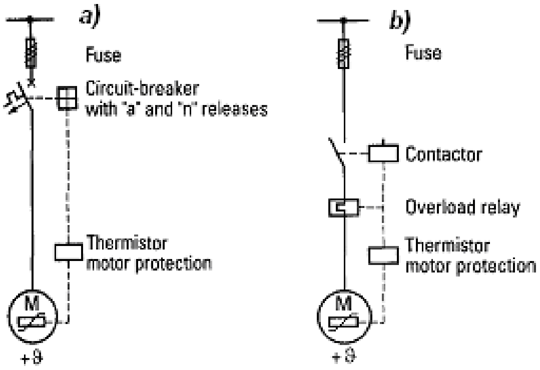


Fig. 8.1. Switchgear assemblies with fuses and thermistor motor-protection devices plus additional overload relay or release (block diagram) [15]

Selecting fuses

Fuses can be used for short-circuit protection of motors. In this case, the following conditions must be fulfilled for nominal current of fuse (rated current) I_{NF}:
for direct starting of motor:

$$I_{NF} \geq \frac{I_{r\max}}{\alpha} = \frac{k_r \cdot I_{nM}}{\alpha} \tag{8.1}$$

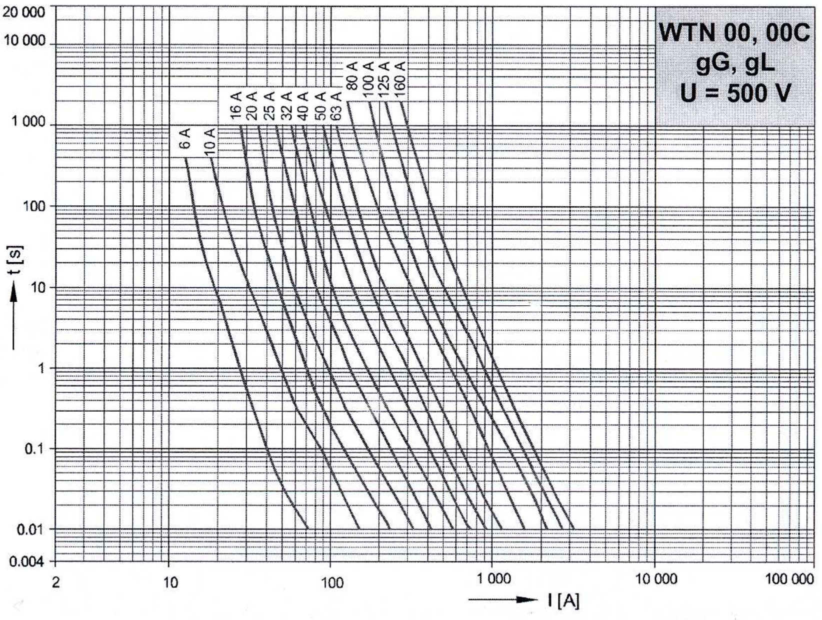
for starting of motor with star-delta switch:

$$I_{NF} \geq \frac{I_{r\max}}{3\alpha} = \frac{k_r \cdot I_{nM}}{3\alpha} \tag{8.2}$$

and additionally irrespectively:

$$I_{NF} \geq I_{nM} \tag{8.3}$$

$I_{r\max}$ – maximum starting current for motor in A,
I_{nM} – rated current for motor in A,
$k_r = I_r / I_{nM}$ – factor of starting motor (starting current/rated current for motor),
α - starting factor (depends on type of a fuse, kind and frequency of a motor start-up, Table 8.2).



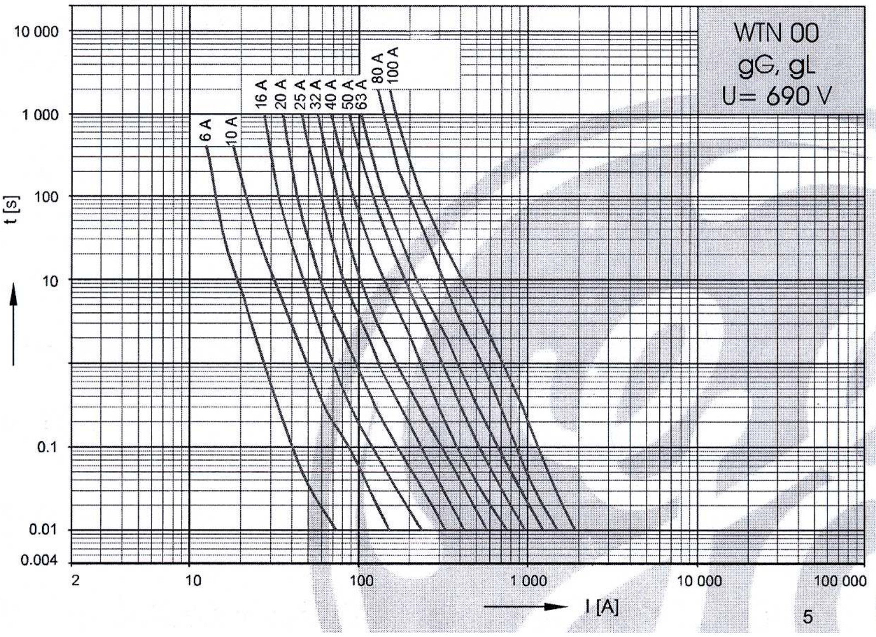


Fig. 8.2. Time/current characteristics for WTN 00 fuse links of duty class gG i gL for rated voltage: 500 and 690 V [77,95]

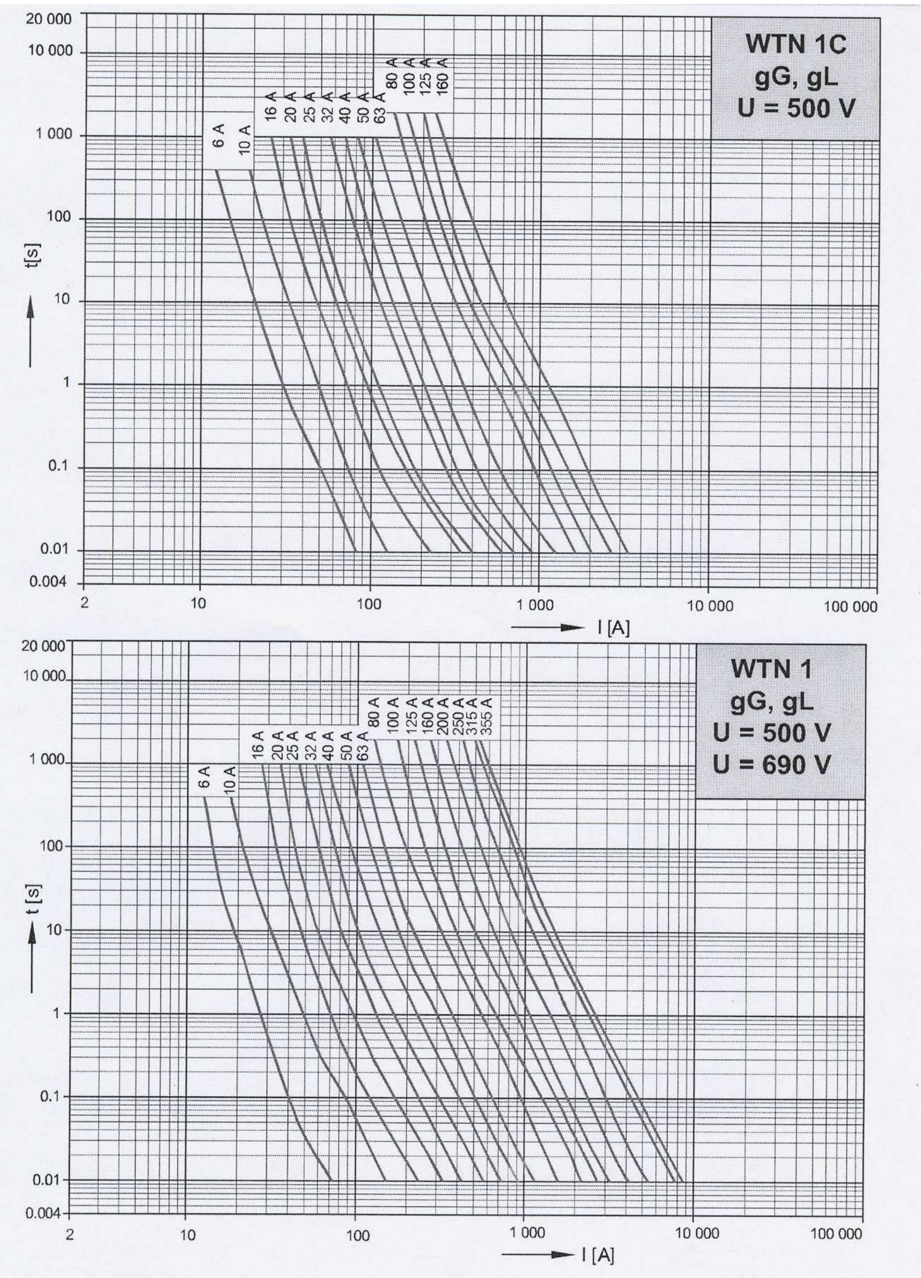


Fig. 8.3. Time/current characteristics for WTN 1 fuse links of duty class gG i gL for rated voltage: 500 and 690 V [77,95]

Table 8.2. Values of factor α for selection of fuse for motor protection [4,6]

Start-up kind	Motor brake torque M_h in start-up time	Fuse			
		Without delay		With delay	
		Start-up frequency		Start-up frequency	
		a few times a day	frequent	a few times a day	frequent
Light	$M_h \leq 0,5\ M_n$	2,5	2,0	3,0	2,5
Medium	$0,5\ M_n < M_h \leq M_n$	2,0	1,8	2,5	2,0
Heavy	$M_h > M_n$	1,6	1,5	1,6	1,5
M_n – nominal motor torque. Start-up - a few times a day correnspondent to 3÷5 start-ups, frequent start-up correnspondent to above this value.					

Generally, the rated current of the fuse must be higher than the highest motor starting current and the rated operating current of the motor. The time/current characteristics of fuses must allow the motor to be run up to speed.

Fuses can be used for short-circuit protection of receivers different than motors (e.g. sockets, furnaces, etc.). In this case for such receiver, the following conditions must be fulfilled for nominal current of fuse I_{NF}:

$$I_{NF} \geq I_{nR} \tag{8.4}$$

I_{nR} – nominal current of a receiver in A.

Fuses can be used for short-circuit protection of group of receivers (included motors in it). In this case, the following conditions must be fulfilled for nominal current of fuse I_{NF}:

$$I_{NF} \geq I_{nGR} \tag{8.5}$$

$$I_{NF} \geq (I_{nGR} - I_{nM\max}) + \frac{I_{rM\max}}{\alpha} \tag{8.6}$$

I_{nGR} – load current for group of receivers (sum of load current for all receivers in the group) in A,

$I_{nM\ max}$ – nominal current of motor with the highest starting current from considered group of motors in A,

$I_{rM\ max}$ – starting current of motor with the highest starting current from considered group of motors in A.

8.4. Circuit-breakers

The circuit-breakers are the basic overcurrent protection devices. They are used both for overload and short-circuit protection. In order to increase the degree of protection, they can also be equipped with additional releases, e. g. for clearance with undervoltage, or with supplementary modules for detecting fault/residual currents.

Circuit-breakers must be capable of making, conducting and switching off currents under operational conditions and under specified extraordinary conditions up to the point of short circuit, making the current, conducting it for a specified period and interrupting it.

The circuit-breakers are distinguished according to their protective function:

- Circuit-breakers for system protection,
- Circuit-breakers for motor protection,
- Circuit-breakers used in motor starters,
- Miniature circuit-breakers.

Depending on their method of operation, circuit-breakers are available as:

- Zero-current interrupters (low current limiting) or
- Current limiters (fuse-type current limiting).

Circuit-breakers are equipped with different releases and relays which are necessary for realisation of protection function by them (Table 8.3). The releases can be integrated in the circuit-breaker or supplied as separate modules for retrofitting or replacement. The releases are electromechanical and electronic which additionally permit new tripping criteria which are not possible with electromechanical releases.

Table 8.3. Circuit-breaker releases and relays with protective function [15]

Function	Release	Relay
Overload protection	Overload release Inverse-time delay or electronic delay	Overload relay Thermal delay or electronic delay Thermistor protection release devices
Short-circuit protection	Overcurrent release Instantaneous electromagnetic or electronic release	Overcurrent relay Instantaneous electromagnetic release
Selective short-circuit protection	Overcurrent release Short electromagnetic or electronic release	-

The protective functions of circuit-breakers are determined by selectable electromechanical or electronic releases:

- Overload protection by means of inverse time-delay overload releases (“a” releases), e. g. bimetallic releases,
- Releases,
- Short-circuit protection by means of instantaneous overcurrent releases (“n” releases), e. g. solenoid releases,

- Short-circuit protection by means of definite short-time-delay overcurrent releases (“z” releases) for selective grading or for I^2- dependent delay ($I^2 \cdot t$ = constant),
- Ground fault protection by means of ground fault current releases (“g” releases) with definite or I^2- dependent delay,
- Fault current protection by means of residual current releases [15].

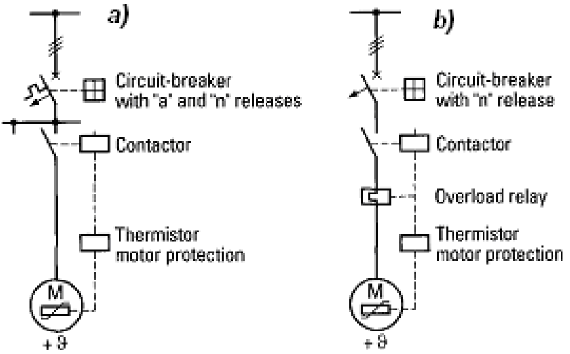


Fig. 8.4. Switchgear assemblies with circuit-breakers and thermistor motor-protection devices plus additional overload relay or release (block diagram) [15]

From arc extinction point of view, circuit-breakers are divided into two groups: non-current-limiting circuit-breakers and current limiting circuit-breakers.

Non-current-limiting circuit-breakers extinguish the arc at the natural alternating current zero crossing. The conducting paths are dimensioned in such a way that they can conduct the full short-circuit current thermally. Downstream system components are also thermally and dynamically loaded with the unlimited peak short-circuit current.

Current limiting circuit-breakers interrupt the short-circuit current before it reaches the peak value of the first half-cycle. The peak short-circuit current is limited to a value (cut off current) that significantly reduces the thermal and dynamic stress on the downstream components. Current-limiting circuit-breakers are particularly suitable for short-circuit protection of switchgear with lower switching capacity (back-up protection).

Miniature circuit breakers with fault-current/ residual-current tripping are used in different system protection applications.

Miniature circuit-breaker assemblies, which are sensitive to universal current, are required for industrial applications for electrical installations in which smooth d. c. fault currents or currents with a low residual ripple occur in the event of a fault.

Selecting circuit-breakers

Suitable selection of circuit breakers for definite system protection require special attention for the following characteristics:

- Type of circuit-breaker and its releases according to the respective protective function and tasks,
- Rated voltages,
- Short-circuit strength and rated short-circuit making and breaking capacity,
- Rated and maximum load currents.

The system voltage comprises crucial factors for selecting the circuit breakers according to the rated insulation voltage (U_i) and the rated operating voltage (U_e). The rated insulation voltage is the standardized voltage value for which the insulation of the circuit-breakers and their associated components is rated, however, the rated operating voltage (U_e) of a circuit-breaker is the voltage value to which the rated short-circuit making and breaking capacities and the short-circuit category refer.

The maximum short-circuit current at the installation location is a crucial factor for selecting the circuit-breakers according to short-circuit strength as well as rated short-circuit making and breaking capacities.

The rated short-circuit breaking capacity (I_{cn}) is the short-circuit current which the circuit-breaker is capable of breaking at the rated operating voltage + 10%, rated frequency, and a specified power factor ($\cos\varphi$). It is expressed as the r.m.s. value of the alternating current component.

The circuit-breaker provides protection against all overcurrents up to its rated short-circuit breaking capacity I_{cn} and ensures all-pole opening and reclosing. If the prospective short-circuit current I_k exceeds the rated short-circuit breaking capacity I_{cn} of the circuit-breaker, the latter must be provided with upstream fuses.

Circuit-breakers have definite switching capacity categories (P-1 or P-2), which specify how often a circuit-breaker can switch its rated making and breaking current as well as the condition of the breaker after the specified switching cycle.

A very important value for circuit-breaker is the rated operating current (I_e). It is the current that is determined by the operating conditions of the switching device, the rated operating voltage and rated frequency, rated switching capacity, the rated duty, utilization category, contact life, and the degree of protection.

The key element for suitable application of circuit-breakers for protection is knowledge about tripping characteristics (time/current) of these circuit-breakers. It is currently commonly available in catalogues of circuit-breakers' manufacturers.

Circuit-breakers with electromagnetic release can be used for short-circuit protection of motors. In this case, the following conditions must be fulfilled for the operating current of electromagnetic overcurrent release I_{MAG}:
for direct starting of motor:

$$I_{MAG} \geq 1.2 \cdot I_{r\max} \tag{8.7}$$

for starting of motor with star-delta switch:

$$I_{MAG} \geq 1.2 \cdot \frac{I_{r\max}}{3} \tag{8.8}$$

$I_{r\max}$ – maximum starting current for motor in A.

According to the standards the operating value of current for electromagnetic overcurrent release may deviate by ± 20% from the set value [4]. For this reason in formulas (8.7) and (8.8) value of maximum starting current is multiplied by 1,2.

The instantaneous electromagnetic overcurrent releases have more frequently fixed setting, rather than variable. That is why for line protection, circuit-breaker has standard value of operating current for electromagnetic overcurrent release on level $6 \div 12 \times$ rated current, however, for motor protection on level $8 \div 15\ \times$ rated current [15].

Comparison between circuit-breakers and fuses

Branch circuits in distribution boards can be provided with short-circuit protection by means of fuses or by means of circuit-breakers without fuses. The level of anticipated current limiting may also be a crucial factor in selecting protection equipment. In such a situation, it is important to compare the protection characteristics of fuses with those of current-limiting circuit breakers. It means exactly the comparison between the tripping characteristics and the rated short-circuit breaking capacity of fuses with those of circuit-breakers with the same rated current and a high switching capacity.

The following should be taken into consideration when comparing the protection characteristics of fuses and circuit-breakers:

- the rated short-circuit breaking capacity,
- the level of current limiting,
- the shape of the prearcing-time/current characteristics of fuses and the tripping characteristics of circuit-breakers,
- clearance conditions [15].

The level of current limiting in fuses with low rated currents is higher than in current-limiting circuit-breakers with the same rated current. The typical test range for fuse currents is between 1,3 and 1,6 times the rated current, while the test range for the limiting tripping currents of the overload release is between 1,05 and 1,2 times the current setting. The adjustable overload release enables the current setting and, therefore, the limiting tripping current, to be matched more closely to the continuous loading capability of the equipment to be protected than it would be possible with a fuse, the different current ratings of which only permit approximate matching. The limit current of the fuse is adequate for providing overload protection for cables and conductors but it is not sufficient for the starting current of motors. In this case a fuse with the characteristic a’ (back-up fuses) is needed for protection.

In the short-circuit current range, the instantaneous release of the circuit-breaker detects short-circuit currents above its operating value faster than the fuse. At higher currents, the fuse trips more quickly and, therefore, limits the short-circuit current more effectively than a circuit-breaker.

The comparison between protective characteristics of fuses and circuit-breakers can be found in Table 8.4 and Fig. 8.5.

Table 8.4. Comparison between the protective characteristics of fuses and circuit-breakers [15]

Characteristic	Fuse	Circuit-breaker
Rated switching capacity (a.c.)	>100 kA, 690V	f(I_r, U_e, type*)
Current limiting	f(I_r, I_k)	f(I_r, , I_k , U_e, type*)
Additional arcing space	None	f(I_r, , I_k , U_e, type*)
External indication of operability	Yes	No
Operational reliability	With additional costs**	Yes
Remote switching	No	Yes
Automatic all-pole breaking	With additional costs***	Yes
Indication facility	With additional costs****	Yes
Interlocking facility	No	Yes
Readiness for reclosing after - clearing overload	No	Yes
- clearing short-circuit	No	f (condition)
Interrupted operation	Yes	f (condition)
Maintenance costs	No	f (number of operations and condition)
Selectivity	No additional costs	With additional costs
Replaceability	Yes*****	With unit of the same make
Short-circuit protection		
- Cable	Very good	good
- Motor	Very good	good
Overload protection		
- Cable	Adequate	good
- Motor	Not possible	good

* The term “type” embraces: current extinguishing method, short-circuit strength through internal impedance, type of construction

** For example, by means of shockproof fuse switch-disconnectors with snap-action closing

***By means of fuse monitoring and associated circuit-breakers

**** By means of fuse monitoring

***** Due to standardization

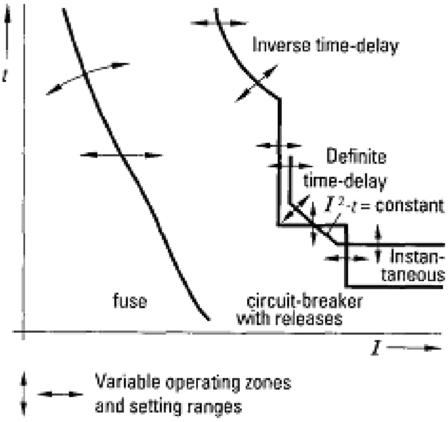


Fig. 8.5. Protective characteristic of low-voltage fuse and low-voltage circuit-breaker with releases [15]

Selectivity

In most cases, several overcurrent protection devices are connected in series between the current source and the apparatus to be protected in case of a short circuit. For example, with series-connected distribution boards, relative to the direction of power flow, it is possible to arrange the following protection devices in series:

- Fuse with downstream fuse,
- Circuit-breaker with downstream miniature circuit-breaker,
- Circuit-breaker with downstream fuse,
- Fuse with downstream circuit-breaker,
- Fuse with downstream miniature circuit breaker,
- Several parallel infeeds with or without coupler units with downstream circuit breaker on downstream fuse.

These devices must operate selectively to limit a fault to the place of its origin as far as possible. It is important because it ensures optimum supply reliability.

Full selectivity means:

- Operational current spikes must not result in disconnection.
- When functioning properly, only the protection device which is the nearest to the fault in the supply direction shall respond.
- If this protection device malfunctions, the next protective device in the series must respond.

Selectivity can generally be determined theoretically by comparison of the breaking characteristics in the overload range and the time-delayed operating characteristics of the upstream circuit-breaker.

The following criteria can be applied for selective operation of series-connected protection devices:

- Time difference for clearance (time grading),
- Current difference for operating values (current grading),
- Combination of time and current grading (inverse time grading).

Full selectivity is operational between two or more overcurrent protection devices when the protection device nearest to the failure in the supply direction trips selectively up to its rated breaking capacity. Partial selectivity means that this protection device will trip selectively only up to a specific short-circuit current.

For motor protection, a special set of protection devices is often used. The set is composed of a fuse, contactor, and thermal inverse-time delay overload relay. The contactor is used to switch the motor on and off. The overload relay protects the motor, motor supply conductors, and contactor against overloading. The fuse upstream of the contactor and overload relay provides protection against short circuits. For this reason, the protection ranges and characteristics of all the components must be carefully coordinated with each other.

8.5. Other protection devices

Contactors

Contactors are remote-control switching devices with restoring force, which are actuated and held by their actuator. They are primarily intended for high-switching frequency for switching currents with equipment in a healthy state, including operational overload. Contactors are suitable for isolation to a limited extent only and they must be protected against short circuit by upstream protection equipment.

Contactors are fitted with current-dependent protection devices to prevent thermal overload of motors. For protection against motor overload, the overload relays are set to the rated current of the motor. Modern overload relays have temperature compensation facility to prevent interference from varying ambient temperatures affecting the trip times of the bimetallic contacts. They also have a phase failure protection; manual or automatic reset can be selected.

Motor starters

The motor starter is the term for the combination of all devices required for starting and stopping a motor in connection with appropriate overload protection (e.g. switchgear assembly comprising contactor and overload relay).

Compact, manually operated motor starters, also referred to as motor protection switches, are suitable for switching short-circuit currents if they meet the conditions for circuit-breakers.

Motor starters are suited for operation with open-circuit shunt releases, undervoltage relays or undervoltage tripping releases, delayed overload relays, instantaneous overcurrent relays and other relays or releases.

Thermistor motor-protection devices

Overload relays and releases cease to provide reliable overload protection when it is no longer possible to establish the winding temperature from the motor current e.g. in case with high switching frequencies or high ambient temperatures. And then, switchgear assemblies with thermistor motor-protection devices are often used. The switchgear assemblies are designed with or without fuses depending on the installation configuration.

The degree of protection that can be attained depends on whether the motor to be protected has a thermally critical stator or rotor.

Motors with thermally critical stators can be adequately protected against overloads and overheating by means of thermistor motor protection devices without overload relays. Feeder cables are protected against short circuits and overloads either by fuses and circuit-breakers or by fuses alone.

Motors with thermally critical rotors can only be provided with adequate protection if they are fitted with an additional overload relay or release. The overload relay and release also protect the conductors against overloads.

Thermistor motor-protection device can be used for overload protection of motors. In this case, the following conditions must be fulfilled for the operating current of overload release I_{NTh}:

for direct starting of motor:

$$I_{NTh} = (1.0 \div 1.1) \cdot I_{nM} \tag{8.9}$$

for starting of motor with star-delta switch:

$$I_{NTh} = \frac{I_{nM}}{\sqrt{3}} \tag{8.10}$$

I_{nM} – rated current for motor in A.

9. LOW-VOLTAGE SWITCHGEARS

9.1. Introduction

Low switchboards and distribution systems represent the links between the equipment for generating (generators), transporting (cables, overhead lines) and converting (transformers) electrical energy and the loads that consume this energy such as motors, solenoid valves as well as heating, lighting, air-conditioning and IT equipment. The example of a low-voltage system in an industrial plant is shown in Fig. 9.1.

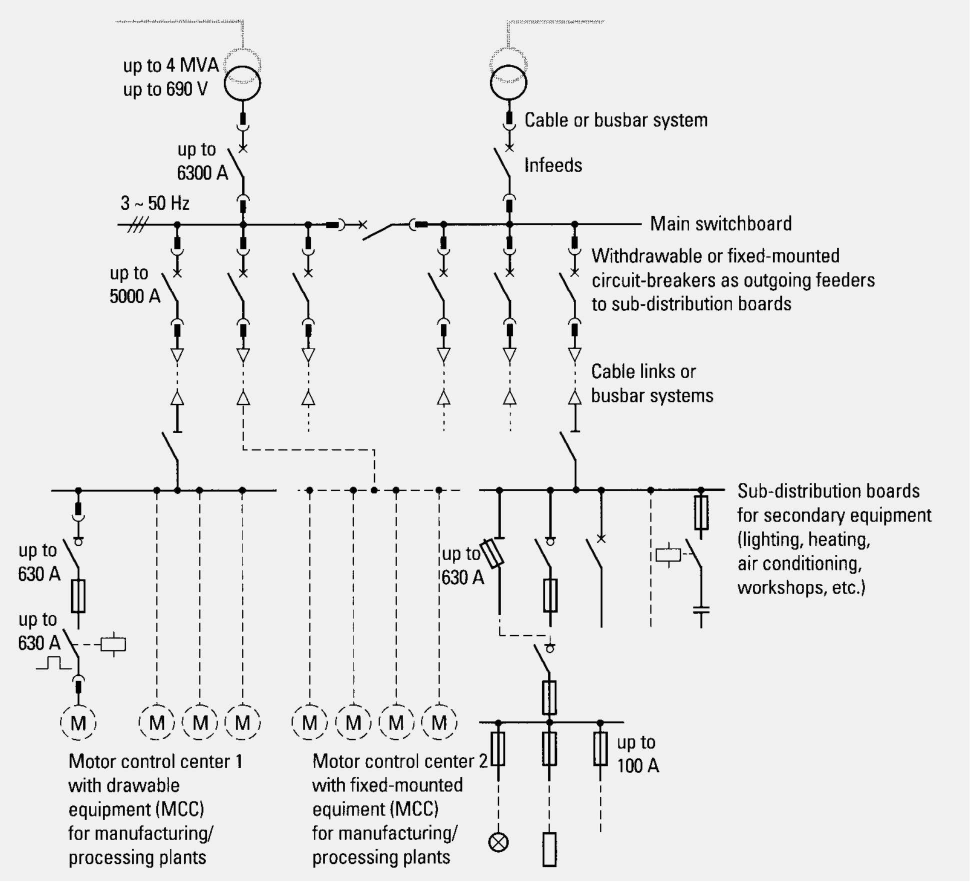


Fig. 9.1. Typical configuration of a low-voltage system in an industrial plant [15]

The low-voltage switchgear is designed for switching and protection of electrical equipment. That's why the switchboard groups the necessary switching, protective and measuring equipment.

The selection of switchgear apparatus is based on the specific switching task, e.g. isolation, load switching, short-circuit current breaking, motor switching, protection against overcurrent and personnel hazard. Depending on the type, switchgear apparatus can be used for single or multiple switching tasks. Switching tasks can also be conducted by a combination of several switchgear units. Fig. 9.2 shows some applications for LV switchgear.

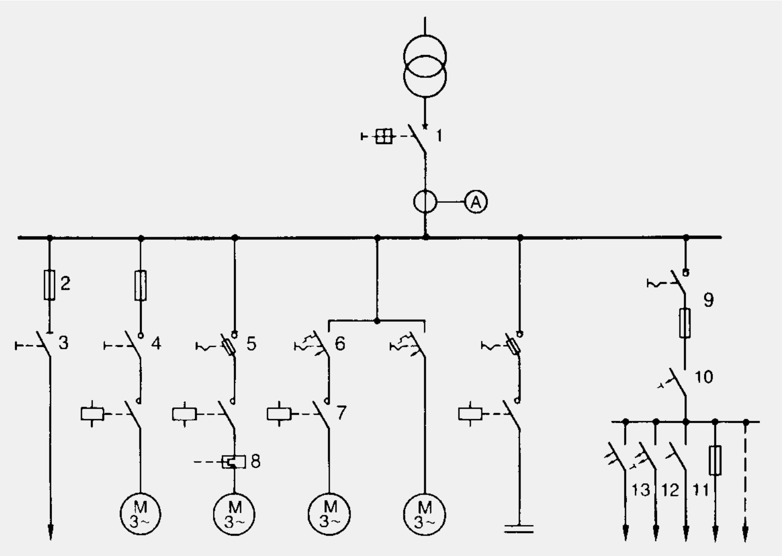


Fig. 9.2. Examples for use of low-voltage switchgear: 1 Circuit-breaker, general 2 Fuse, 3 Disconnector, 4 Loadbreak switch, 5 Fused Switch-disconnector, 6 Motor starter (motor protection switch), 7 Contactor, 8 Overload relay, 9 Switch disconnector with fuses, 10 Residual current-operated circuit breaker (RCCB), 11 Miniature circuit-breaker, 12* Residual current-operated circuit breaker with overcurrent tripping (RCBO), 13* Residual current-operated miniature circuit-breaker (RCD) /* Graphic symbols not standardized/ [1]

The variety of applications results in many different designs of low-voltage switchgear assemblies. They can be classified under different criteria.

9.2. Switchboards in industrial plants

Switchboards, which are located in an industrial plant, divide into: the main switchboard and sub-distribution boards.

The main switchboard is supplied directly via one transformer for each busbar section. The motor control centers, control systems, distribution boards for lighting, heating, air conditioning, etc. which are connected downstream and thus supplied from the main switchboard, are classed as sub-distribution boards.

The block diagram in Fig. 9.1 illustrates how an industrial power supply can be logically divided into “the main switchboard” (supplied directly by transformers) and various “sub-distribution boards” (for a wide range of different applications).

The main switchboard is installed in the immediate vicinity of the infeed transformers. The cable or busbar connections to the transformers are short. The sub-distribution boards are located centrally in relation to their loads with the cables that fee them being short.

The main switchboards perform an extremely important task in supplying all downstream sub-distribution boards.

The following criteria must a be taken into consideration when dimensioning the transmission equipment between the main switchgear and the sub-distribution boards:

- protection against overloading,
- protection in the event of short circuit,
- protection against electric shock in the event of indirect contact,
- compliance with the maximum permissible voltage drop,
- selective behavior with respect to up stream and downstream protective devices.

The low-voltage switchboards are characterised mostly by:

- High rated equipment currents $\leq$ 6300 A (approx.),
- High short-circuit strength $\leq$ 220 kA peak,
- Sheet steel as enclosure material,
- Overall height of at least 2000 mm,
- Equipment mounting types: fixed, removable, withdrawable,
- Protection degree of enclosure between IP 20 and lP 55.

The low-voltage switchboards for rated currents $\leq$ 6300 A (approx.) are used primarily as: the main switchboards in industrial plant or large commercial establishments, in power stations.

9.3. Constructions of switchboards

Switchboards and distribution boards can have the following types of construction:

- open-type assemblies,
- dead front assemblies,
- enclosed assemblies,
- withdrawable units,
- box-type assemblies.

In the open-type assemblies, parts that may be live during operation, such as main busbars, vertical busbars, items of equipment, terminals and conductors, are accessible from all sides because the open frame is not fitted with any covers. Such assemblies must be installed in closed electrical operating areas. They are used very rarely.

Dead front assemblies provide protection against contact with live parts on the operating side, but are not enclosed on the other sides which permit access. Such assemblies must be installed in closed electrical operating areas. They are used very rarely.

Enclosed assemblies are enclosed on all sides so that contact with parts which may be live during operation is prevented. Such assemblies are the most widely used nowadays as they offer users optimum protection with regard to personnel and equipment.

Withdrawable units are the replaceable assemblies in which the number of items of equipment is grouped together and interconnected to form a functional unit. A withdrawable unit can be installed in such a way that one isolating gap is open whereas the unit itself remains mechanically connected to the switchgear assembly.

Switchgear with withdrawable arrangement has the totally-enclosed cubicle construction, which is divided into individual compartments for the withdrawable units (outgoing feeder, infeed or coupling unit). Such solutions characterise an extremely high level of operational and personal safety.

Box-type assembly consist of individual boxes which are permanently connected to each other and contain items of equipment such as main busbars, fuses, switches and contactors. Contact with parts that may be live during operation is prevented by means of enclosures and covers. Such assemblies can be installed in generally accessible operating areas.

9.4. Selection of switchboards

It is very important to choose and select suitable switchboard or distribution board type for a considered application. Selected system should fulfill such requirements as: econornic efficiency, flexibility, safety and reliability.

Now, planners are often used, for designing and dimensioning switchboards and distribution boards, special software tools. These tools are also very useful for assessment of switchboards from reguirements point of view determined by planner.

The selection criteria of low-voltage switchboards and distribution-boards are grouped into the following four categories:

- Currents,
- Degree of protection and type of installation,
- Equipmnent mounting type,
- Application.

In process of suitable selection of switchboards, the following currents are considered: rated currents of busbars, rated currents of infeeds, rated currents of outgoing feeders and short-circuit strength of busbars.

The prospective short-circuit current at the point at which the switchboard or distribution board is installed must not be higher than the short-circuit strength values specified for the product by the manufacturer. The prospective short-circuit currents are: peak short-circuit current (i_p) and initial symmetrical short-circuit current (I''_k).

Details of the short-circuit strength can be provided by the manufacturer by specifying:

- the maximum permissible prospective rated short-circuit current at the input terminals of the switchgear assembly with integrated short-circuit protective device in the infeed,
- the rated short-time current and rated peak withstand current,
- the prospective rated short-circuit current together with the current-limiting switching device [15].

In frames of category connected with degree of protection and type of installation the following elements are considered: degree of protection, protection against electric shock, enclosure material, type of installation (against a wall, free-standing) and number of operating faces.

Depending on the installation location and surrounding conditions, a switchboard or distribution board type should be chosen which provides the necessary degree of protection against contact and against the ingress of solid foreign bodies and water. It is described with using IP code. Enclosure of switchboards must be fulfilled by the requirement connected with the degree of protection.

In rooms of an industrial plant that are accessible to everyone, switchboards and distribution boards must have the protection degree of at least lP 20.

Switchgear assemblies must be designed in such a way that they provide the necessary protection against contact with live parts. It must also be possible to be able to implement appropriate measures to provide protection against electric shock.

From point of view of equipment mounting type, switchboards can be: fixed-mounted, removable or withdrawable. The mounting type is important. It determines possibilities and options for replacing equipment in the event of a fault and for modifying switchgear assemblies. The best solution is installation of removable units or withdravable units in switchgear assemblies.

Suitable selection of switchgear or distribution board require analysis of such characteristic features of system installation as: installation location, type of installation, type of access and installation dimensions.

In aspect of installation location, a planner's knowledge about: generally accessible operating areas, electrical operating areas and closed electrical operating areas is necessary. Moreover, knowledge about type of installation or type of acess is important. The types of installation in an industrial plant can be the following: on the floor (against a wall or free-standing in the room), fixed to a wall (in a stairwell or a recess), suspended from the ceiling, on a mounting structure or in a cavity wall. The types of access can be the following: for operation by non-experts, on one or two sides (for operation), top and rear access for installation of and maintenance inspections on busbars or front and rear access for connection work and modifications.

For localisation of switchboard, it is important to ensure that sufficient space is left on the operating side between the switchboard and the opposite surface (wall, the next switchboard, machines etc.) to allow access to personnel to operate, maintain or replace the equipment.

9.5. Additional remarks about system solutions

Switchboards in the immediate vicinity of the transformers can be supplied effectively via enclosed busbar ducts. Entry into the switchboard is then possible either from below (as with cables) or from above via additional extensions.

Outgoing feeders are always connected via cables. Depending on the distances involved, parallel cables are also used as of 250 A (approx.) due to the voltage drop and currents to be carried.

The cables are usually routed downwards in this type of arrangement. Cables racks can be mounted on wall brackets or are suspended from the ceiling using hangers and clamping brackets. In ground floor factory areas, false floors are often used so that the cables can be installed easily and accessibly in the space provided (height: approx.0,5 m).

Main switchboards usually take the form of a so-called four-conductor system with the three phase conductors L1, L2 and L3 as well as a PE or PEN conductor bar laid in the lower part of the panels. This is due to the fact that unbalanced loads such as heating, lighting and single-phase motors are rarely connected to the main switchboards. The phase conductors are located either in the upper part of the switchboard or at the rear in a staggered formation.

The rated currents and rated short-circuit currents of the busbars have different values according to the type of switchboard and depend on:

- the mounting position within the sections,
- the relationship of the conductors to each other,
- the cross-sectional area of the conductor material,
- the strength of the conductor material,
- the clearances between the supports,
- possible thermal effects of other components.

9.6. SIVACON low-voltage switchboards

SIVACON low-voltage switchboards (Fig. 9.3) are used as the main switchboards (≤ 6300 A) in power centers or as the main and sub-distribution boards (≤ 4000 A). They fulfill requirements concerned, among other things, with: economic efficiency, flexibility, safety and reliability.

Fig. 9.3. SIVACON switchoard in industrial plant

The design is based on a sophisticated modular concept with a large number of standardized components. Only modules and components which provide the required funcionality are used.

Solutions can be implemented as power centers and the main and sub-distribution boards thanks to different equipment mounting types. Moreover, they can be easily adapted to modified operating conditions thanks to appropriate cubicle and device modules.

SIVACON low-voltage switchboard system is based on a functional-based modular structure. A switchgear cubicle or a switchboard consist of modular groups, which are made up of individual modules, and individual modules. Such modular structure enables components to be combined in many different ways even if these have different designs. All of the switchgear cubicles have a standard outer size.

These are divided into functional compartments, which for the most part cannot be modified. The individual functional compartments can be configured as demanded thus providing the flexibility required by the individual functions. The device compartment can, for the most part, be freely configured in accordance with the needs of the user.

The device compartment is divided into ten 175 mm modules (175 mm = 1 M). By inserting additional racks, the device compartment can be divided into compartments ranging from 1 M to 10 M depending on the module size.

The possibilities for configuring the device compartment are based on the following equipment designs:

- Withdrawable-unit design,
- Circuit-breaker design,
- Fixed-mounted design.

9.7. MNS low-voltage switchboards

MNS low-voltage switchboards (Fig. 9.4) are used as the main switchboard in power centers or as the main and sub-distribution boards.

MNS switchboards are a cost-effective compact switchgear system. It consists of functional units in the form of modules that can be combined as it is necessary (combination modules). The basis for the design is a basic grid dimension E of 25 mm in all three dimensions (height, width, depth).

The standardized subdivision of a section into various functional compartments, i.e. equipment compartment, busbar compartment and cable terminal compartment, offers advantages for design and operation, maintenance, change and also safety.

Overview of the modular arrangement options of the MNS system is shown in Fig. 9.5. The sizes of the used modules in a MNS switchboard is shown in Fig. 9.6.

The possibilities for configuring the equipment compartment are based on the following equipment designs:

- Withdrawable-unit design,
- Fixed-mounted design.

A particular advantage of the MNS system is the configuration of the busbars at the rear of the section (in contrast to the formerly common configuration above in the section). It offers supplementary safety for personnel in the event of an accidental arc on the busbar, provides space for two busbar systems if required, enables an advantageous back-to-back configuration with only one busbar system and allows cables to be fed in through cable racks from above.

Fixed and withdrawable parts basically have plug-in contacts as busbar-side terminals, In fixed parts the equipment is arranged two-dimensionally on the functional units, while it has a three-dimensional design in withdrawable parts with maximum usage of the cabinet depth. With a majority of smaller modules (<7,5 kW), the demands on switch cabinet volume are around 40% less with the withdrawable part design. The withdrawable part sizes are adjusted to one another to enable small and large modules to be economically combined in one bay.

The example of the withdrawable unit for MNS switchgear is shown in Fig. 9.7.

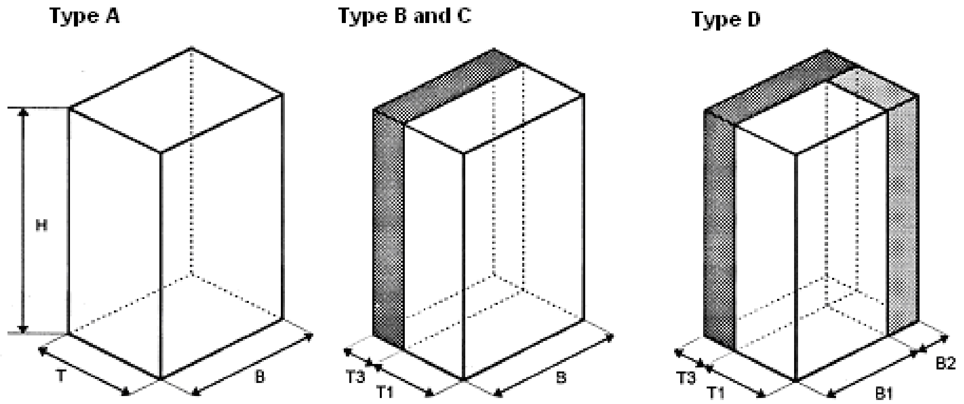
The reliable mechanical and electrical interlocking of the switchgear prevents operating errors when moving the withdrawable parts.

Fig. 9.4. MNS switchboard in industrial plant

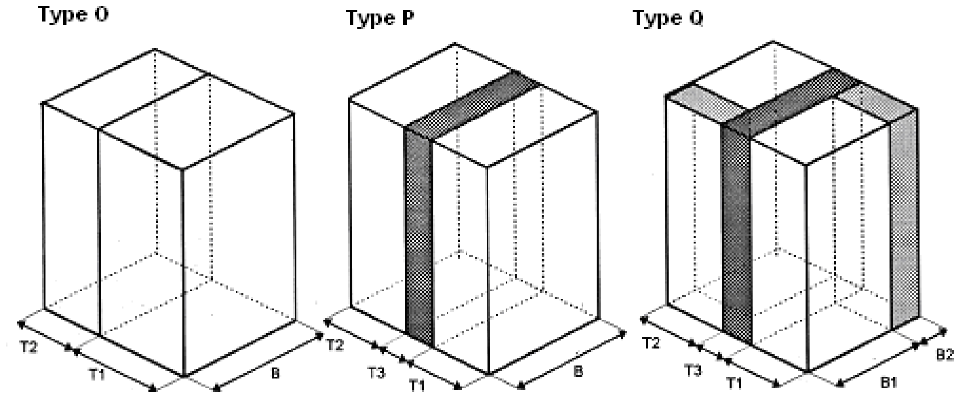
The circuit diagrams of example withdrawable branch modules are shown in Fig. 9.8. The circuit diagrams of example motor starters, which can be obtained as withdrawable parts, are shown in Fig. 9.9.

Table 9.1 shows standard electrical and mechanical parameters of MNS.

Single control



Double control



▒ - cable terminal compartment ▓ - busbar compartment ☐ - equipment compartment

Fig. 9.5. Examples of the modular arrangement options for MNS switchboard [4,72]:
B – width of a swichboard, T – depth of a switchboard, H – high of a switchboard, B1 – width of a equipment compartment, B2 – width of a cable terminal compartment, T1,T2 – depths of equipment compartments, T3 – depth of a busbar compartment

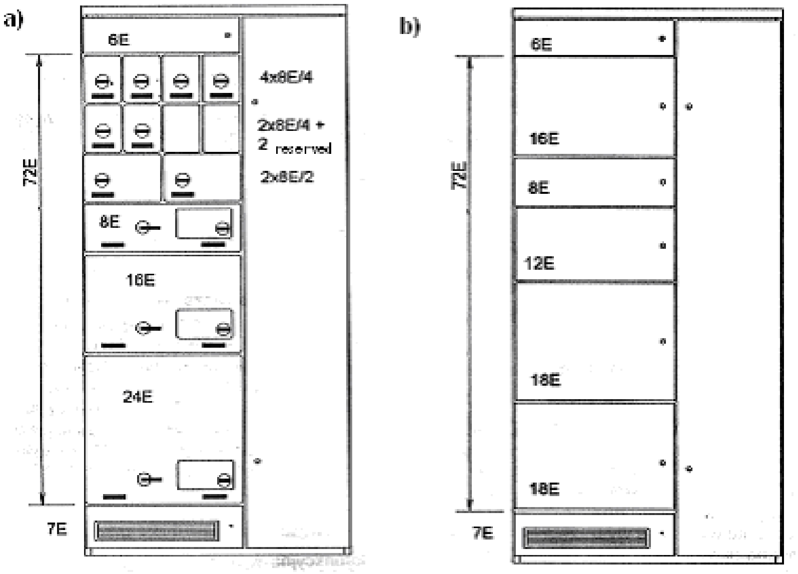


Fig. 9.6. Examples of MNS switchboards with module sizes [2,72]: a) MNS section with withdrawable units, b) MNS section with fixed-mounted units; E – basic dimension of a module, E = 25 mm

Fig. 9.7. Example of MNS withdrawable unit

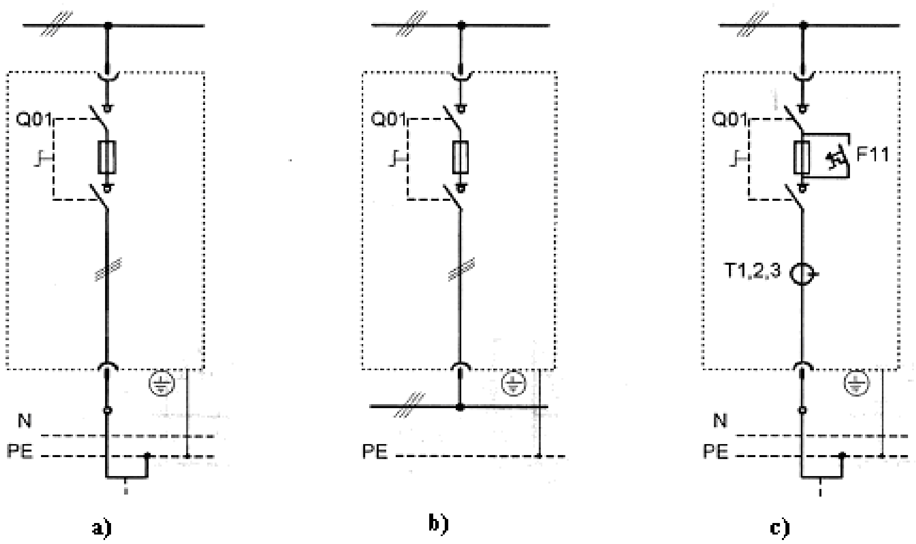


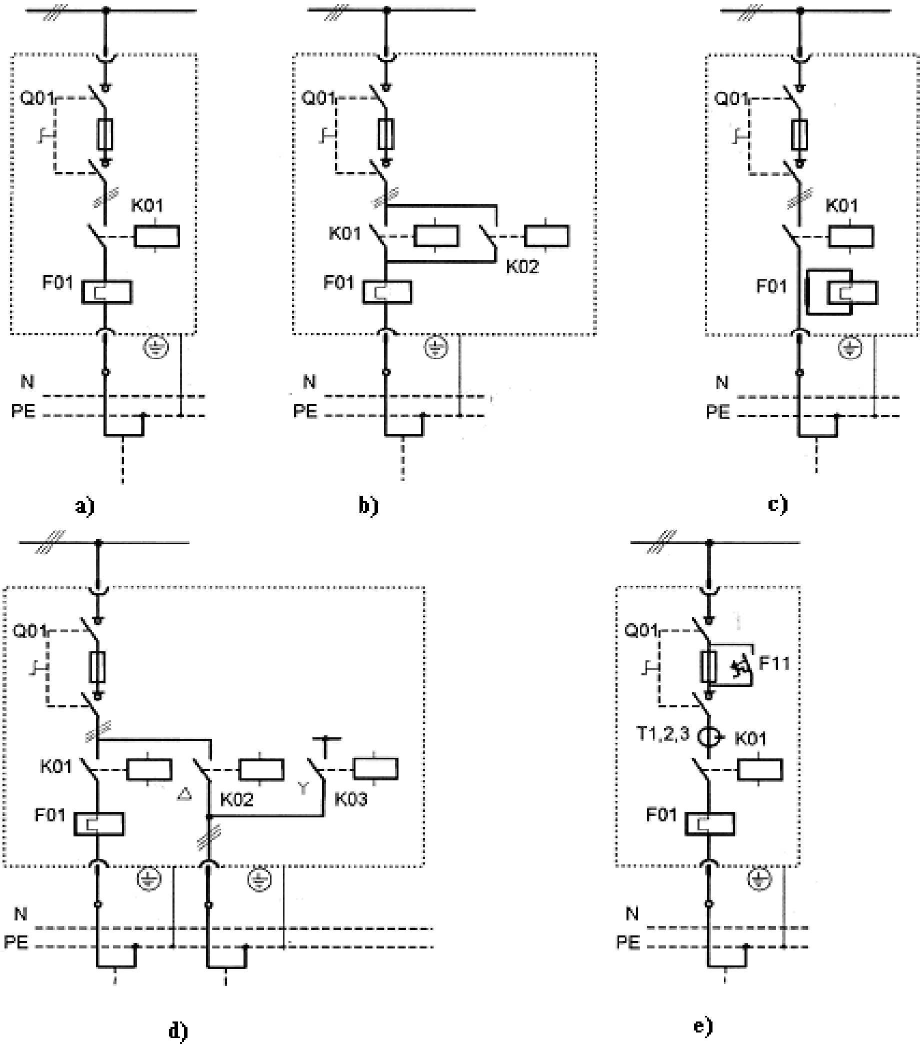
Fig. 9.8. Examples of standard MNS branch modules for main circuits with a load-break switch and fuse (withdrawable-part design) [72]: a) cable branch module, b) busbar sectioning branch module, c) options: control of fuse states and current measurement

Table 9.1. MNS system characteristics data [1,72]

Electrical parameters		
Rated voltages	rated insulation voltage U_i	1000 V
	rated operational voltage U_a	690 V
	rated impulse withstand voltage U_{imp}	8 kV
	overvoltage category	III
	pollution severity	3
	rated frequency	to 60 Hz
Rated currents		
busbars:	rated current I_e	to 6300 A
busbars:	rate peak withstand current I_{pk}	to 250 kA
busbars:	rated short-time withstand current I_{cw}	to 100 kA
distribution busbars:	rated current I_e	to 2000 A
distribution busbars:	rate peak withstand current I_{pk}	to 165 kA
distribution busbars:	rated short-time withstand current I_{cw}	to 86 kA
Mechanical parameters		
Dimensions	preferred module sizes, height	2200* mm
	preferred module sizes, width	400, 600*, 800, 1000*, 1200 mm
	preferred module sizes, depth	400, 600*, 800, 1000*, 1200 mm
	basic grid dimension	E = 25 mm
Degrees of protection	according to lEC 60529	lP 00 to lP 54
Internal subdivision	section - section	

	busbar compartment-cable terminal compartment
	busbar compartment-equipment compartment
	equipment compartment-cable terminal compartment
	sub-section - sub-section
Specifications	lEC 60439-1, EN 60439-1

* - prefered



a) b) c) d) e)

Fig. 9.9. Examples of standard MNS modules with circuit diagrams for motor starter with a load-break switch, fuse and thermal relay (withdrawable-part design) [72]: a) one-direction drive, b) reversing drive, c) one-direction drive for heavy start-up, d) one-direction drive star-delta, e) options: control of fuse states and current measurement

10. LIGHTING IN INDUSTRIAL BUILDING

10.1. Introduction

Requirements concerned with lighting indoors are described by norm IEC [19]. This norm concerns an exact description of lighting indoor requirements for workplaces. For worker, realisation of these requirements gives him a very good field of vision and secures him a work comfort, a good mood, a safety and a proper visual efficiency which is necessary for realisation of concrete work.

A certain specific set of terms, definitions and parameters is used in relation to lights and lighting.

Basic and key light parameter is a luminous flux. It is a photometric measure of radiant flux, i.e. the volume of light emmited from the light source. It is a very important parameter because all other photometric parameters are derivatives of luminous flux. Some examples of luminous flux for different lamps are shown in Table 10.1.

Table 10.1. Luminous flux for selected light sources [88]

Lamp type	Luminous flux in lm
10W compact fluorescent lamp	600
20W energy-saving lamp	1200
18W fluorescent lamp	1350
100W incandescent lamp	1380
25W compact fluorescent lamp	1800
36W fluorescent lamp	3350
100W high-pressure sodium lamp (colour corrected)	4700
38W fluorescent lamp	5200
70W metal halide lamp	5500
125W high-pressure mercury lamp	5700
250W metal halide lamp	20000

Not the whole amount of luminous flux emitted by the lamp reaches the work plane. Light that falls on a surface can be absorbed, transmitted or reflected, depending on the properties of the material involved. There are losses in the luminaire (absorption, transmission, reflection losses) and at the room perimeters (reflectance). In the normal case about $60 \div 70\%$ of luminous flux will reach the work plane (light output ratio).

The work plane is the theoretical plane to which service illuminance E_n relates. In the normal case the work plane is treated as a horizontal plane 0,85 m above the floor.

In a lighting system electrical energy is converted into light. In the process of light generation, there are certain losses in the lamp, and further losses are caused by the material properties of the luminaire components. In addition, not the whole amount of light emitted by the luminaires reaches the working plane to be illuminated, because of losses to reflected light at the room perimeters.

The important parameter of lamps is luminous intensity. It is a relation of luminous flux of a lamp to electrical energy input according to the formula:

$$\eta_l = \frac{\Phi}{P} \tag{10.1}$$

η_l - luminous efficiency in lm/W,
Φ - luminous flux from the lamp in lm,
P - electrical energy input in W.

The very important light parameter is luminous intensity. It is an expression of the amount of light beamed in a certain direction within the interior. It is calculated as the ratio of luminous flux to the relevant element of solid angle according to the formula:

$$I = \frac{d\Phi}{d\omega} \tag{10.2}$$

I - luminous efficiency in cd,
Φ - luminous flux from the lamp in lm,
ω - solid angle in sr.

The luminous intensity of a lamp or luminaire is not equal in all directions. By plotting luminous intensity in the room (or in planes) around the lamp or luminaire, luminous intensity distribution can be defined. This offers a precise description of the photometric characteristics of the lamp or luminaire. Luminous intensity distribution is normally represented in the form of either a poled or linear diagram.

10.2. Review of light sources

Today, the lighting industry offers a wide range of light sources for a variety of lighting situations and requirements in industry. The various lamp types differ not only in size and shape but, above all, with regard to the light generation processes involved, and to such factors as power, luminous flux, colour of the light, base system, etc.

The most common types of lamps in use today can be divided into three main groups, namely:

- thermal radiators,
- discharge lamps and
- fluorescent lamps.

The thermal radiators include: incandescent lamps, mains voltage tungsten halogen lamps and low-voltage halogen capsule lamps.

The discharge lamps and fluorescent lamps include: fluorescent lamps, compact fluorescent lamps, high-pressure mercury lamps, high-pressure sodium lamps and metal halide lamps.

The incandescent lamps are thermal radiators. Light is produced as a result of the high temperature of the filament when current is passed through it. Although incandescent lamps have a low luminous output and short service life, they are commonly used because of the pleasant colour of the light and good colour rendition characteristics and above all because of the low price. They are mainly employed in the households, offices, restaurants, store windows, etc. However, they are rarely used in industrial plants.

The advantages of these lamps are the following: small size, very good colour rendition, wide range of wattage and shapes, immediate switching and very low price. However, disadvantages are the following: low luminous output ($10 \div 20$ lm/W), short lamp life (1000 h) and high thermal load.

The fluorescent lamp is a low-pressure discharge lamp comprising a glass tube with electrodes at both ends. The tube is filled with argon or krypton gas plus a small amount of mercury. The tube also contains a quantity of inert air for faster starting. On the inside the glass tube is coated with a thin layer of fluorescent powder. When current is passed through a tube, the gas discharge produces mainly invisible ultraviolet light, which is only converted to visible light when it penetrates the powder coating.

Fluorescent lamps offer long service life, high luminous output and good colour rendition, and are therefore used for a wide range of lighting requirements. They are operated with a ballast and starter.

The advantages of these lamps are the following: high luminous output ($75 \div 95$ lm/W), wide range of wattage, very good colour rendition and long lamp life ($7500 \div 12000$ h). However, main disadvantage is size.

Compact fluorescent lamps work on the same principle as tubular fluorescent lamps. The use of compact fluorescent lamps greatly extends the range of applications for fluorescent lamps. Compact fluorescent lamps require a ballast for starting, current limitation when operating and a starter.

The advantages of these lamps are the following: small size, wide range of wattage, high luminous output ($50 \div 88$ lm/W), up to 80% energy savings, very good colour rendition and long lamp life (8500 h). However, the main disadvantage is higher price of such lamp.

High-pressure mercury lamps combine high luminous output and long lamp life with small size. In view of their poor colour rendition properties and long starting time, they are employed mainly for industrial plant and outdoor locations. High-pressure mercury lamps are operated with a ballast. Additional ignition gear is not required.

The advantages of these lamps are the following: good luminous output ($32 \div 60$ lm/W), wide range of wattage, long lamp life ($10000 \div 12000$ h) and small size. However, the disadvantages are the following: poor colour rendition, long starting and restriking times (approx. 5 min.) and high price.

Conventional high-pressure sodium lamps offer a very high luminous output but inferior colour rendition. Their small size and long lamp life make them highly suitable for highway and tunnel lighting systems. High-pressure sodium lamps are operated with ballasts and igniters.

Conventional types of sodium lamps have the following advantages: very good luminous output ($70 \div 130$ lm/W), long lamp life ($9000 \div 10000$ h) and small size. However, the disadvantages of conventional types of these lamps are poor colour and long starting and restriking times (sometimes up to 10 min.).

Now, more modern types of high-pressure sodium lamps are also suitable for interior lighting systems. Although luminous output is lower, colour rendition is good and restriking time is short.

New types of high-pressure sodium lamps have the following advantages: good luminous output ($40 \div 50$ lm/W), good colour rendition, interior climate similar to incandescent lamps, fast hot restrike and small size. However, the disadvantage is ballast, igniter and stabilising gear required.

Metal halide lamps combine high luminous output and long lamp life with compact dimensions. Although these lamps have long starting time, their good colour rendition properties make them a common choice for industrial plant and office lighting systems.

The advantages of these lamps are the following: good luminous output ($62 \div 112$ lm/W), long lamp life ($6000 \div 8000$ h), very good colour rendition and small size. However, the disadvantages are the following: long starting and restriking times and high price.

10.3. Key parameters of lighting installation

Installations for indoor lighting are characterized by different parameters such as: illuminance, colour redition, colour appearance and luminance limit angle.

Illuminance

The most important key parameter of lighting installation is illuminance. It is a measure of luminous flux striking a given surface according to the formula:

$$E = \frac{\Phi}{S} \tag{10.3}$$

E – illuminance in lx,

Φ - luminous flux in lm,
S – surface in m^2.

The performance of the human eye is highly dependent on the level of illuminance within the field of vision. But general performance and motivation also improve with increasing illuminance, while the frequency of mistakes decreases.

In the individual case the level of illuminance required will depend on the tasks involved and the precision of visual performance required. Adequate illuminance at the workplace is dependent on the choice of luminaires and lamps, correct calculation of the number of luminaires required, and installation in an efficient configuration.

The required levels of illuminance are defined in by the mentioned norm IEC [19]. The IEC standard defines minimum illuminance which must be maintained at all times and at all points within the interior.

The levels of illuminance quoted in the IEC standard are graded as follows: 3, 5, 10, 20, 30, 50, 100, 200, 300, 500, 750, 1000 and 1500 lx.

Service illuminance is always quoted relative to the position of the plane to be illuminated. Horizontal illuminance, for example, is an expression of the level of illuminance on a horizontal work plane, while vertical illuminance relates to a vertical plane.

Typical values for illuminance in interiors are shown in Table 10.2.

Table 10.2. Typical illuminance in interiors [4,19,88]

Type of interiors	Illuminance in lx
Office	300 ÷ 1000
Industrial plant	100 ÷ 500
Living room	100 ÷ 300
Cellar	50 ÷ 100

The distribution of illuminance on a plane can be represented by isolux lines, i.e. points of equal illuminance oined together to form a curve. The areas between the curves relate to intermediate values of illuminance. The increments selected for the individual isolux lines must offer a meaningful picture for the whole range of illuminance (e.g. increments of 100 lx). A sector with very dense curves represents an area with pronounced differences in illuminance, whereas ample spacing between the isolux lines indicates a high degree of uniformity in the pattern of illuminance.

Colour rendition

One of the important parameters of lighting installation is colour rendition. It is the term used to describe the degree to which an object or surface colour (walls, ceiling, furniture, workpiece) seems "normal" when viewed under artificial light. It is an important quality criterion. The concept of colour rendition is based on the assumption that an object colour appears normal when illuminated by a thermal radiator or daylight.

The general colour rendering index (Ra) expresses the sum of the differences measured for various test colours when comparing a given illuminant with a reference light source. A simple overview is available in the form of colour rendition classes for light sources. It is shown in Table 10.3.

Table 10.3. Colour rendition classes [88]

Classification	Colour Rendition Class	Colour Rendering Index *Ra*
Very good	1A	$Ra \geq 90$
	1B	$80 \leq Ra \prec 90$
Good	2A	$70 \leq Ra \prec 80$
	2B	$60 \leq Ra \prec 70$
Not so good	3	$40 \leq Ra \prec 60$
	4	$20 \leq Ra \prec 40$

Various levels of colour rendition are prescribed in the standards depending on the type of the interior and the activities involved. Colour Rendition Class 1A indicates the best possible quality of colour rendition.

The decisive factor in the quality of the colour rendition available from a lighting system is the choice of lamps. Thermal radiators such as incandescent lamps have very good colour rendition characteristics, while fluorescent lamps come in a variety of quality classes.

Selection of lamps with using colour rendition classes is shown in Table 10.4.

Table 10.4. Selection of lamps from point of view of colour rendition classes [88]

Classification	Colour Rendition Class	Colour Rendering Index Ra	Incandensent lamps	Compact-fluorescent lamps	Fluorescent lamps	High-pressure mercury lamps	Halogen-metal halide lamps
Very good	1A	$Ra \geq 90$	X	X	X		X
	1B	$80 \leq Ra \prec 90$	X	X	X		X
Good	2A	$70 \leq Ra \prec 80$			X		X
	2B	$60 \leq Ra \prec 70$			X	X	X
Not so good	3	$40 \leq Ra \prec 60$			X	X	
	4	$20 \leq Ra \prec 40$				X	

Colour appearance

One of the important parameters of lighting installation is colour appearance. It is the term given to the chromaticity of a primary radiator, i.e. a light source. Colour appearance is a product of the spectral composition spectrum of the radiated light. The chromaticity of a light source is compared with the colour of a black body or Planckian radiator and is expressed in terms of the nearest temperature (Colour Temperature). Red chromaticity is in the low colour temperature range, changing to white and then blue with rising temperature. Colour temperature is expressed in Kelvin degrees (K).

In both the DIN and CIE (Commission International de l'Eclairage) standards which are shown in Table 10.5, artificial light sources are classified in terms of their colour appearance. To the human eye they all appear to be white; the difference can only be detected by direct comparison. Visual performance is not directly affected by differences in colour appearance.

Table 10.5. DIN-Classification and CIE-Classification for colour appearance [1,88]

DIN-Classification		CIE-Classification		
	Abbreviation		Abbreviation	Colour Temperature Range T_n in K
Warm colour appearance	ww	Group I	Warm	< 3300
Intermediate colour appearance	nw	Group II	Mittel	3300 ÷ 5000
Cool colour appearance	tw	Group III	Kalp	5000

Luminance limit angle

One of the important parameters of lighting installation is luminance limit angle.

An unshielded lamp in the direct line of vision is a potential source of direct glare caused by excessive luminance. There are two ways of avoiding direct glare: either the lamp is shielded, e.g. by the housing itself or by fitting solid vanes or louvres, or the high level of luminance is reduced through the use of opal or prismatic diffusers.

The luminance limit angle α of a luminaire as measured from the horizontal plane is the maximum angle at which the lamp is not yet in the direct line of vision.

Luminance limit angle is specified per lamp type and glare cut-off class. Kinds of glare cut-off classes for different types of lamps are shown in Table 10.5.

Table 10.5. Kinds of glare cut-off classes for different types of lamps [88]

Type of lamps	Direct glare cut-off class			
	A	1	2	3
Fluorescent lamps	20°	10°	0°	0°
Compact fluorescent lamps	20°	15°	5°	0°
High-pressure discharge lamps with fluorescent or matt bulbs	30°	20°	10°	20°
low-pressure sodium lamps	30°	20°	10°	20°
High-pressure discharge lamps with clear bulbs	30°	30°	15°	10°
Incandesent lamps with clear bulbs	30°	30°	15°	10°

The United Glare Rating method (UGR) has been developed by the ClE in order to harmonise glare classification procedures worldwide.

The UGR formula can be used to assess the glare characteristics of a complete lighting system. The formula takes account of every luminaire in a given interior and also background luminance (ceiling, walls) with reference to a standard viewing point.

A standard table is available listing uncorrected UGR values for various room sizes and reflectance combinations. These values have to be corrected to take account of such factors as the luminous flux of the light sources.

The final UGR scores tend to lie between 10 ("no glare") and 30 ("pronounced physiological glare"). The higher the UGR score, the greater the probability of glare. Completely different results can be achieved with luminaire locations that deviate from the standard configuration and for other viewing points.

Table 10.6 offers a rough conversion guide between the conventional glare classes and the UGR system.

Table 10.6. Glare cut-off class for UGR method [88]

Illuminance in lx			UGR_{max}
≤ 300	500	1000	
		A	16
	A	1	17,5
A	1	(C)	19
1	(C)	2	20,5
(C)	2	3	22
2	3		23,5
3			25

There are plans to lay down maximum UGR scores for various requirements and activities on the line of the glare quality classes used to date.

10.4. Procedures of lighting installation planning

Installations for indoor lighting and their auxiliary equipment are subject to very varied requirements regarding service illuminance (sometimes determined as intensity of lighting, rated lighting intensity), colour (especially colour appearance), colour reproduction (mainly concerns colour rendering group) and limiting glare (mainly concerns direct glare restriction class).

The mentioned norm IEC [19] specifies nominal service illuminances (lighting intensities) for iluminating workplaces.

The standard values for metalworking industry for service illuminance (rated lighting intensity), colour appearance, colour rendering group, and direct glare restriction class are listed in Table 10.7 for various types of interior or activity. The ratings for service illuminance, colour rendering group, and direct glare restriction class represent minimum values to be met by the lighting system.

Table 10.7. Standard values for metalworking industries. Recommendations for various lighting tasks [88]

Interiors/Activities	Rated lighting intensity in lx	Colour appearance	Colour rendering group	Direct glare restriction class
Hammer-forging small part	200	ww, nw	3	2
Welding	300	ww, nw	3	2
Machining centers, automatic and semiautomatic machine plant	300	ww, nw	3	3
Rough and medium-accuracy machining, max. tolerance > 0,1 mm	300	ww, nw	3	1
Precision machining, max. tolerance < 0,1 mm	500	ww, nw	3	1
Robot workstations	300	ww, nw	3	1
Marking, checking, measuring	750	ww, nw	3	1
Toolmaking, construction of jigs and fixtures templates, precision engineering, precision assembly work	1000	ww, nw, tw	3	3
Cold rolling mills	200	ww, nw	3	2
Wire and tube drawing mills, cold strip production	300	ww, nw	3	2
Sheet metal working	300	ww, nw	3	2
Production of small tools	500	ww, nw	3	1
Assembly - rough	200	ww, nw	3	2
Assembly - medium	300	ww, nw	3	1
Assembly - fine	500	ww, nw	3	1
Drop-forging	200	ww, nw	3	2

Remarks:
Warm-white (wm), Neutral white (nw), Daylight white (tw)

The table with recommendations for various lighting tasks is sometimes different from Table 10.7. For example in Germany, columns of the table are the following:

- Type of space activity,
- Rated lighting intensity,
- Light colour,
- Stages of colour reproduction properties,
- Quality class of glare restriction.

In this case first three columns are the same as first three columns in Table 10.7, but next two are different.

Stages of colour reproduction properties give information about colour and colour reproduction of light sources (Table 10.8). It is connected with rated lighting intensity.

Table 10.8. Colour and colour reproduction properties of light sources [1]

Stages of colour reproduction properties	Light colour	Typical light sources	Remarks	Typical application
1	Daylight white (tw)	Xenon lamps, fluorescent lights (daylight) and halogen metal-vapour lamps with very good colour reproduction properties		Textile industry, graphical, commercial, factory sheds, Outdoor manufacturing halls, sale rooms
	Neutral white (nw)	Fluorescent lights (white) with very good colour reproduction properties	Can be combined with daylight	Offices, schools, laboratories, sale rooms, art galleries
	Warm-white (wm)	Incandescent lights, halogen incandescent lights, fluorescent lights (warm tone) with very good colour reproduction properties	Can be combined very well with incandescent lights	Mood lighting, living area, restaurants, sales rooms
2	Daylight white (tw)	fluorescent lights (daylight) and halogen metal-vapour lamps with very good colour reproduction properties		Factory halls, exhibition halls
	Neutral white (nw)	Fluorescent lights (white) with very good colour reproduction properties	Can be combined with daylight	Offices, schools, laboratories, sale rooms, industrial commercial work rooms
	Warm-white (wm)	fluorescent lights (warm tone) with very good colour reproduction properties	Can be combined well with incandescent lights	Hallways, stairwell houses, outdoor lighting
3	Neutral white (nw)	Fluorescent lights (white) with a few good colour reproduction properties, mercury vapour high-pressure lamps with fluorescent material mixed lamps	Can be combined with daylight	Industrial and commercial work rooms, outdoor lighting
	Warm-white (wm)	fluorescent lights (warm tone) with a few good colour reproduction properties		Warehouses, outdoor lighting
4		Sodium-vapour lamps, mercury vapour, high-pressure lamps without fluorescent material		floodlighting, outdoor lighting

The quality class of glare restriction give information about three quality classes which are distinguished with very individual criteria with the requirements for the glare limitation:

- Quality class 1: high demands, approx. 10 % of persons surveyed still detect distracting glare.

- Quality class 2: moderate demands, approx. 30 % of persons surveyed still detect distracting glare.
- Quality class 3: low demands, approx. 40 % of persons surveyed still detect distracting glare.

For the metalworking industry, for the majority of activities, stage of colour reproduction properties is equal 3 and the quality class of glare restriction is equal 1.

The loss of illuminance caused by ageing and contamination in a lighting system can be anticipated in the planning phase with the help of design factor (*p)*. This means that more "light" is installed at the beginning of the service life of a new system, so that required service illuminance can be guaranteed over a longer period of time.

Planners of lighting installations should take into consideration that lights become dirty and that they deteriorate with age. For this reason, a planning factor is calculated into new installations. Planning factor for contamination and deterioration is determined as design factor (*p*).

For interiors subject to normal levels of contamination, a design factor of 1,25 is usually applied. If above average contamination is to be expected or maintenance costs will be high, the design factor can be increased as required. Values of design factors are listed in Table 10.9.

Table 10.9. Design factors [4,88]

	Design factor
Reduction in illuminance due to contamination and ageing in lamps, luminaires and interiors	*p*
Normal (standard)	1,25
High (enhanced)	1,43
Very high (strong)	1,67

Design factors are multiplied with the rated value of the required illumination intensity to find the required installation service illuminance.

The set rated lighting intensities (service illuminance) are rated values of the average lighting intensity. They must not be below these values.

The selection of light sources can depend on a height of industrial rooms (halls). Fluorescent lamps are predominantly used in industrial halls with a luminaire mounting height of up to 5 m. However, high-pressure discharge lamps (mercury, sodium and metal halide) are used in industrial buildings with a luminaire mounting height of more than 8 m. For height of industrial rooms (halls) between 5 and 8 m, fluorescent and discharge lamps are used in correlation of light quality requirements.

10.5. Emergency lighting

There are two types of emergency lighting for production and office areas: stand-by lighting and safety lighting.

The stand-by-lighting system performs the tasks of the normal artificial lighting system for a limited period of time. Installation depends on the requirements of the individual company and is, therefore, the responsibility of the owner.

The safety lighting system is necessary for general safety and accident prevention. It is divided into:

- Safety lighting for escape routes,
- Safety lighting for workplaces that are particularly hazardous.

The local minimum illuminance value at the end of the service life of the lamp is for escape routes 1 lx measured in a plane 0,2 m above floor level along the axis of the escape route [15,59]. However, it is for workplaces with special hazards 10% of the rated illuminance required for the workplace, but not less than 15 lx [59].

The specified electrotechnical requirements for safety lighting equipment are applied for:

- stand-by power sources,
- system type and protective measures,
- distribution boards,
- cables and line systems,
- current-using equipment [15].

10.6. Calculation methods of indoor lighting installation

The requirements for a lighting installation are determined by the following criteria:

- horizontal illuminance (lighting intensity),
- even lighting distribution,
- colour appearance and colour rendering group (colour reproduction stage),
- direct glare restriction class (limitation of glare).

The following must also be considered:

- industrial hall dimensions (length, width and height),
- colour of the reflecting surfaces around the inside of the hall (floor, walls, ceiling) /important for the definition of the reflection factor/,
- mounting height above working plane.

Two standard methods serve to provide approximate calculations for planning indoor lighting systems. The first one is efficiency method, sometimes determined as a lumen method. The second one is a point calculation method.

These methods are used to determine the number of luminaires and lamps required to achieve a given illuminance.

The point calculation method is generally recommended for outside lighting systems and for demanding interior applications (such as control rooms in power substations, network control rooms in power substations).

The efficiency method is generally sufficiently accurate for offices and workshops, industrial halls, switchgearrooms in power substations and access passages.

Comparable methods for calculating mean illuminance have been developed and published by other national and international bodies. All these methods are based on the same assumptions as far as calculations of the indirect portion of light are concerned, but they differ in the methods used to calculate direct utilised flux and in their tabular form of presentation of calculated efficiency.

The results depend on room geometry and reflectance, the luminous intensity distribution of the luminaires and their configuration in the room (hall).

The accuracy of the luminaire data used is also critical. Apart from that, the calculation methods based on a number of assumptions made to ensure that the method is easy to use. The more actual conditions deviate from these assumptions in the individual case, the less accurate the calculations.

Calculations of indoor lighting systems are made with using specialised computer programs. One of the most popular lighting programs are: DIALux [88], RELux [89], Calculux and CADLux.

Results of calculations are necessary in lighting designing. The designed lighting should satisfy all of the requirements for indoor lighting in industrial rooms (halls).

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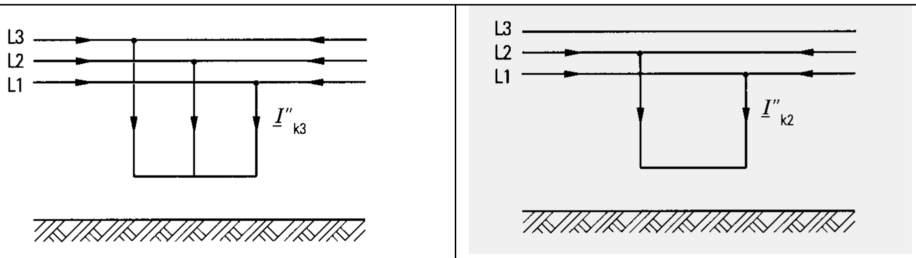
APPENDIX

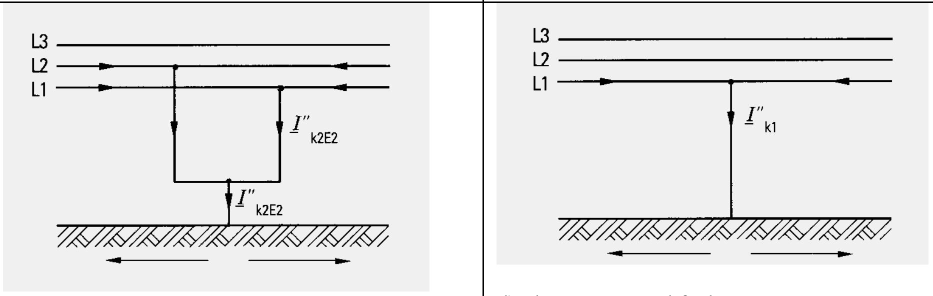
Short-circuit currents

Four types of fault can occur in three-phase installations. These faults and their associated short-circuit currents are illustrated in Fig. A.l. The types of fault can be divided into symmetrical and asymmetrical faults.



a) Three-phase short circuit (symmetrical fault)

b) Phase-to-phase ungrounded fault



c) Phase-to-phase grounded fault

d) Phase-to-ground fault

Fig. A.1. Designation of fault types and short-circuit currents to IEC 60909: →Transferred short-circuit currents [15]

Three-phase fault is the most important of the symmetrical faults. The three-phase short circuit is the least complex and easiest of these fault types to calculate. The three voltages are zero at the fault location and all three conductors are loaded symmetrically by the symmetrical short-circuit currents. The equations for calculation are in Section 7.

Three-phase short circuits represent a relatively small proportion of the faults that occur. But the highest short-circuit currents usually occur at a given fault location in a three-phase short circuit and that these values are, therefore, decisive when dimensioning the electrical equipment in the normal operating circuit.

Generally, the three-phase short circuit is the most important in three-phase systems with regard to the making and breaking loads of the switching devices and the dynamic load placed on the equipment as it produces the highest short-circuit current.

For phase-to-phase ungrounded fault, initial symmetrical short-circuit currents are mostly lower than those resulting from a three-phase short circuit, occur at the fault location. But sometimes, the phase-to-phase fault current may, in certain cases, be higher than the three-phase short-circuit current in the latter stages of the fault. Under these conditions, the phase-to-phase fault current may be a determining factor when dimensioning the switching devices with regard to the necessary symmetrical breaking current or when selecting the protective devices. Similar relationships may result when phase-to-phase grounded faults occur.

Phase-to-ground fault is the most important of the asymmetrical faults. This type of fault is definitely the most frequently encountered fault. The phase-to ground fault current is of particular importance when determining the pace and touch voltages as well as in matters concerning interference and when dimensioning grounding systems.

Calculations of the short-circuit currents require to take into consideration short-circuit current sources such as: system infeed and/or synchronous machines and/or asynchronous machines. The time characteristic of short-circuit currents depends on the point in time at which the short circuit occurs. Moreover, the waveform of the short-circuit current at the fault location largely depends on the associated system infeed or infeeds. Two cases are analyzed: remote from generator terminals or close to generator terminals.

Fig. A.2 shows the short-circuit current waveform for a three-phase short circuit remote from the generator terminals occurring in the phase conductor at the least favourable switching instant for a three-phase short circuit. This waveform should be expected for short circuits which are supplied via system infeeds. The symmetrical short-circuit current does not vary with time. In the case of short circuits remote from the generator terminals, the three-phase short circuit is important with respect to thermal stress of the equipment.

Fig. A.3 shows the short-circuit current waveform for a synchronous generator occurring in the phase conductor at the least favourable switching instant for a three-phase short circuit. This short circuit is classified as being close to the generator terminals since the symmetrical short-circuit current decays (over time) from the initial value I''_k to the sustained short-circuit current I_k.

The short-circuit currents shown in Fig. A.2 and A.3, in approximately 10 ms (one half-cycle at 50 Hz), reach their maximum possible value. It is the maximum asymmetrical short-circuit current (i_p). This value is the determining factor in evaluating the dynamic stress in the event of a fault.

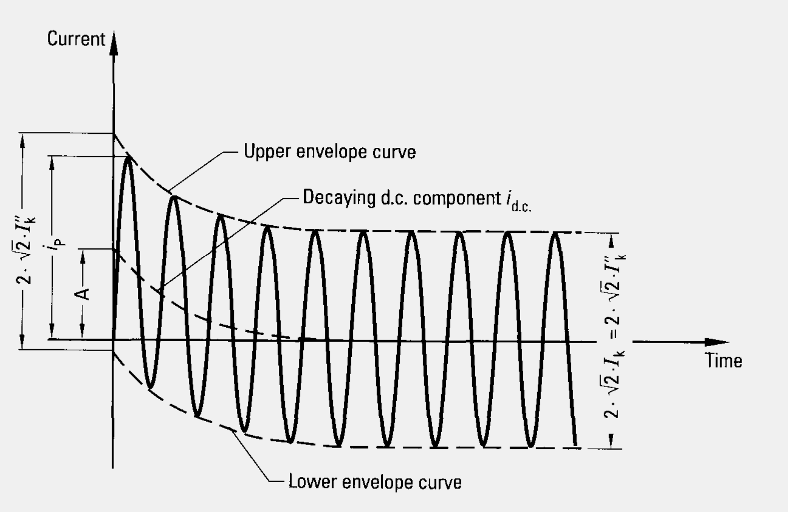


Fig. A.2. Waveform of short-circuit current for three-phase short circuit remote from generator terminals with constant alternating current component (schematic characteristics): I''_k = Initial symmetrical short-circuit current, i_p = Maximum asymmetrical short-circuit current, I_k = Sustained short-circuit current, i_{dc}= Decaying direct current component of short-circuit current A = Initial value of direct current component i_{dc} [6,15]

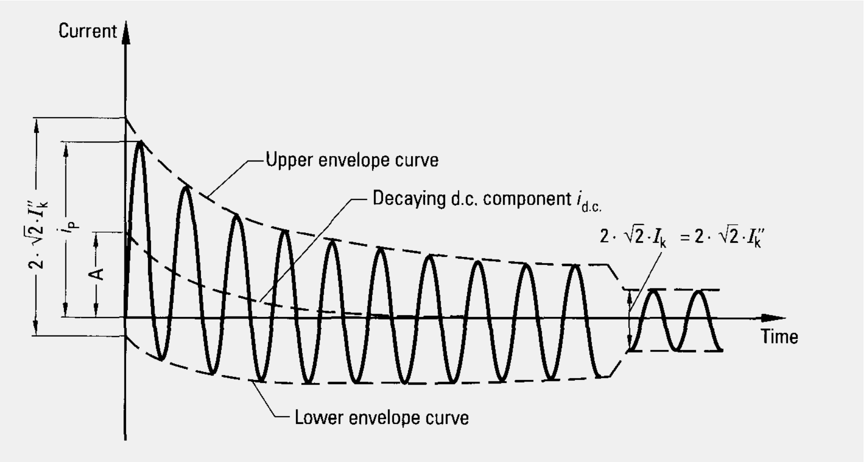


Fig. A.3. Waveform of short-circuit current for three-phase short circuit close to generator terminals with decaying decaying alternating current component (schematic characteristics): I''_k - Initial symmetrical short-circuit current, i_p - Maximum asymmetrical short-circuit current, I_k - Sustained short-circuit current, i_{dc} - Decaying direct current component of short-circuit current, A- Initial value of direct current component i_{dc} [6,15]

The highest maximum asymmetrical short-circuit current (i_p) depends on the time constant of the decaying d.c. current component and the frequency (*f*), i.e. on the ratio *R/X* of the short-circuit impedance (Z_K), and is reached if the short circuit occurs at voltage zero.