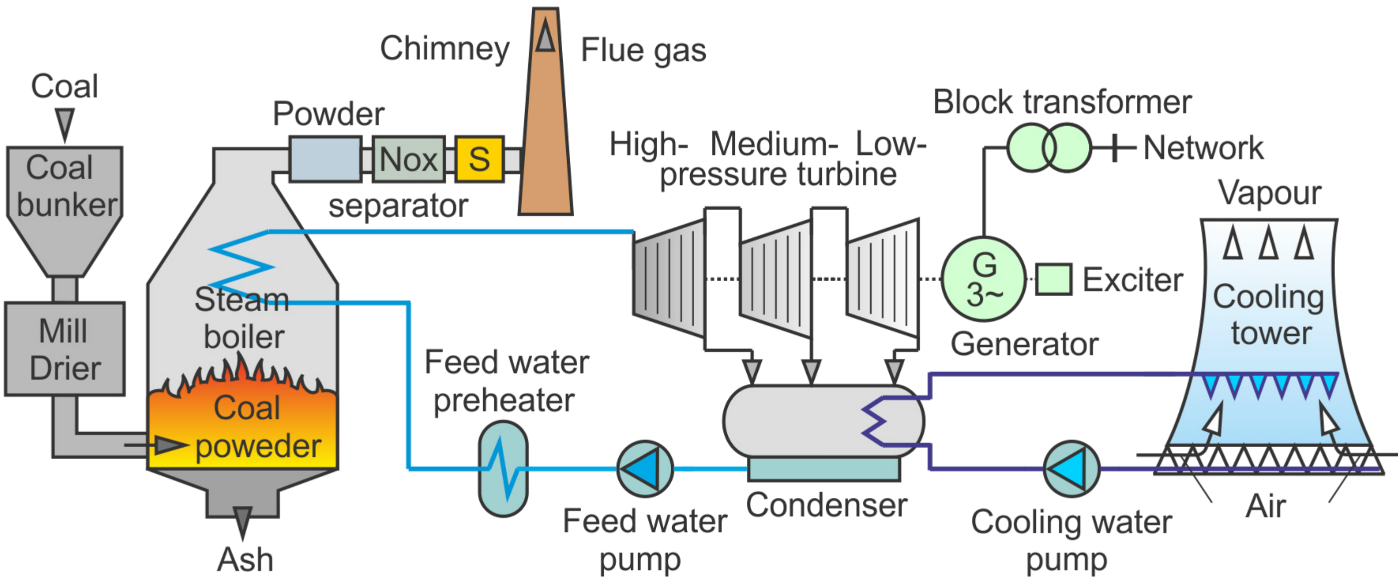
Electric Power Engineering I.



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UNIVERSITY OF PÉCS

György Elmer

Electric Power Engineering I

Pécs

2019

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Az Electric Power Engineering I tananyag az EFOP-3.4.3-16-2016-00005 azonosító számú„Korszerű egyetem a modern városban: Értékközpontúság, nyitottság és befogadó szemlélet egy 21. századi felsőoktatási modellben” című projekt keretében valósul meg.

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egy 21. századi felsőoktatási modellben

Electrical Power Engineering I

Textbook for BSc students of the Electrical and Electronic Engineering.

Content

1 Electric energy demand of mankind

The demand for energy of mankind increases continuously, the annual consumption achieved the amount of 23816 TWh in 2014, which equals to 2048 million tons of oil equivalent (toe). This increasing demand is valid for developed industrial countries with high standard of living in the past as well, but is typical to a greater extent for countries with increasing industrialization, population and standard of living. *Fig. 1.1* shows the world's energy consumption by energy source with outlook to 2040.

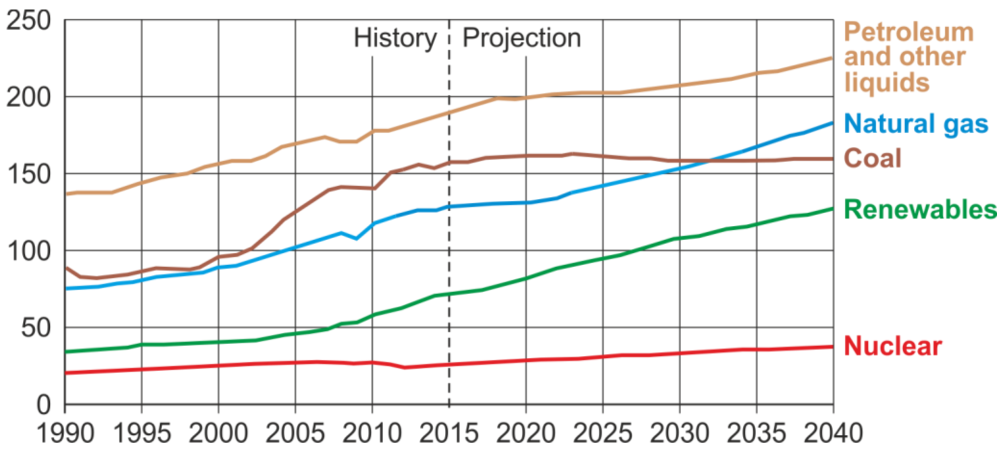


Fig. 1.1. World energy consumption by energy source [1.1]

Most of this growth is expected to come from countries that are not in the Organization for Economic Cooperation and Development (OECD), and especially in countries where demand is driven by strong economic growth, particularly in Asia (*Fig. 1.2*).

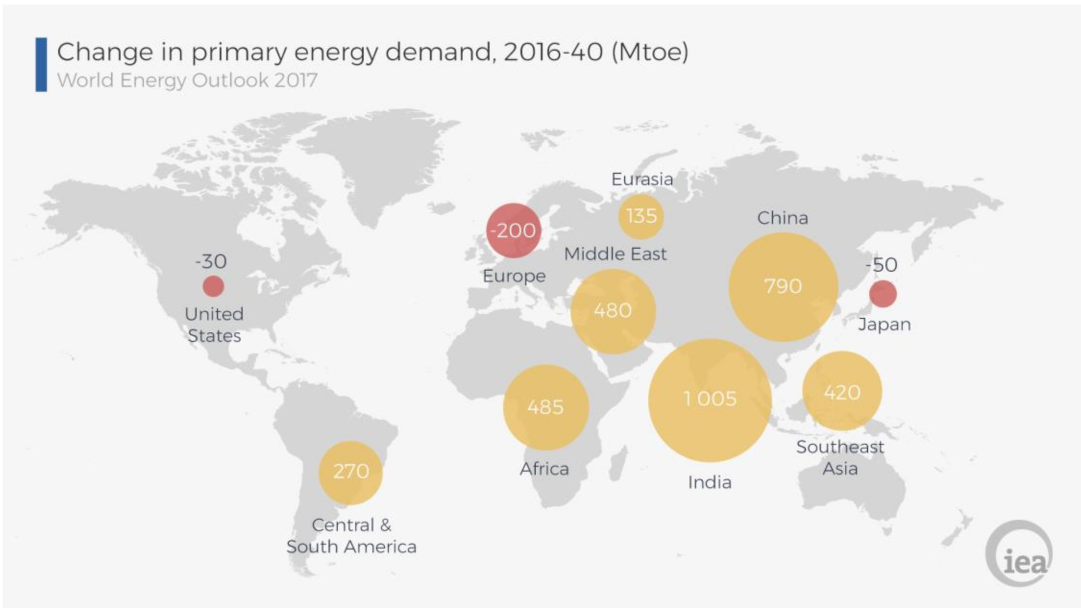


Fig. 1.2. Increase in world energy consumption by regions [1.1]

Non-OECD Asia (including China and India) accounts for more than 60% of the world's total increase in energy consumption from 2015 through 2040.

From energy consumption point of view mankind can be considered as one system the technical regularity of which has to be maintained. Within a system only processes take place by themselves, which increase the entropy of the system. For maintaining the regularity of the system energy has to be introduced from outside. However in this case regularity of the internal processes will be maintained or increased, but the entropy of the outer system, i.e. that of the environment increases. This natural, outer system radiates a great part of the increase of entropy into the outer space. However not all of it, e.g. a part of the excess is bound to the atmosphere by carbon-dioxide emission.

Preconditions of the sustainability of the system of society:
- Usage of renewable energies instead of exhausting energy reserves.
- Total re-usage of wastes arising during sub-processes by establishing closed material flow similar to the natural system.
- Increase of entropy leaves to the outer space.

1.1 Energy need by sectors of the economy

Energy need of a country builds up from the following components:

- Energy need of production:
  - Energy need of sectors:
    - industry,
    - agriculture,
    - traffic/transport,
    - construction industry,
    - services;
  - direct productive part:
    - proportional to the production,
    - other (e.g. idling, heat-up, etc.);
  - additional (e.g.: sanitary, kitchen, heating, lighting).

- Public (nonproductive):
  - Room heating,
  - room cooling,
  - hot water,
  - cooking,
  - cooling,
  - freezing,
  - lighting,
  - mechanical work (domestic appliances),
  - amusement electronics,
  - individual vehicle traffic.

1.2 Electric energy

Uniquely among energy arts electric energy has numerous advantages like:
- It can be simply and economically produced from nearly all other energy arts;
- it can be easily transported to great distances with low losses;

- it can be simply and economically transformed to nearly all other energy arts;
- it is continuously available at the location of its consumption;
- its consumption is clean and comfortable.

The most problematic disadvantage of electric energy is the fact that it can not be stored in high amounts and as a consequence of this always the required amount has to be produced. Nowadays electric utility companies make great efforts to develop new storage technologies and to install local storage capacities because of the continuously increasing number of decentralized power plants supplying electric energy to the public network.

In general electric energy is produced from the following energy arts:
- Chemical energy of fuels like coal, oil and gas;
- thermal energy of sunlight and thermal springs;
- mechanical energy of water and wind;
- nuclear energy of uranium, thorium and plutonium;
- light of the Sun.

The transformation of energy takes place in general in several parts, e.g. in thermal power plants
- chemical energy of the fuel is converted first to thermal energy in the boiler;
- then the thermal energy transforms to mechanical energy in the turbine;
- finally the mechanical energy is converted to electric energy in the generator.

Flow chart of electric energy production in traditional thermal power plants is shown in *Fig. 1.3*.

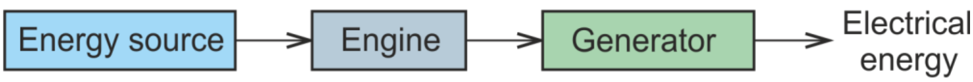


Fig. 1.3. Electric energy production in traditional thermal power plants

1.3 Energy sources

Energy is the ability to do work. Energy in its desired art is produced by converting energy stored in energy sources. Definition of energy source is as follows:

Energy source is a source from which useful energy can be extracted or recovered either directly or by means of a conversion or transformation process.

Energy sources can be split to primary and secondary energy sources. The definition of the primary energy sources is:

Primary energy sources can be used directly, as they appear in the natural environment.

Primary energy sources are:

- Coal
  - lignite (*Fig. 1.4.a*),
  - brown coal with 10-12 MJ/kg,
  - black coal,
  - anthracite (*Fig. 1.4.b*),
- mineral oil, 40 MJ/kg;
- natural gas, 35 MJ/kg;
- wood (biomass);
- nuclear fuels;
- sun;
- wind;
- rivers;
- tides;
- mountain lakes;
- Earth supplying geothermal energy.

Fig. 1.4.a. Lignite with 60-70% C, calorific value 6-6.5 MJ/kg (source: Encyclopedia Britannica)

Fig. 1.4.b. Anthracite with a calorific value of 29 MJ/kg (source: Wikipedia)

Secondary sources derive from the transformation of primary energy sources.

Secondary energy sources are for example:

- Briquette;
- coke;
- petrol, that derives from the treatment of crude oil and electric energy;
- diesel oil;
- fuel oil;
- mazout, heavy oil product;
- chamber gas;
- town gas;
- propane-butane gas;
- steam;
- hot water;
- electrical energy.

Coke is a fuel with high carbon content and few impurities, made by heating coal in the absence of air. It is the solid carbonaceous material derived from destructive distillation of low-ash, low-sulfur bituminous coal. Energy sources can be distinguished to non-renewable and renewable energy sources.

A non-renewable energy source is a resource that is not replaced in a continuous basis or is replaced very slowly, but dependent completely on natural processes. [1.2]

Renewable energy is considered as any energy resource that is available naturally on a continuous basis or can be continually generated over short period of time. [1.2]

Non-renewable energy sources are e.g.:
- Coal;
- mineral oil;
- natural gas;
- Uranium and Thorium.

Renewable energy sources are e.g.:
- Hydro-energy;
- Solar-energy;
- wind-energy;
- soil heat;
- geothermic energy;
- biomass.

Energy sources can be classified by their state, to solid, liquid and gaseous materials. Solid sources need more preparatory work before their combustion. Coal requires to be sorted, broken and to be made powder before it will be blown into the boiler. Also solid renewables need more preparation, e.g. wood has to be chopped into small pieces before firing.

Most of the energy need of the World is covered now with energy from fossil sources, like coal, oil and natural gas, having been fossilizing for millions or hundreds of millions of years in the Earth's crust. Thus their exploitation takes place more rapid than their formation by many orders of magnitude. Taking into account the trend of excavation the supposed reserves can run out within the following periods:
- Coal 200 years;
- natural gas 65 years;
- mineral oil 45 years.

Gas and oil from shale can elongate the period at the second and third material, i.e. gas and oil. A remarkable ability to unlock new resources cost-effectively pushes combined United States oil and gas output to a level 50% higher than any other country has ever managed; already a net exporter of gas, the US becomes a net exporter of oil in the late 2020s.

Some countries have already made changes mainly in the field of electricity generation. Norway produces all and e.g. Sweden nearly all electric energy from water energy. This could be economically achieved because of the natural potentialities of these countries. Denmark covers nearly the half of its electricity need from wind energy.

On the world 440 reactors are running covering 14% of the total electricity demand. In France 74% of the total electricity is generated in nuclear power plants, thus decreasing the dependability on fossil resources but increasing the problem of deposing radiating wastes. In Hungary 46% of the total electricity is generated in the nuclear power plant near Paks.

1.3.1 Disadvantages of fossil energy sources

Apart from their limited stocks combustion of fossil energy sources cause other serious problems namely the environment pollution and climatic changes (*Fig. 1.5*).

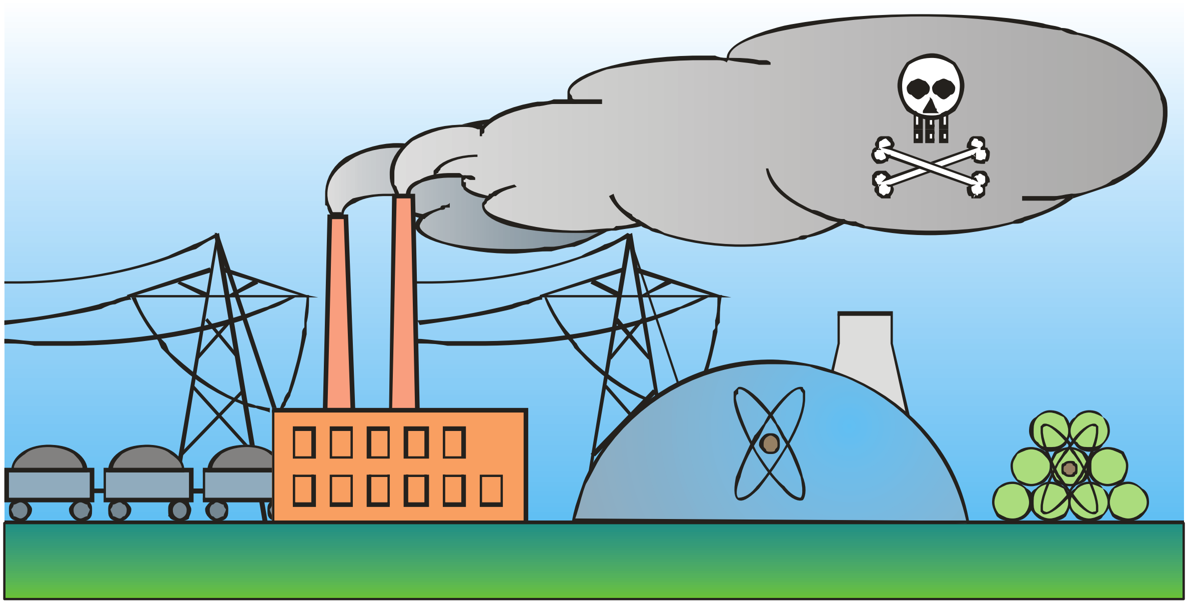


Fig. 1.5. Mineral energy sources are environment polluting

Energy transformation concludes always in impacts on the environment. As energy consumption increases and as information about harmful impacts accompanying it is becoming well-known the social opposition against traditional, nuclear but also against water and even wind power plants strengthens as well. Environment destructive impacts of electric power plants can be summarized as follows:

Decrease of fossil energy resources of the Earth

Fossil energy resources of the Earth are not renewable ones, since they do not reproduce themselves with the same velocity as their consumption takes place, i.e. their stocks are limited. Consumption of these resources can take place up to million times faster than the period required for the accumulation of the stocks. When evaluating this viewpoint it has to be considered as well which other application arts do a certain energy source have beyond its combustion for electric energy production. Coal, mineral oil and natural gas can be used for many other important objectives, while in case of uranium no such possibilities are known.

Oxygen usage

During the combustion i.e. oxidation of fuels the power plant consumes oxygen from the air. As a consequence of the termination of forests and of the changes in the flora of the oceans taking place now or in the future because of environment pollution the composition of the air will change in turn. Because of the high velocity of the changes in the composition of the atmosphere only primitive arts of life can probably follow it, but humans surely not. If oxygen content of the air drops under 15%, then advanced animals and humans would stink, however above 25% fire hazard would increase to a high extent, a lightning bolt would cause a fire on a large surface.

Carbon dioxide emission

Main cause of greenhouse effect is the carbon dioxide content of the atmosphere, however other gases like methane contribute to it as well. The higher the proportion of carbon dioxide, the stronger is the greenhouse effect causing global warming. This phenomenon takes already place that is supported by many observations. Number of icebergs floating from the Arctic to the South have been recorded since a long time. Until 1970 the average number of such icebergs were about 400, while at the end of the last millennium this number has been growing above 1000.

As a result of global warming a part of the ice stock on the poles melted, level of the seas increased, while a significant part of mankind lives at seashores the most of which will be covered by water according to calculations. However melting ice in the Arctic reduces the salt content of the seas influencing global sea streams. It is supposed that the Golf Stream will not reach Europe with a consequence of an ice age like weather.

Power plants operating in Hungary alone produce about 20 million tons of carbon dioxide per annum. However China emits 6877 and the United States of America 5195 million tons in a year (*Fig. 1.6*).

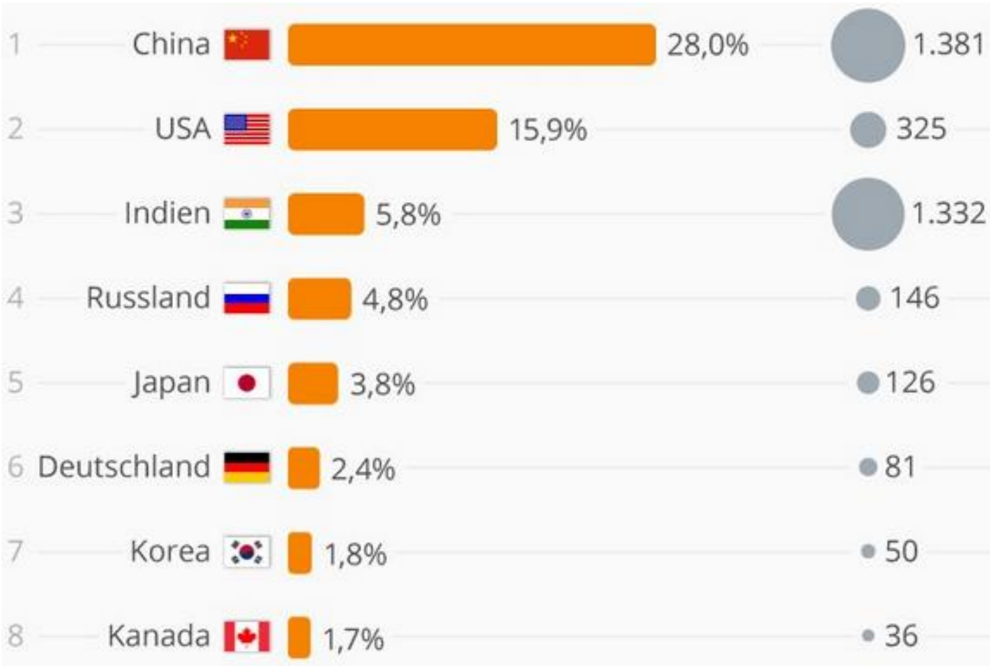


Fig. 1.6. Carbon-dioxide emission of several countries (source: STAISTA, 2015)

Air pollution

Most of the fossil energy sources contain contaminants emitted as poisoning materials into the atmosphere when combusted. Coal contains much sulfur composing sulfuric acid or when combusted as such emitted into the ambient air. Acidic rain with other pollutants have already caused damages in the fauna and agriculture of the Earth. Power plants of Hungary emit about 4 million tons of sulfur dioxide per annum;

Radioactive pollution

Thank to the high number and rather long term operation of nuclear power plants their environment polluting impacts can already be statistically evaluated. A nuclear power plant operated with perfect safety would emit theoretically no radioactive pollution. Coal based power plants at Ajka and Tatabánya emit radioactive pollution to a much greater extent than the nuclear plant at Paks the cause of which is the high Uranium content of coal stocks in Transdanubia.

However according to experiences a perfect safety can not be ensured and malfunctions and accidents happen periodically. Accidents do not seem to be bound to country groups, to political directions or to industrial development level. Serious accidents have happened in the US, Ukraine, Japan and India as well.

Apart from radioactive pollution emitted because of accidents this problem is engraved by the deposition of radiating wastes as well. During the ’50-eth it happened in socialist as well as in developed capitalist countries that, nuclear waste was simply poured into the sea and not proper disposal can happen today as well because of the difficulty of control. Consequences of this can have impacts during several thousands of years because of the long halving period of these materials and the results caused in life is not yet known.

Modification of the environment

In case of fossil fuelled power plants the mines delivering the fuel move a huge amount of rocks leaving empty hollows in the Earth’s crust and deposit hills on it. A waste amount of water is extracted from rivers for cooling down the steam and this water returns the river with a higher temperature. However in case of renewable ones there are changes in the environment as well. As a best example hydro power plants can be mentioned resulting a new lake upstream a decrease in deposit flow downstream, the dam hinders he animals in their movement, new ecosystem will develop, etc.

Phenomena listed above will gradually be known by the public showing a growing antipathy to power plants also to renewable propelled ones. Electricity generating end selling companies are under a growing pressure to solve the problem of increasing demand for electric energy with alternative solutions instead of building new fossil fuelled power plants.

1.3.2 Renewable energy sources

To cover increasing demands with the same installed power a more even, i.e. most possible constant consumption has to be achieved with support or force. Another possibility is when the consumer generates electric energy itself with alternative sources. As an ideal solution electric energy should be generated at the location of its consumption. In this case no high cost transmission and distribution systems are necessary. The objective can be formulated as:

Let the electric energy be produced at the location of its consumption with environment friendly technology.

Environment friendly technologies can be alternative or with other words non-conventional technologies being methods different from those widely used for electric energy production. These alternative/non-conventional methods include e.g.

- cogeneration, tri-generation:
    - diesel or gas engine driven generators,

- gas turbine (e.g. micro gas turbine) driven generators,
- fuel cells.

A higher importance is however owed to renewable sources because of their beneficial characteristics. Most kinds of renewable energy sources available now on the Earth are maintained by solar energy (*Fig. 1.7*). Solar energy can be transformed to electric energy directly by solar cells, however it can be utilized indirectly in the form of e.g. wind, waves or bio-mass. The *Table 1.2* shows the renewable energy potential of Hungary.

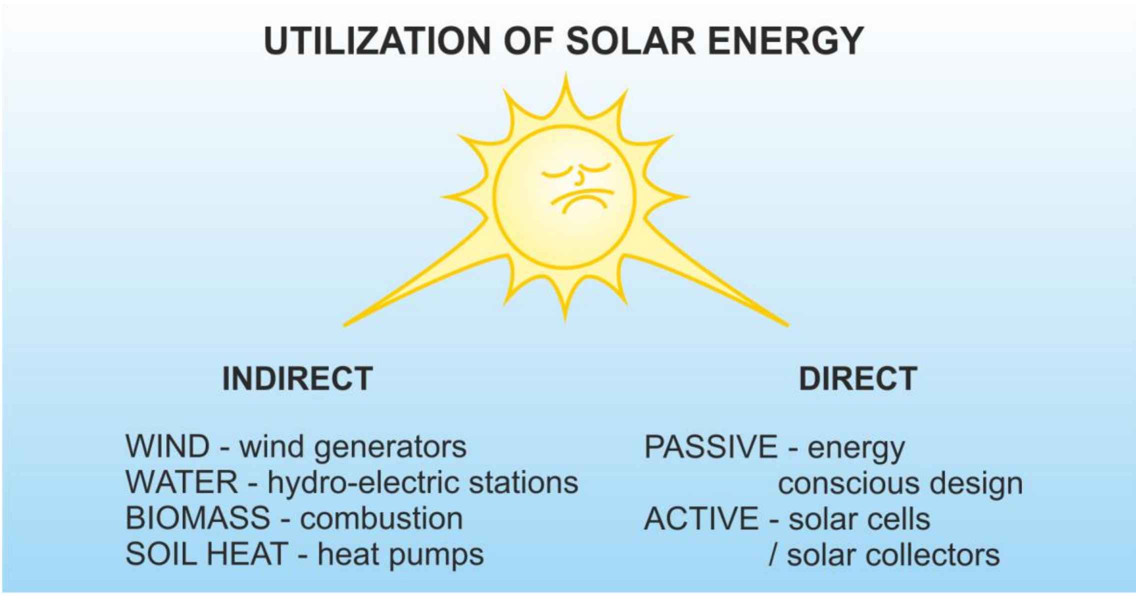


Fig. 1.7. Opportunities for utilizing solar energy

Table 1.2. Renewable energy potential of Hungary

Energy art	**Potential (PJ)**	**Exploited (PJ)**
Solar energy	1838.0	0.1
Water energy	14.4	0.7
Geothermic energy	63.5	3.6
Biomass	average 265.0	49.2
Wind energy	532.8	0.16
Total	2650.0	53.8

Renewable energy sources can be utilized for electricity generation with the following technologies:
- Hydro energy:
  - Flush type stations,
  - barrage power stations,
  - pump-storage stations,
  - wave power stations,
  - tidal power stations,
  - oceanic heat conversion stations.

- Solar energy:
  - Tower method,
  - traditional solar power plant (solar-therm),
  - solar cells.

- Wind energy:
  - Continental wind farms,
  - wind farms on seas.

- Geothermal energy:
  - Traditional geothermal power plants,
  - binary Rankine cycle geothermal power plants,
  - Hot Dry Rock plants.

- Bio-mass energy:
  - Bio-gas energy,
  - energy plantations.

There are renewable sources having some disadvantages, e.g. if wood produced in energy forests or bio-diesel is combusted then oxygen consumption and CO_2 emission takes place as well. However in these cases neutral sources are mentioned because plants bound CO_2 and produce oxygen during their growth, i.e. the equilibrium will not be disturbed. When combusting fossil energy sources then the coal bound during millions of years is emitted into the atmosphere within a very short time, destroying the equilibrium of component gases.

References - 1

[1.1] EIA - U.S. Energy Information Administration, September 14, 2017.
[1.2] T. Ghosh, M. Prelas, Energy Resources and Systems, ISBN 978-90-481-2383-4, Springer, 2009.

2 Electric energy generation

The process of conversion of energy resources embodied in the nature, i.e. of primary energy sources into electric energy and its transport and consumption is shown in *Fig. 2.1*.

NATURAL ENERGY SOURCE	→	CONVERSION (POWER PLANT)	→	NETWORK	→	CONSUMER
Coal, oil, gas, U, water, wind, etc.		Production of electric energy		Transport of electric energy		Utilization of electric energy

Fig. 2.1. Way of the energy from energy source to energy consumer

Facilities, machines and other equipment realizing the above process – excluded the consumption – are called electricity works composing parts of the electric energy system of a country.

Appliances, machines performing the generation, transmission, conversion and distribution of electric energy are electricity works.

Electricity works, their control and cooperation compose the electric energy system.

Main part of the electric energy is still now produced by traditional power plants including synchronous generators as the machines actually transforming the mechanical energy to electric energy.

Working principle of the synchronous generator is based on Faraday's law of induction. According to this law the magnitude of the voltage V_i induced along a closed path within or around a magnetic field is proportional to the intensity of the variation of the magnetic flux Φ in time t as

$$V_i = -\frac{d\Phi}{dt}. \tag{2.1}$$

The negative sign is prescribed by Lentz's law stating that the phenomenon causing voltage induction is hindered by the magnetic field of the current flowing as a consequence of the induced voltage in a closed circuit.

Like other rotating electric machines a synchronous generator builds up of a stator and a rotor as well. In *Fig. 2.2* a winding with a single turn is placed on the stator of the synchronous machine inside of which a permanent magnet composing the rotor rotates.

In *Fig. 2.2* "N" stands for the Northern pole and "S" for the Southern pole of the magnet and Φ for the complete magnetic flux of the magnet, while ω marks the angular frequency of the rotation.

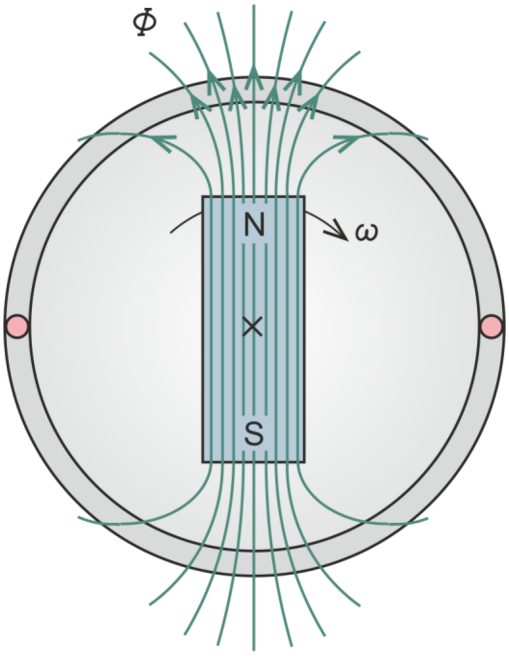


Fig. 2.2. Magnet rotating inside a conductive frame

At the moment shown in *Fig. 2.2* the rotating frame (the single turn winding) surrounds the total magnetic flux of the magnet. If the magnet rotates by 90 grades then it surrounds no magnetic flux as shown in *Fig. 2.3*. Between these two extreme positions the flux with a maximum value of Φ_m surrounded by the frame varies with the sine of time t. Thus the absolute value of the voltage V_i induced in the conducting frame is

$$|V_i| = \frac{d\Phi(t)}{dt} = \frac{d\Phi_m \sin \omega t}{dt} = \Phi_m \omega \cos \omega t \,. \qquad (2.2)$$

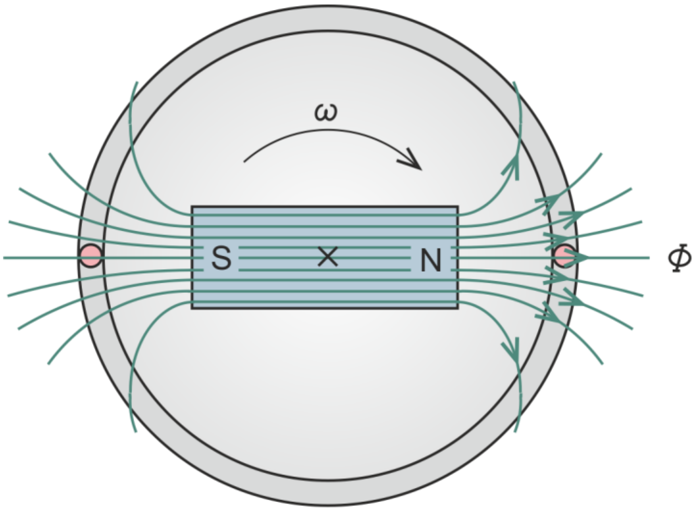


Fig. 2.3. Now the rotating magnet lies in the plane of the conducting frame

Most of the synchronous generators produce three-phase voltages in three windings placed around the stator of the machine as shown in *Fig. 2.4*. In large scale generators electromagnets supplied with direct current rotate instead of permanent magnets. Then the time function of the voltages induced in the three windings are

$$V_1(t) = V_m \sin \omega t \,; \quad V_2(t) = V_m \sin\left(\omega t - \frac{2\pi}{3}\right); \quad V_3(t) = V_m \sin\left(\omega t - \frac{4\pi}{3}\right). \qquad (2.3\text{-}5)$$

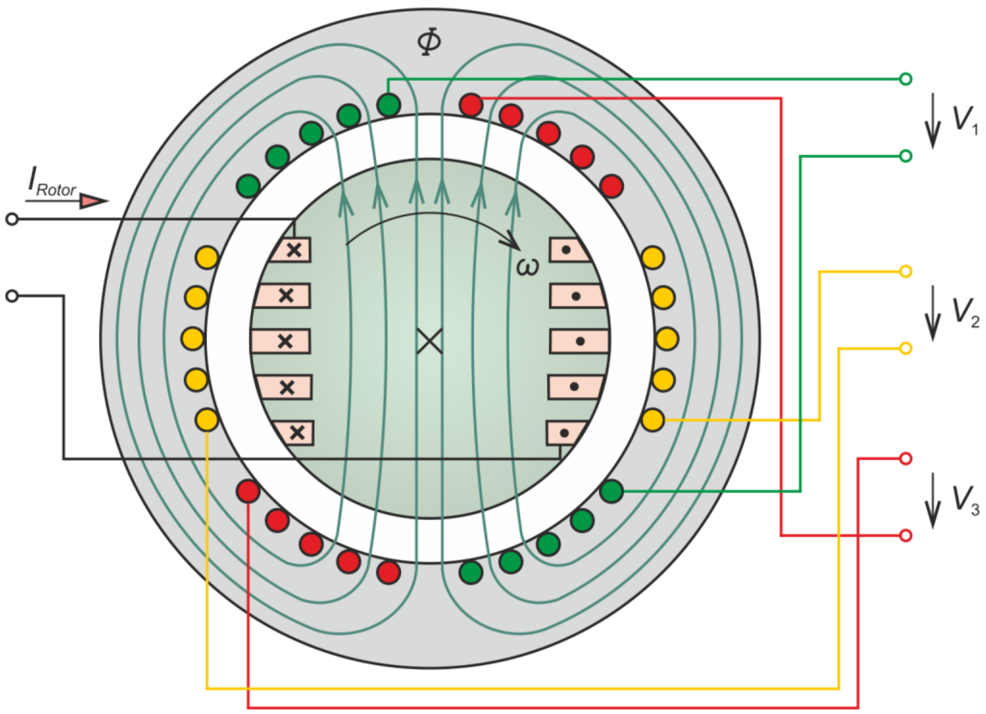


Fig. 2.4. Draft of a three-phase synchronous generator

Time functions of the induced voltages are shown in *Fig. 2.5*. Advantages of this three-phase system are:

- Synchronous generators, asynchronous motors and three-phase transformers can have optimum place utilization.
- On three wires three times as high power can be transported than on a single-phase line with two wires.
- It enables the operation of simple and cheap asynchronous motors.

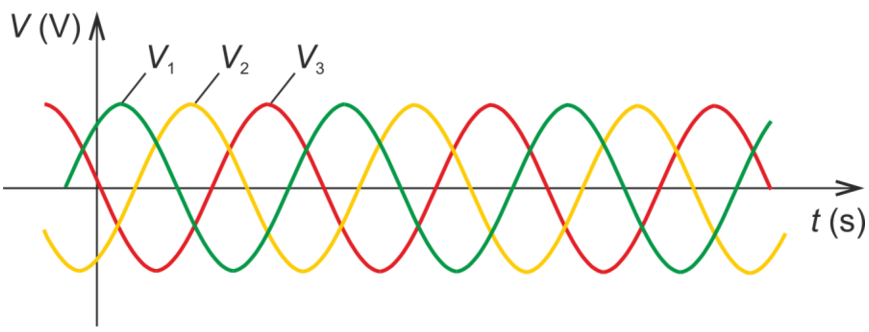


Fig. 2.5. Time functions of the three-phase voltage system

2.1 Arts of power plants

Electric power plants can be classified by several aspects. Classification of power plants by the energy source used is:

- Fuel - thermal power plants;
- water - hydro power plants;
- nuclear energy - nuclear power plants;
- Sun - solar power plants;
- wind - wind power plants.

Arts of power plants by their function:

- Electric energy production;
- production of heat (e.g. for district heating);
- combined heat and power generation.

Classification of power plants by the built in power:

- $P < 50$ MVA - small power plants;
- 50 MVA $< P <$ 500 MVA - medium power plants;
- $P > 500$ MVA - large power plants.

Apart from the above there are the so-called house-hold sized power plants with powers of maximum 50 kVA.

Arts of power plants by their connection to the consumers are:

- Cooperating power plants;
- islanding power plants.

Arts of power plants by their main task:

- Base-load power plants (in general coal, nuclear fuelled plants);
- intermediate peaking power plants (natural gas, combined cycle);
- fast peaking power plants (gas, hydro, combustion turbine).

Classification of power plants by the area supplied:

- Country-wide power plants;
- industrial power plants.

Power plants serving for heat generation are **heating plants** mainly supporting district heating and producing electric energy at the same time to a less extent.

Combined heat and power means the generation of thermal and electric energy to nearly the same extent.

Base-load power plants operate with a most possible constant power. In Hungary the only nuclear power plant belongs to this group operating with the lowest cost. In some countries hydro power plants with high installed power compose this group.

Task of **intermediate peaking power plants** is to fit the power of production to the power required by the consumers in the system. More flexible power plants, e.g. thermal power plants belong to this group.

Fast peak power plants cover the power excess required in peak hours. In general these plants work periodically and can be started and stopped easily, like gas turbine and pumping plants with reservoir.

Cooperating power plants supply the electric energy into the electric energy system, thus these are public plants.

Islanding power plants are not connected to the country-wide electric energy system, they supply a given facility or facilities as an island system.

Country-wide power plants are cooperating power plants and have high installed power and high significance for the whole country or a region.

Industrial power plants are not public plants and supply a factory or another industrial facility with electric energy.

2.2 Thermal power plants

Basically thermal power plants convert thermal energy to electrical energy. The highest efficiency of fuel based power plants is 45%, i.e. maximum 45% of the calorific value of the fuel is converted into electric energy. Actually the chain of energy conversion consists of the following steps:

- At first the chemical energy of the fuel is converted to thermal energy through combustion/firing of the fuel in the boiler.
- Thermal energy is converted to mechanical energy through an intermediate medium (steam) in a turbine.
- Mechanical energy is converted to electrical energy through a generator.

Main auxiliary procedures in thermal power plants:

- Preparation of the fuel;
    - receiving, storage and internal transport of the fuel,
    - collection and removal of the combustion products;
- management of the cooling water
    - obtaining, cooling and internal transport of the coolant.

Arts of thermal power plants:

- Steam turbine power plants:
    - fuelled with coal,
    - fuelled with oil,
    - fuelled with gas,
    - nuclear power plants,
    - biomass fuelled plants,
    - plants fuelled with waste,
    - some kinds of solar power plants;
    - some kinds of geothermal power plants;
- gas turbine power plants;
- combined gas/steam turbine power plants;
- soil heat plants.

Grouping of power plants by the art of the heat engine:
- Steam turbine power plants (*Fig. 2.6*);
- gas turbine power plants (*Fig. 2.7*);
- combined cycle gas turbine power plants (*Fig. 2.8*);
- power plants propelled by internal combustion engines (*Fig. 2.9*).

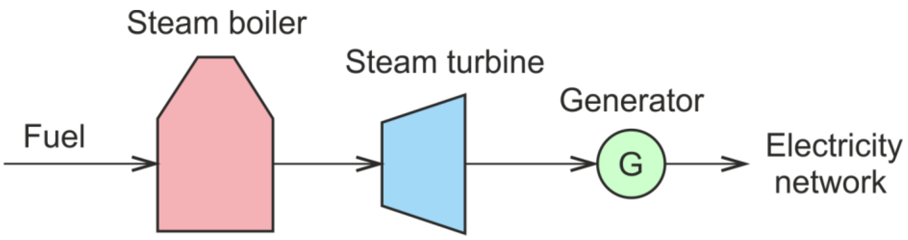


Fig. 2.6. Block diagram of a steam turbine power plant

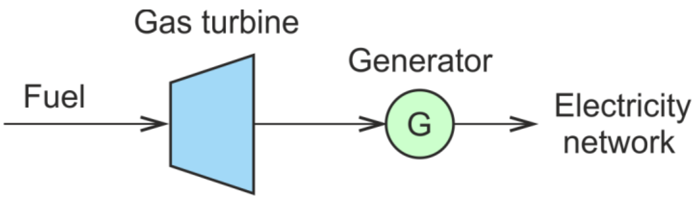


Fig. 2.7. Block diagram of a gas turbine power plant

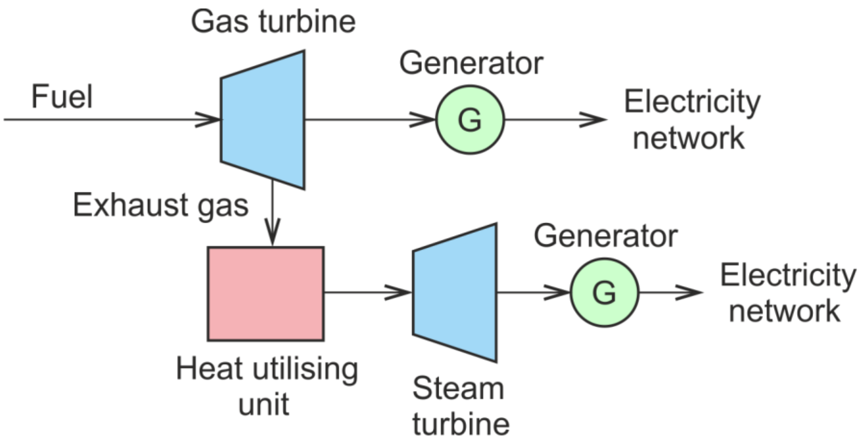


Fig. 2.8. Block diagram of a combined cycle gas turbine power plant

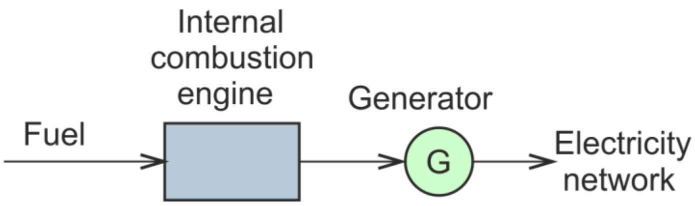


Fig. 2.9. Block diagram of a power plant propelled by an internal combustion engine

Grouping of steam turbine power plants by their energetic system:
- Condensing power plants;
- power plants with back-pressure turbines;
- power plants with steam extraction turbines.

In case of **condensing power plants** steam leaving the turbine travels to the condenser. This kind of power plants produces only electrical energy.

Main task of **power plants with back-pressure turbines** is the production of thermal energy, steam leaving the turbine travels to thermal energy consumers and steam consumers.

In **power plants with steam extraction turbines** a part of the steam travels to the thermal energy consumers and the other part to the steam turbine then to the condenser.

Block diagram of a condensing power plant is shown in *Fig. 2.10*. In the example of this figure the station is fuelled with coal. This kind of fossil fuel requires the most preparatory work. In the figure the coal bunker, mill and drier are drawn. Coal powder is blown into the boiler where it is fired and the high temperature converts the feed water to high pressure and high temperature steam. Before the flue gas reaches the chimney powder, Nitrogen oxides and Sulfur (S) are separated from it.

The high pressure and high temperature steam enters first the high pressure turbine then the medium pressure one, finally the low pressure turbine. Steam leaving the turbines enters the condenser where it is cooled down by the cooling water coming from the cooling tower where it has been cooled down by air. If the thermal power plant is installed near to a river then the river can take over the cooling task and no cooling tower is necessary, like in case of Paks.

Turbines rotate the generator generating the electric energy. En exciter is necessary for producing direct current for the rotor of the generator creating the rotating magnetic field. In case of large-scale generators the optimum stator voltage is calculated individually for the given generator thus this voltage is often a non-standard voltage (15.75 kV in case of Paks). This special voltage is then converted to a standard one (400 kV in case of Paks) by the unit transformer.

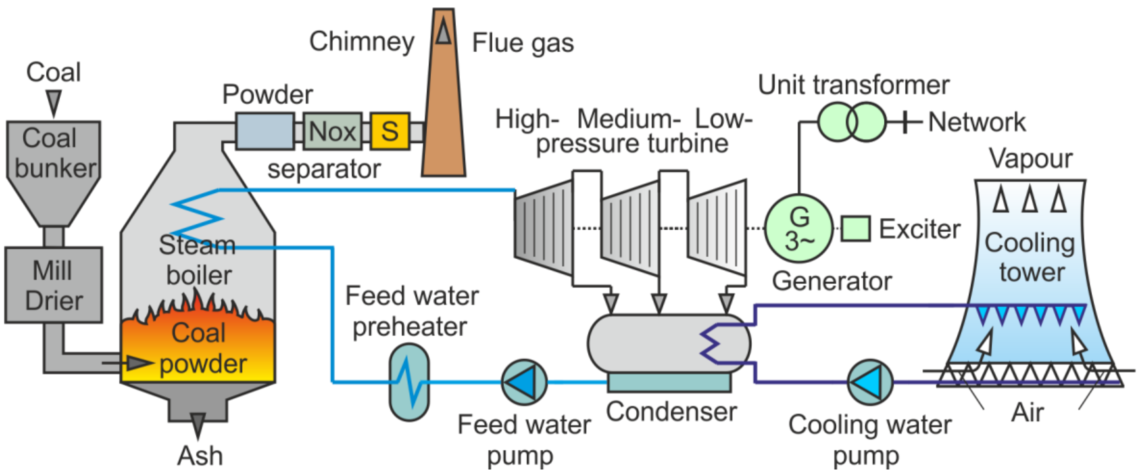


Fig. 2.10. Block diagram of a condensing power plant

2.3 Hydro-electric power plants

Hydro-electric power plants utilize the potential and kinetic energy of water for electric energy generation (*Fig. 2.11*). Arts of hydro-electric power plants:

- River plants:
    - By-pass canal type power plants,
    - power plants built into river-bed;
- Hydro-accumulation plants:
    - Natural hydro-accumulation plants;
    - pumping plants with reservoir;
- Tide power plants.

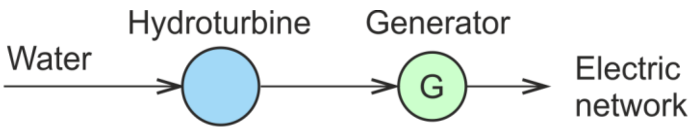


Fig. 2.11. Block diagram of a hydro-electric power plant

Apart from electric energy generation hydro-electric power plants can have other purposes as well, like irrigation, navigation or water supply.

The layout of a **hydro-electric power plant with by-pass canal** is shown in *Fig. 2.12*. The by-pass canal is an artificial canal ensuring a more optimum fall of the water than that in the river-bed. In general a barrage is built at the intake works for ensuring the advantageous water fall at the power plant. Apart from this other characteristics of the canal can be ensured as well like its optimum cross section.

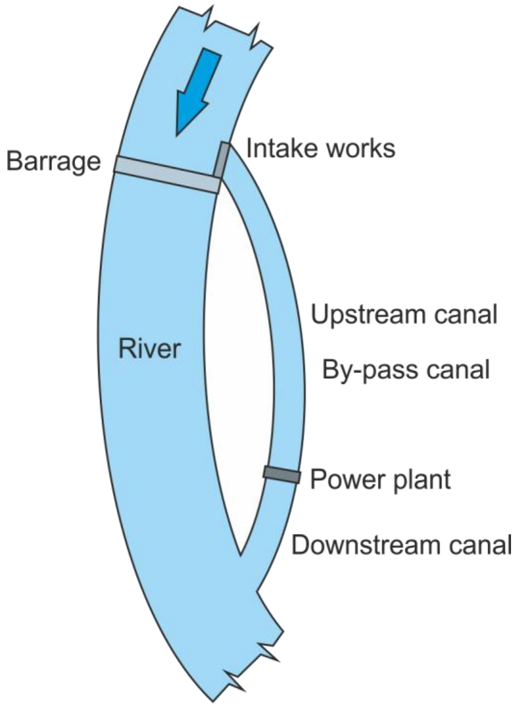


Fig. 2.12. Layout of a hydro-electric power plant with by-pass canal

The oldest Hungarian hydro-electric power plant has been installed in Gibárt on the river Hernád (*Fig. 2.13*) in 1903 and works till now. The by-pass canal was already present because of the mill operated there before the construction of the power plant. The total built in power of the two generators is 0.5 MW shown in *Fig. 2.14*.

Fig. 2.13. The oldest hydro-electric power plant in Hungary with by-pass canal

Fig. 2.14. The two hydro-generators in Gibárt having been operating since 1903

The upper view of a **hydroelectric power plant built into river-bed** is shown in *Fig. 2.15*. In general a barrage is built in this case as well for a higher flow of the water. Navigability of the river is ensured by the lock.

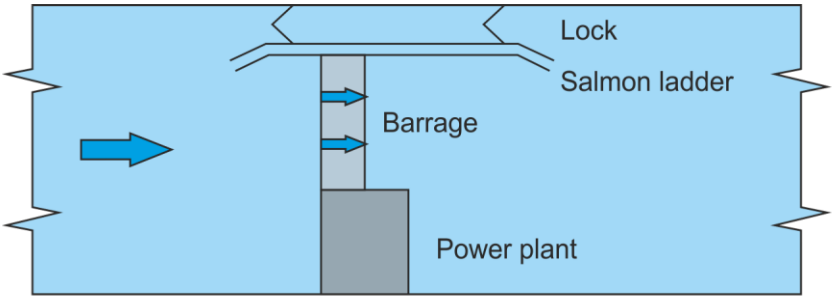


Fig. 2.15. Upper view of a hydro-electric power plant built into river-bed

In *Fig. 2.16* the cross section of the power plant of a hydro-electric power plant built into river-bed is shown. Turbine and generator rotate on a vertical axis in this case. Because of the rather low speed of such turbines the generator has higher diameter related to its length (in vertical direction) in contrast to turbo-generators rotating with a much higher speed.

The synchronous speed of a two-pole generator is 3000 rpm in case of a frequency of 50 Hz and 3600 rpm in case of a frequency of 60 Hz.

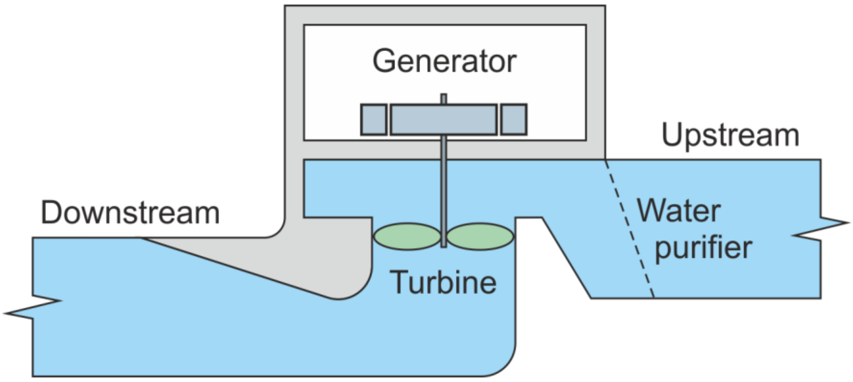


Fig. 2.16. Cross section of a hydro-electric power plant built into river-bed

The World's largest hydro-electric power plant built into river-bed and as a same time the World's largest power plant at all is the Three Gorges power plant operating in China on the river Jangce (*Fig. 2.17*). Its total built-in power is 21,000 MW.

Fig. 2.17. The World's largest hydro-electric power plant built into river-bed

Cross section of a **natural hydro-accumulation plant** is shown in *Fig. 2.18*. Hydro-accumulation plants can be installed mainly in mountains by utilizing natural lakes or by barrages. Water is led to the equalizing work through a pressure water canal.

The equalizing work can store the water if e.g. the power plant is out of operation. The equalizing work prevents the eventual arising of an overpressure in the delivery tube.

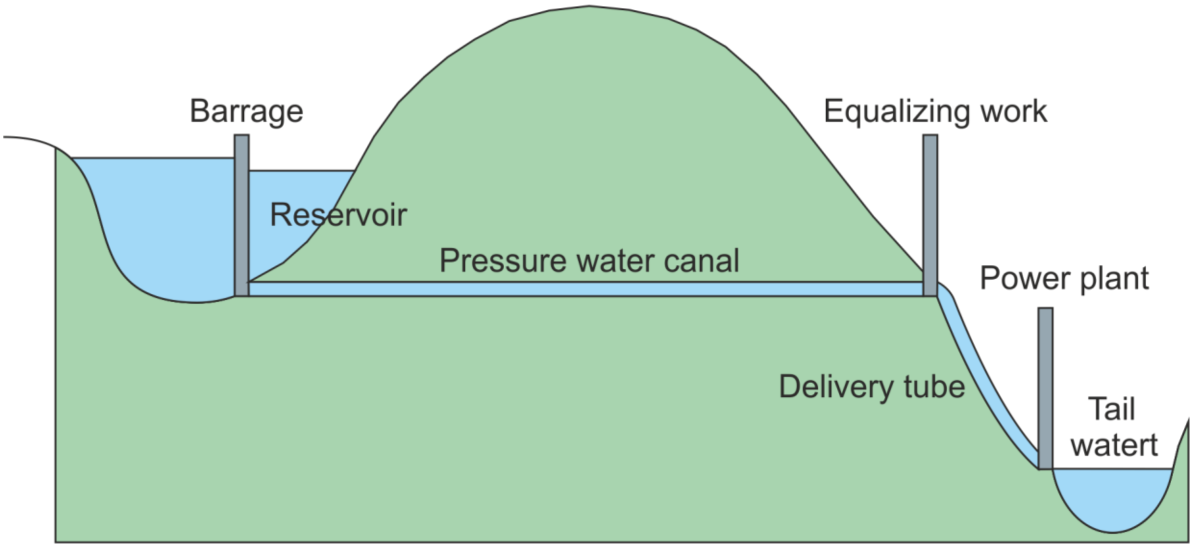


Fig. 2.18. Cross section of a natural hydro-accumulation power plant

In a **pumping hydro-electro power plant with reservoirs** an upper basin (reservoir) is installed in most cases with no natural water intake (*Fig. 2.19*). Water is pumped up into this basin with the help of a high power pump from a lower basin or a natural surface water e.g. a river during hours with low need for electricity e.g. at nights.

This procedure is the charging procedure which consumes electric energy converted into potential energy of the water. In this case the synchronous generator works as a motor. During hours with high need for electricity e.g. at late afternoons the flow of water changes direction and the water flowing down propels the turbine driving the generator in turn which generates electric energy during this discharging procedure.

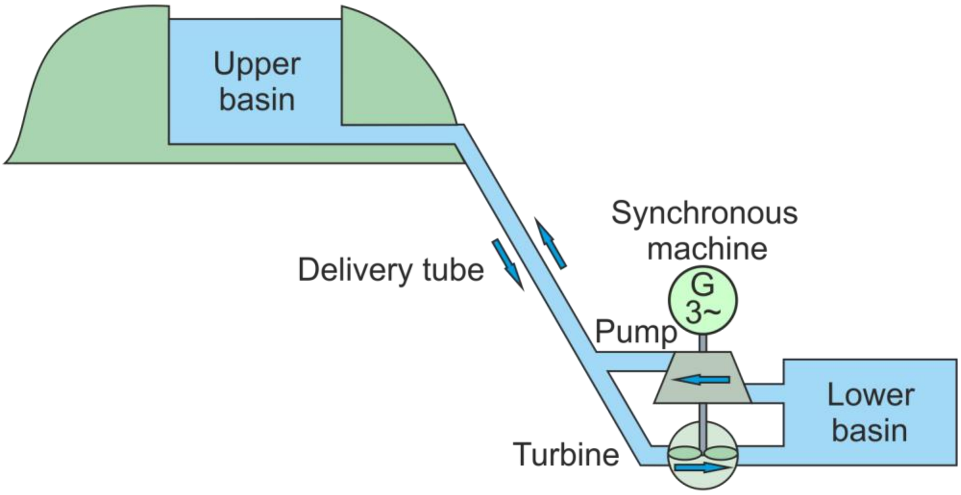


Fig. 2.19. Cross section of a pumping plant with reservoirs

2.4 Nuclear power plants

Nuclear power plants use the atomic energy for electricity generation. When elements with large atoms split into two other atoms with smaller size, a part of the energy of the core converts into heat energy. Thus nuclear power plants differ from other thermal power plants only in the unit producing heat. Conversion of heavy elements to medium elements can be accelerated by colliding neutrons to the heavy cores. During this conversion fast neutrons get free as well contributing to the splitting further heavy elements. This phenomenon is known as chain reaction. This chain reaction is controlled in reactors of nuclear power plants. The block diagram of a nuclear power plant is shown in *Fig. 2.20*.

A **nuclear reactor** is a device used to initiate and control a self-sustained nuclear chain reaction. [2.1]

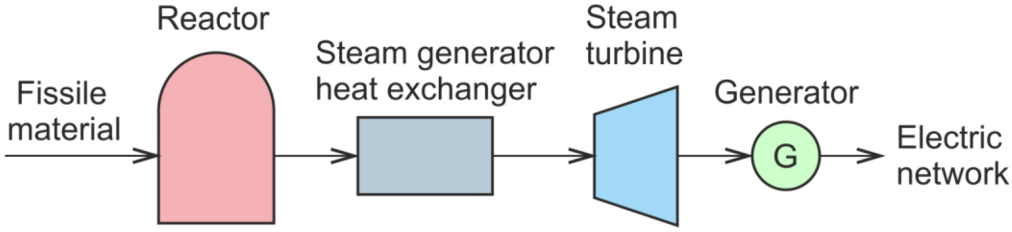


Fig. 2.20. Block diagram of a nuclear power plant

As of early 2019, the IAEA reports there are 454 nuclear power reactors and 226 nuclear research reactors in operation around the world. [2.1]

When a heavy nucleus splits into two or more lighter nuclei, the fission products are:
- Kinetic energy;
- gamma radiation;
- free neutrons.

The energy of gamma radiation is transformed into thermal energy as well. A part of the free neutrons triggers further fission events.

Fuel of nuclear reactor can be:
- Uranium-235 (U-235) releasing approximately three million times more energy than a kilogram of coal burned conventionally during its fission;
- Thorium (Th-232);
- Plutonium-239, Plutonium-241.

For the control of the nuclear chain reaction in most cases moderator is necessary. Moderator materials are:
- Graphite;
- heavy water;
- light water;
- light element such as Lithium or Beryllium.

Types of reactors are:
- Heterogeneous thermal reactor;
- heterogeneous breeding reactor;
- homogeneous reactor.

In case of heterogeneous reactors the fuel and the moderator are separate media. In case of homogeneous reactors the fuel and the moderator build a homogeneous mixture. In high power nuclear power plants mainly thermal reactors are used. Great advantage of fission with thermal neutrons is its easy controllability. In thermal reactors only the U235 isotope can be utilized.

Main parts of reactors are:
- Active zone for the fuel (reactor core);
- moderator zone for deccelerating the neutrons in thermal reactors (moderator);
- reflector reflecting the neutrons back into the reactor core;
- cooling medium transporting the generated heat to the steam collector.

Block diagram of the Hungarian nuclear power plant at Paks is shown in *Fig. 2.21*. The primary circuit is composed by the nuclear reactor containing the Uranium fuel and the graphite moderator, the circulating circuit with the pumps and the heat exchanging pipes of the steam generators where the medium – the feed water – of the secondary circuit is heated up by the primary medium.

The heated up steam enters then the steam collector from which it reaches the turbines. After leaving the high, medium and low pressure turbines the steam enters the turbine condenser where it is cooled down by the cooling water pumped out from the river Danube.

The two generators propelled by the turbines produces electric energy with a voltage of 15.75 kV which is then converted to standard 400 kV by the main transformers.

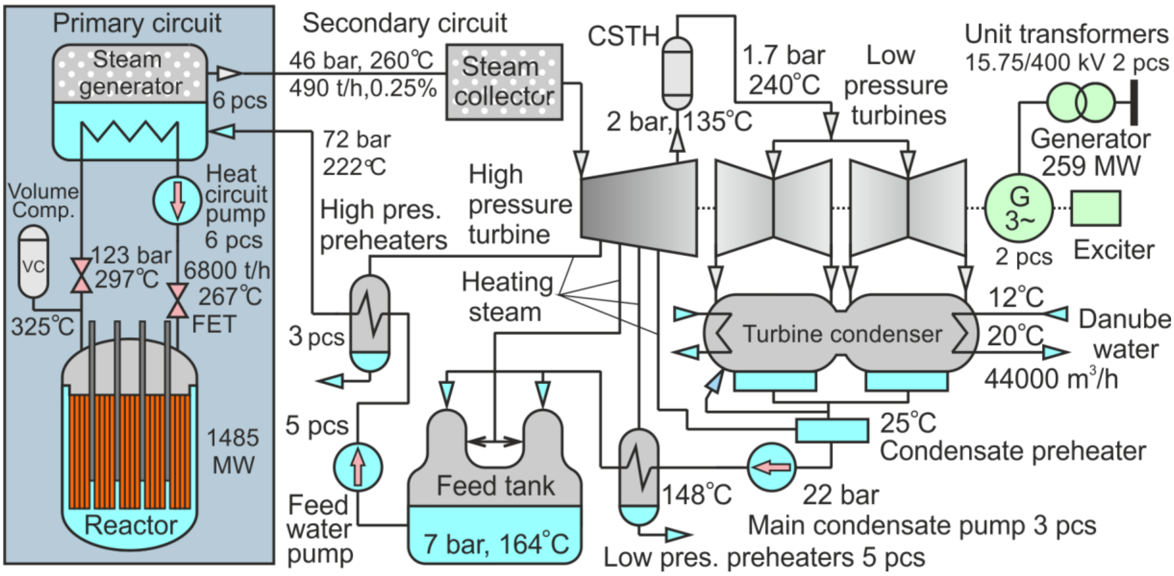


Fig. 2.21. Block diagram of the nuclear power plant at Paks

References – 2

[2.1] Nuclear reactors, *Wikipedia*.

3 Electrical networks

3.1 Components of the electrical system

This subchapter describes the functions and features of the elements composing the electrical system.

Elements with the highest value in the system are generators. Most of the electricity is produced by synchronous generators (*Fig. 3.1*).

Fig. 3.1. Turbo-generator (source: PANNONPOWER)

Transformers are electric machines converting the voltage to levels appropriate for transmission, distribution and consumption of electricity (*Fig. 3.2 - 3.5*).

Fig. 3.2. Transformer (400/132 kV, 250 MVA)

Fig. 3.3. Pole transformer, 22/0.4 kV, 250 kVA

Fig. 3.4. Medium/low voltage transformer - 1

Fig. 3.5. Medium/low voltage transformer - 2

Switches play an important role in networks, like isolators serving for determining and making dead current paths (*Fig. 3.6*). This kind of switches has to be interlocked with circuit breakers.

Fig. 3.6. 400 kV isolators

Circuit breakers serve for switching operational and short circuit currents. These are the most complex and valuable switches. *Fig. 3.7* shows 400 kV circuit breakers.

Fig. 3.7. 400 kV circuit breakers

Current transformers are measuring transformers designed for short circuit operation to convert high (or low) currents to low currents and voltage (*Fig. 3.8*). Secondary currents (5 A or 1 A) are used for measurement and protection purposes.

Fig. 3.8. 400 kV current transformers [4]

Fuses have the task to automatically cut over-currents, e.g. short circuit currents (*Fig. 3.9*). Apart from circuit breakers these are the only devices being able to cut short circuit currents.

Fig. 2.9. Medium voltage fuse

Busbars compose branch points in electric circuits (*Fig. 3.10*). Functional elements connected to busbars are branches. There are line branches and transformer branches, etc.

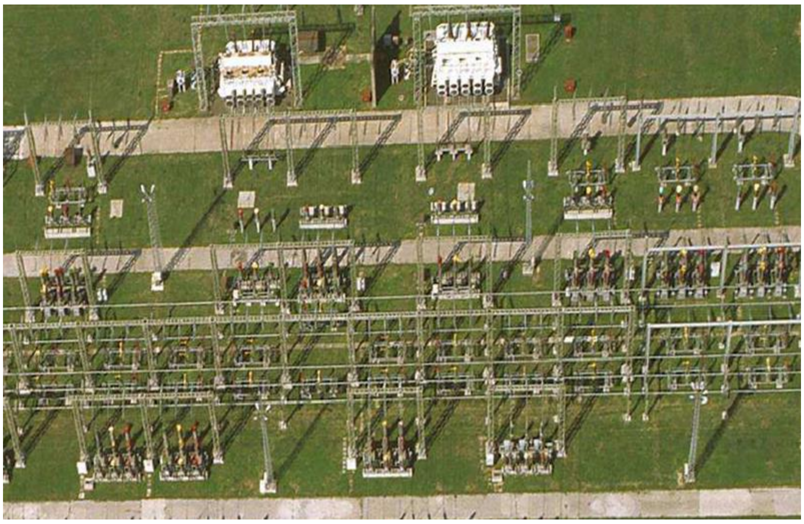


Fig. 3.10. Transformer station with two busbars [4]

Fig. 3.11. Medium voltage circuit breaker (left), current transformer (middle) and a voltage transformer (right)

3.2 Electrical power networks

3.2.1 Rated voltages

Rated electric voltages now valid in Hungary are listed by the standard **MSZ 1** (MSZ – Magyar Szabvány = Hungarian standard). Rated voltages in other countries can differ from these listed here. Public electrical power networks have rated voltages naming the network at the same time. Apart from networks, electric devices and equipment have rated voltages as well.

> Rated electric voltage of a network is the voltage by which the network is named and some operational characteristics relate to.

The different levels of the voltage ranges are as follows:

- Low voltage – with rated voltages up to maximum 1 kV AC or 1.2 kV DC;
- high voltage – with rated voltages above 1 kVAC/1.2 kVDC;
  - medium voltage – with rated voltages above 1 kVAC/1.2 kVDC up to 35 kV;
  - high voltage – with rated voltages above 35 kV.

Rated low voltage values are listed in *Table 1.1* and *1.2*, medium voltage levels are listed in *Table 1.3* and those of high voltage in *Table 1.4*.

Table 1.1. Rated voltage values lower than 120 VAC and 750 VDC

DC (V)	6	12	24	36	-	48	60	72	96	110	220	440
AC (V)	6	12	24	-	42	48	-	-	-	110	-	-

Table 1.2. Other rated low voltage values

- 120 VAC - non-public standard voltage;
- 230 VAC - public standard voltage;
- 400 / 230 VAC - public standard voltage;
- 690 / 400 VAC - non-public standard voltage;
- 1000 VAC - non-public standard voltage.

The later voltage may temporarily exceed the rated value by 15%.

Table 1.3. Rated voltage values of medium voltage networks are:

Rated value (kV)	Highest voltage of the equipment (kV)	Note
3	3.6	for industrial use
6	7.2	for industrial use
11	12.0	
22	24.0	
30	36.0	
35	40.5.	

Table 1.4. Rated voltage values of medium voltage networks are:

Rated value (kV)	Highest voltage of the equipment (kV)
132	145
220	245
400	420
750	800.

3.2.2 Arts of electrical power networks

Electric power is transferred to the consumers by electric networks. Electric power networks of Hungary are shown in *Fig. 3.12*.

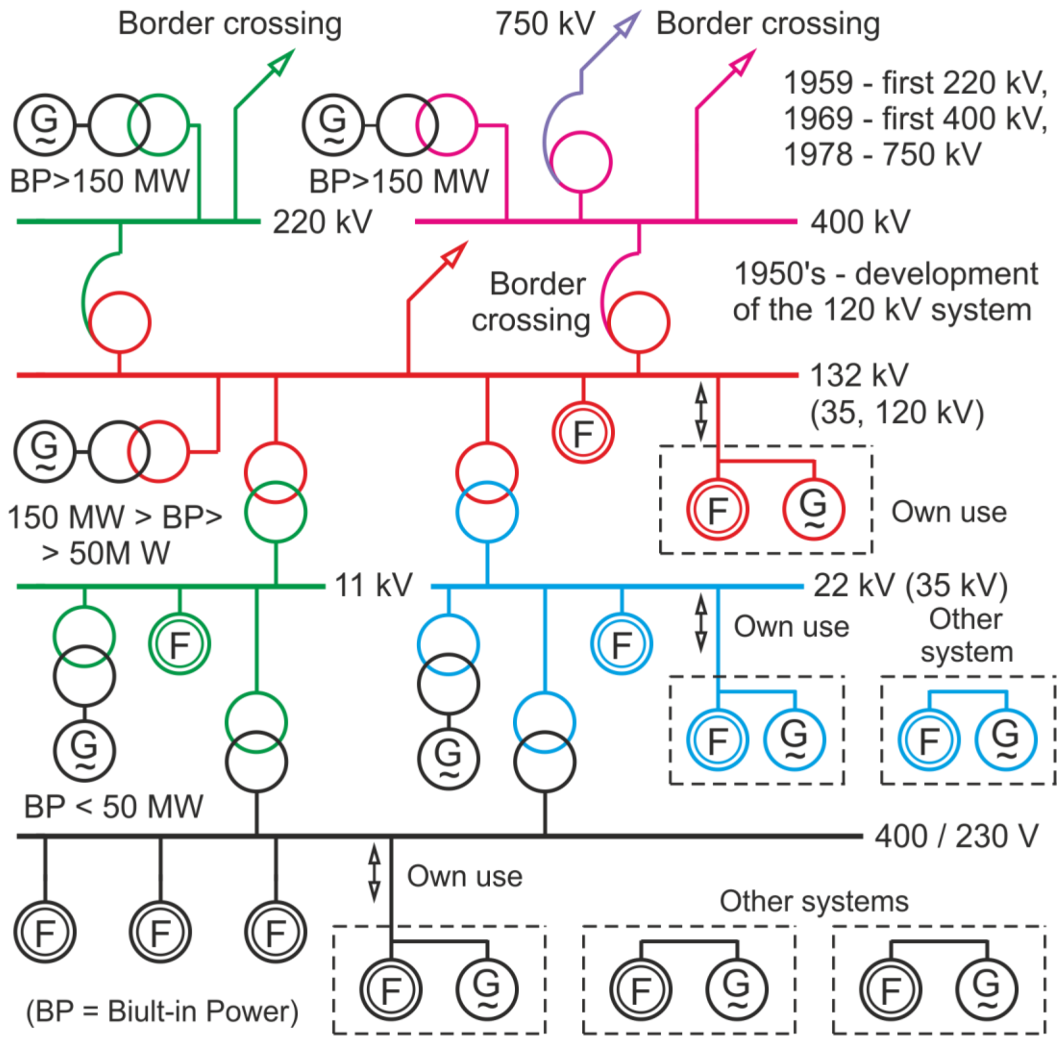


Fig. 3.12. Electric power networks of the Hungarian system

Electric power networks can be distinguished by their role as follows:

- International cooperation networks transport electrical energy between neighboring countries.

- Transmission networks transport electrical energy from large power plants to big consumer nodes.

- Distribution networks:
  - Main distribution networks transport electric energy on regional level,
  - medium voltage distribution networks transport electric energy on local level,
  - low voltage distribution networks transport electric energy on local level;
- Consumer networks.

Fig. 3*.13* shows the transmission network in Hungary. The oldest transmission lines are those with the rated voltage of 220 kV drawn green spreading nearly only on the northern part of the country with industry also in the past. This voltage level will not be further developed only the newer voltage level of 400 kV.

The only 750 kV line in Hungary (drawn lila in *Fig. 3.13*) used to spread from Albertirsa to Zapad (Ukraina), however in 2018 the Hungarian 750/400 kV transformer station has been moved from Albertirsa to Szabolcsbáka, close to the border of Ukraina.

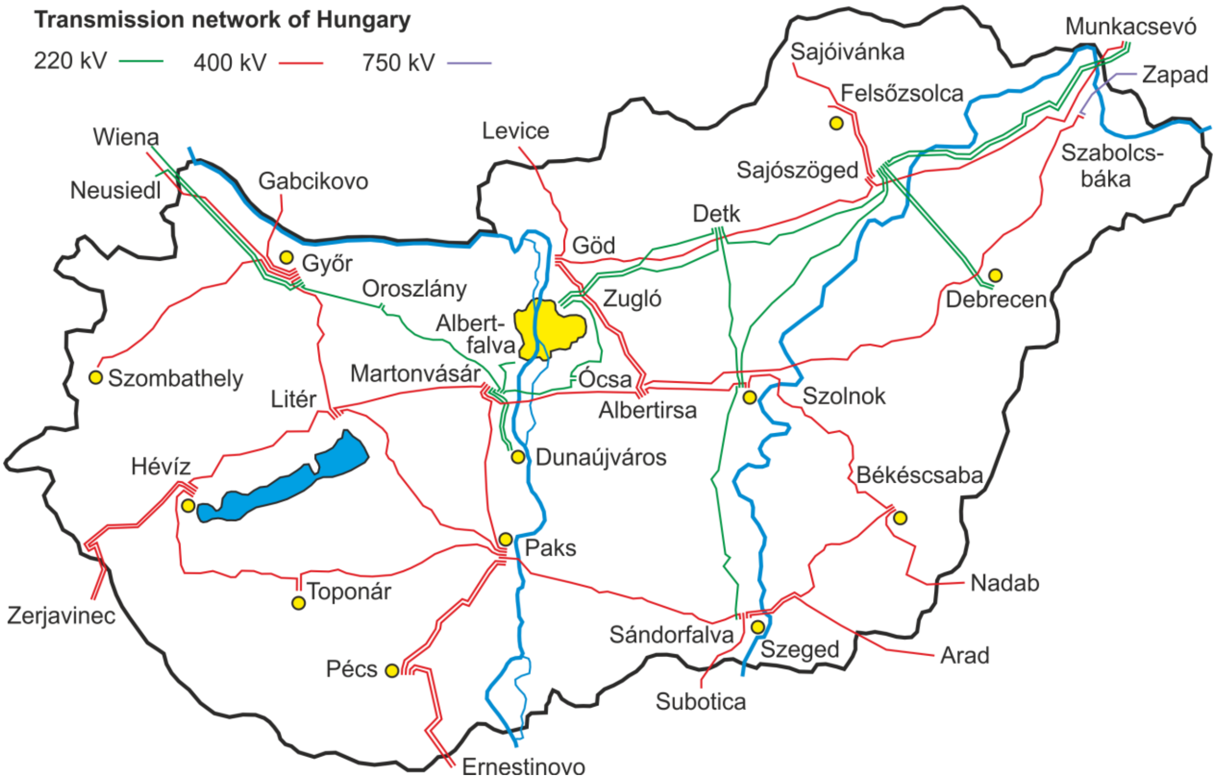


Fig. 3.13. Transmission network of Hungary (source: MAVIR [3.1])

In *Fig. 3.14* the memory cover is shown issued after the commissioning of the 750 kV line between the Soviet Union and Hungary in 1979 with the stamp issued by the Hungarian Post for this event.

Bunching of the conductors which can be observed on the stamp as well as on the seal serves for decreasing the corona loss. On the left side of the envelop a graphic of the transformer is shown. Because of the power of the line – 2000 MVA – and the required machine size three single phase transformers has been manufactured for each end of the line.

Fig. 3.14. Memory cover of the Hungarian 750 kV line

3.2.3 Substations/transformer stations

Substations are parts of electrical power networks. Substations can contain transformers. Between the different networks with different voltages transformer stations change the voltage levels. It is well-known that electric energy can be transported to big distances only at high voltage levels. As the voltage increases the current decreases at the same power and the less conductive material is necessary for the electricity transport. *Fig. 3.15* shows the sequence of voltage changes from a large power plant to a public consumer.

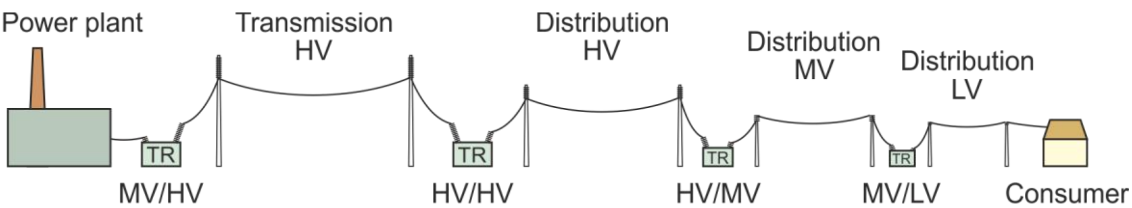


Fig. 3.15. Voltage levels from the power plant to the consumer

In general high power generators in large power plants have special, i.e. non-standard voltages optimized to the given task and circumstances there. These voltages belong to the medium voltage range in most cases. A unit transformer belongs to each generator transforming the voltage of the generator to a standard voltage level.

Main part of the electric energy produced in large power plants is transported to consumer centers by the lines composing the transmission network on very high voltage (HV) levels. Far from the power plant high voltage/high voltage transformer stations convert the voltage from very high level to lower but still high voltage level of the main distribution network.

The main distribution network supplies medium voltage (MV) distribution networks through high voltage/medium voltage transformer stations and the medium distribution network supplies low voltage (LV) distribution networks through medium voltage/low voltage transformer stations supplying the public consumers.

In *Fig. 3.16* the single line circuit diagram of an existing HV/MV (132/22 kV) substation can be seen. This is an average public substation with single busbars on the 132 and 22 kV side as well. The MV (22 kV) busbar can be split in two halves with a circuit breaker. This circuit breaker is called busbar splitting circuit breaker.

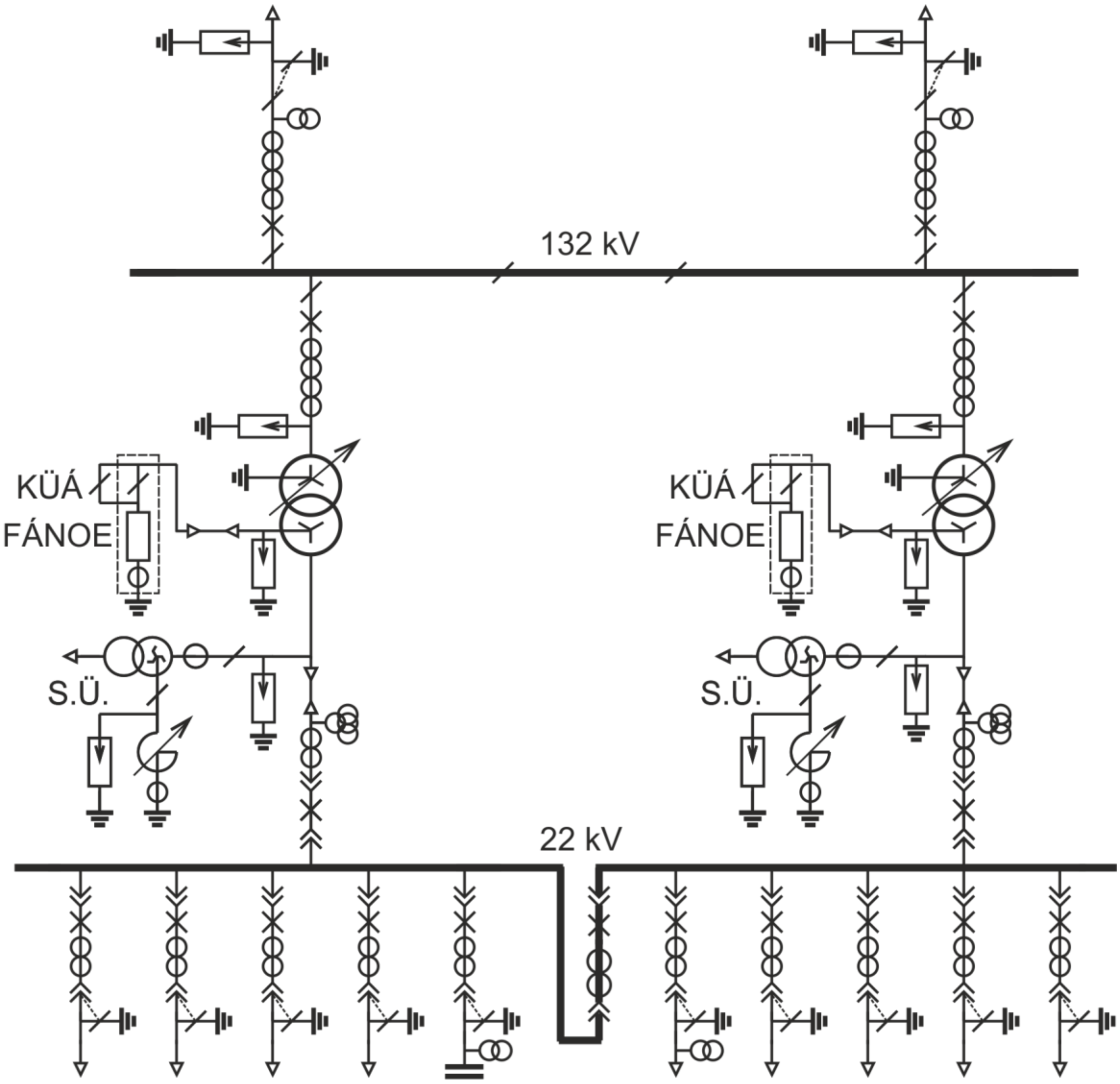


Fig. 3.16. Single line diagram of an HV/MV substation

As in case of most substations two HV overhead lines enter the station. Both can be switched by a circuit breaker each (symbol “X” in the figure). On the busbar side of the circuit breaker the busbar isolator and on the other side of it the line isolator with a grounding isolator are installed. All the current transformers have at least two secondary circuits, however on the VH side they have four secondary circuits for measurement and protection purposes.

On both sides of the transformer and in the secondary star point overvoltage protective devices are installed as well as at the overhead lines. Symbols around the 22 kV circuit breakers mean that the circuit breaker serves for isolating purposes at the same time.

3.2.4 Layouts of electrical power networks

Radial type networks

In case of radial type networks electric energy have only a single path from the source S to the consumer C (*Fig. 3.17*).

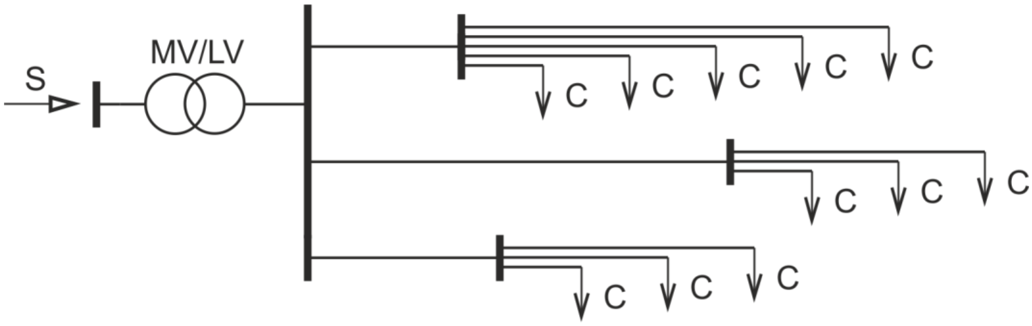


Fig. 3.17. Radial type network

Most low voltage networks are radial type networks in their layout and operation as well.

Arc line

An arc line in the network starts in one substation and ends in another substation (*Fig. 3.18*).

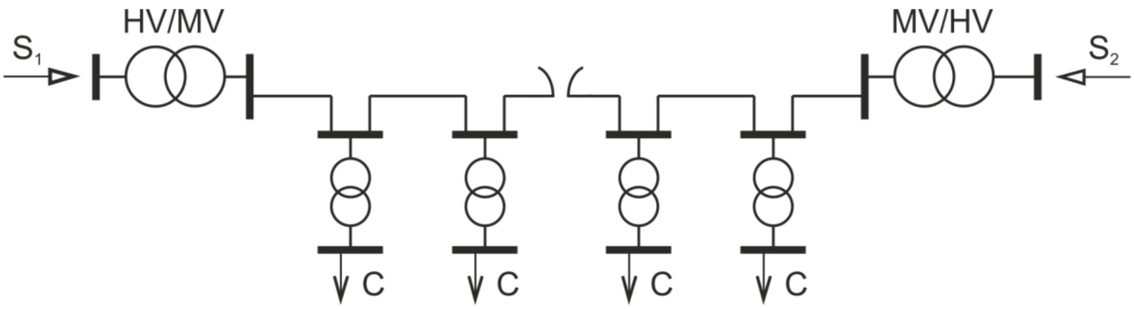


Fig. 3.18. Arc line in the network

This layout is typical for medium voltage (MV) networks, however there it works radially because there is always an open switch in the middle of the line.

Electric energy can only reach the consumer through a single path.

Ring line

A ring in the network starts in one substation and ends in the same substation (*Fig. 3.19*) usually at another section of the same busbar.

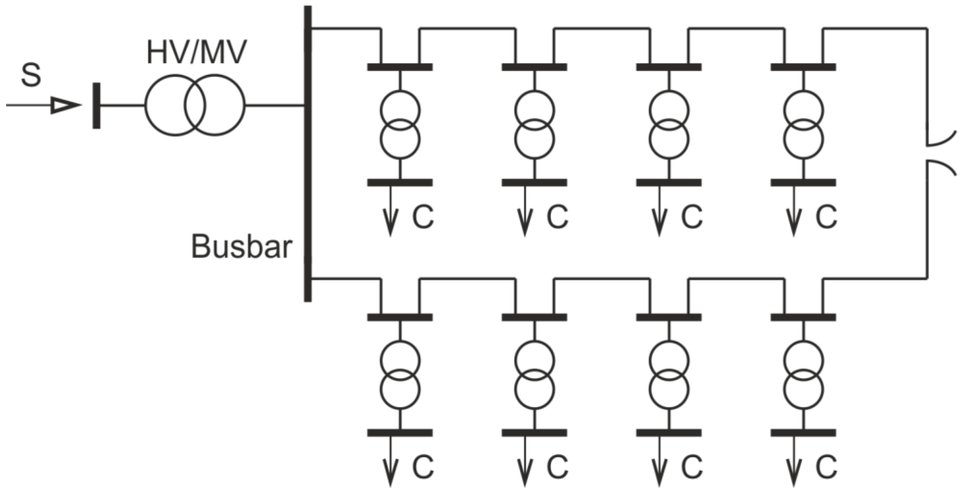


Fig. 3.19. Ring line in the network

The same is true for this layout as for the arc layout. Medium voltage networks are installed with meshed layout, i.e. with arc and ring lines, however they are operated radially.

Meshed layout

In case of meshed networks electric energy can reach a consumer through several paths thus increasing service continuity. This layout is typical for high voltage (HV) networks, i.e. for the transmission and the main distribution networks.

3.3 The three-phase system

Most of the electric energy is produced by three-phase synchronous generators and this electric energy is transported by three-phase networks. The three-phase system is the most simple among the symmetrical polyphase systems with the lowest number of phases owning the benefits of the polyphase systems.

The three phases with the namings „*a*", „*b*" and „*c*" can be configured in "Y" (or Wye, "star") or "delta". In case of delta configuration the three phase impedances of a generator, transformer or consumer (e.g. motor) compose a ring by connecting them in series as shown in *Fig. 3.20*.

In *Fig. 3.20* the three inductors standing on the left side of the figure for the source, i.e. for the windings of a generator or transformer, are drawn in delta form. The three phase impedances of the consumer are drawn vertically, however they are in delta configuration as well. In this case always $\overline{V}$ line voltage can be measured along the phases and between the lines.

Since voltage $\overline{V}$ characterizes the network as its rated voltage, thus it has no sub-index in normal cases and similarly the line current $\bar{I}$ has no sub-index as well. Letters with overbar are complex scalar variables and those written italic are real scalar variables.

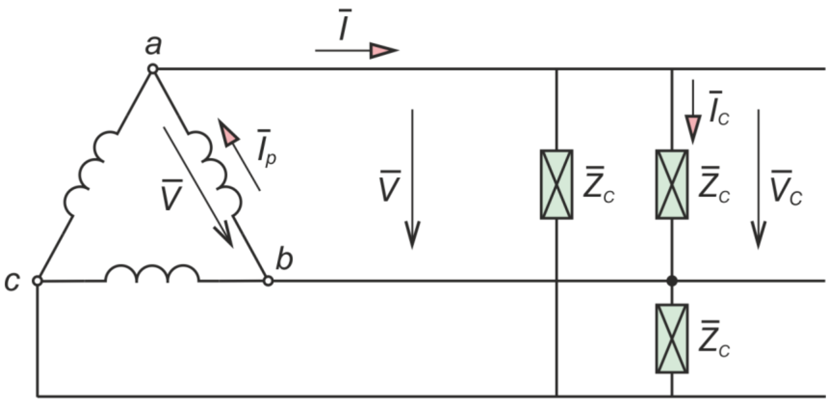


Fig. 3.20. Source and consumer with delta (triangle) configuration

In *Fig. 3.20* it can be seen that $\bar{V}$ line voltage and $\bar{I}_p$ phase current appears on the secondary winding of the transformer as the source. The consumer is in delta configuration as well, thus the phase delta current signed with sub-index „*p*" flows through its phases the absolute value of which is

$$I_C = I_p = \frac{I}{\sqrt{3}}, \tag{3.1}$$

i.e. it equals to the absolute value of the line current divided by square root of three. Voltage V_C along the consumer phases equals to the line voltage, as

$$V_C = V\ . \tag{3.2}$$

The three phases can be connected so that one terminal of each is connected together as shown in *Fig. 3.21*. This is the so-called Y configuration. Consumer impedances in the figure have this configuration as well.

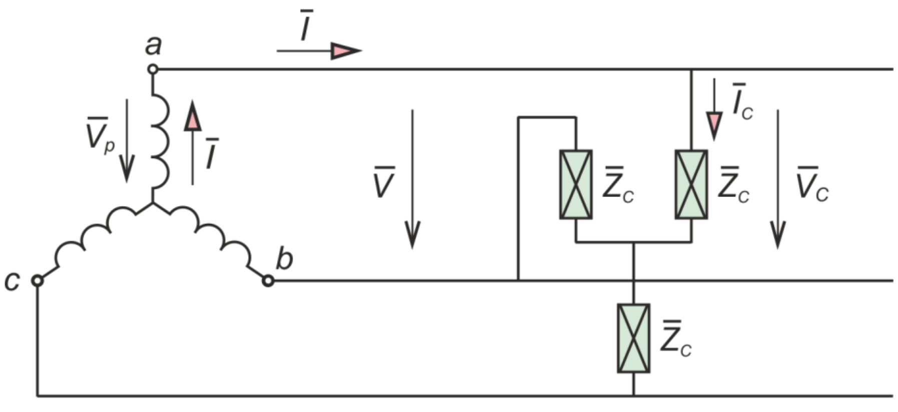


Fig. 3.21. Source and consumer in Y configuration

Terminals of the three phases connected together compose the „neutral point". This neutral point and the Earth as an electrode can be connected together several ways determined by the "grounding" ("earthing" in USA and some other countries) of the given network. Different networks have different (or identical) grounding methods which are characteristic to the given networks.

In *Fig. 3.21* the neutral point of the secondary winding system of the transformer supplying the consumer is not connected to the Earth, thus this is a network with insulated neutral. However in case of a symmetrical voltage system on the secondary windings of the transformer, which case is discussed now, has a potential of 0 V, i.e. earth potential. Between the lines and the neutral $\overline{V}_p$ phase voltage can be measured. The consumer has a Y configuration as well, thus phase voltage with sub-index „*p*" can be measured on its phase impedances the absolute value of which is

$$V_C = V_p = \frac{V}{\sqrt{3}}, \tag{3.3}$$

i.e. it equals to the absolute value of the line voltage divided by $\sqrt{3}$. Current flowing through the phase impedances equals to the line current, as

$$I_C = I\ . \tag{3.4}$$

3.3.1 Power of the three-phase system

Power of a three-phase system is the sum of the powers of the different phases. In case of symmetrical three-phase systems this equals to the three times the power of a single phase. Power can be

- apparent (S),
- active (P),
- reactive (Q).

An apparent power can have active and reactive components.

a) Apparent power

The apparent power S equals to the sum of the product of the voltages and currents of each phases. This is the power with the highest absolute value on a circuit element in unit VA (volt-amper), as

$$S = 3 \cdot V_C \cdot I_C, \tag{3.5}$$

where U_C is the voltage of the phase impedance of the consumer (V) and
I_C is its current (A).

In case of **delta configuration** line voltage can be measured, i.e. $V_C = V$, along the phase impedances and phase delta current, i.e. $I_C = I_p$, flows through them being equal to the line current divided by $\sqrt{3}$. Thus the apparent power is

$$S = 3 \cdot V_C \cdot I_C = 3 \cdot V \cdot I_p = 3 \cdot V \cdot \frac{I}{\sqrt{3}} \tag{3.6}$$

and after reducing the equation by $\sqrt{3}$

$$\boxed{S = \sqrt{3} \cdot V \cdot I}, \tag{3.7}$$

where V is the a line voltage and
I is the line current.

In case of **star configuration** phase voltage, i.e. $V_C = V_P$ can be measured along the phases being equal to the line voltage divided by $\sqrt{3}$ and line current, i.e. $I_C = I$ flows through them. Thus the apparent power is

$$S = 3 \cdot V_C \cdot I_C = 3 \cdot V_p \cdot I = 3 \cdot \frac{V}{\sqrt{3}} \cdot I , \tag{3.8}$$

and after reducing the equation by $\sqrt{3}$ (3.7)

$$\boxed{S = \sqrt{3} \cdot V \cdot I}.$$

If expressed with line quantities the apparent power can be calculated with the same equation in case of delta and Y configuration. If expressed with complex numbers the equation for the calculation of the three-phase apparent power for delta and Y configuration is

$$\boxed{\bar{S} = \sqrt{3} \cdot \bar{V} \cdot \bar{I}^*}, \tag{3.9}$$

i.e. it equals to $\sqrt{3}$ times the product of the complex voltage and the conjugated of the complex current.

b) Active power

P active power equals to the sum of the products of the voltage and current components being in the same phases of each phase impedances expressed in unit W (watt) (*Fig. 3.22*), as

$$P = 3 \cdot V_C \cdot I_{Cw} , \tag{3.10}$$

where V_C is the voltage of the phase impedance of the consumer (V) and
$I_{Cw} = I_C \cdot \cos\varphi$ is the active component of the current of the phase impedance (A). Sub-index *w* refers to the unit „watt” of the active power.

Work can be done only by active power. Active power is able to do work e.g. in electric motors and is converted to heat in electric heating and other devices. In *Fig. 3.22* the ω circular speed with its arrow shows the direction of rotation of the voltage and current phasors on the Gaussian complex plane.

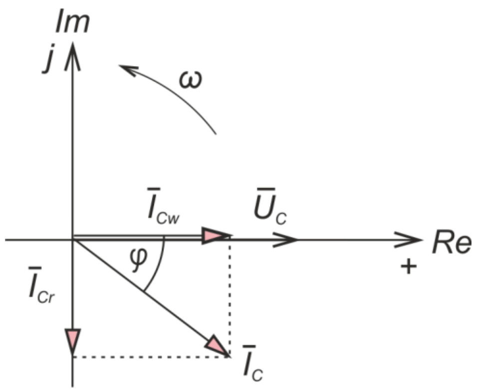


Fig. 3.22. Active and reactive components of the consumer current

Delta configuration

Phase delta current ($I_C = I_p$) flows through the phase impedances in delta configuration

$$P = 3 \cdot V_C \cdot I_{Cw} = 3 \cdot V \cdot I_C \cdot \cos\varphi = 3 \cdot V \cdot \frac{I}{\sqrt{3}} \cos\varphi \tag{3.11}$$

and after reducing the equation

$$\boxed{P = \sqrt{3} \cdot V \cdot I \cdot \cos\varphi}. \tag{3.12}$$

Y configuration

In case of Y configuration phase voltage can be measured along the phase impedances ($V_C = V_p$), as

$$P = 3 \cdot V_C \cdot I_{Cw} = 3 \cdot V_C \cdot I_C \cdot \cos\varphi = 3 \cdot \frac{V}{\sqrt{3}} \cdot I \cdot \cos\varphi \,, \tag{3.13}$$

i.e. (3.12)

$$\boxed{P = \sqrt{3} \cdot V \cdot I \cos\varphi}.$$

c) Reactive power

Q reactive power equals to the sum of the products of the voltage and current component being perpendicular to the voltage phasor of each phase impedances expressed in unit VAr (*Fig. 3.22*), as

$$Q = 3 \cdot V_C \cdot I_{Cr} \,, \tag{3.14}$$

where V_C is the voltage of the phase impedances (V) and
$I_{Cr} = I_C \cdot \sin\varphi$ is the reactive current component on the phase impedance (A).

Thus the reactive power for delta end Y configuration is

$$\boxed{Q = \sqrt{3} \cdot V \cdot I \cdot \sin\varphi}. \qquad (3.15)$$

This kind of reactive power is typical for inductive circuit elements, however capacitive parts have reactive power as well being in opposite phase related to the inductive one. The inductive reactive power is necessary for the operation of certain consumers like electric motors for maintaining the magnetic field inside them. Some current converters and other consumers need inductive reactive power as well.

Since most of the consumers require inductive reactive power for their operation, this kind of reactive power is considered as „consumed reactive power", while the reactive power of capacitors is called „produced reactive power". That is the basis of the power factor correction: Capacitive reactive power of capacitors can cover the reactive power need of inductive loads.

Relationships between powers

Apparent power can have active and reactive components the sum of the phasors of which equals to the apparent power phasor, the absolute value of which is (*Fig. 3.23*)

$$\boxed{S = \sqrt{P^2 + Q^2}}. \qquad (3.16)$$

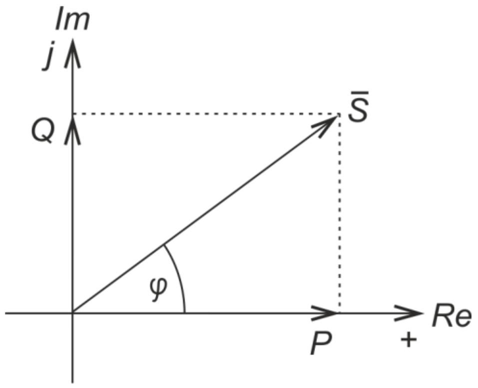


Fig. 3.23. Relationship among power components

When calculating with phasors the apparent power is

$$\bar{S} = P + jQ\,. \qquad (3.17)$$

Not to forget that like impedance phasors neither the power phasors rotate, rather they lay still on the complex plane.

3.4 Problems

a) Problem

Properties of a three-phase transformer with a phase displacement of Dy5 hours are as follows:

- Rated power: S_n = 630 kVA,
- rated voltage: V_1/V_2 = 11000/400 V.

The problem is to calculate the rated line and phase currents at the primary and secondary sides.

Solution

The rated power expressed with the primary line current and voltage is

$$S_n = \sqrt{3} \cdot V_1 I_1 = 630 \text{ kVA} \tag{3.18}$$

and the rated line current at the primary side is

$$I_1 = \frac{S_n}{\sqrt{3} \cdot V_1} = \frac{630000}{\sqrt{3} \cdot 11000} = \underline{\underline{33.07 \text{ A}}}. \tag{3.19}$$

The phase current in the primary winding with delta configuration is

$$I_p = \frac{I_1}{\sqrt{3}} = \frac{33.07}{\sqrt{3}} = \underline{\underline{19.1 \text{ A}}}. \tag{3.20}$$

The rated power expressed with the secondary line voltage and current is

$$S_n = \sqrt{3} \cdot V_2 I_2 = 630 \text{ kVA} \tag{3.21}$$

and the rated line current at the secondary side is

$$I_2 = \frac{S_n}{\sqrt{3} \cdot V_2} = \frac{630000}{\sqrt{3} \cdot 400} = \underline{\underline{909.3 \text{ A}}}. \tag{3.22}$$

The phase current in the secondary winding with Y configuration is

$$I_p = I_2 = \underline{\underline{909.3 \text{ A}}}. \tag{3.23}$$

b) Problem

Data of the three-phase squirrel-cage asynchronous motor are as follows:

- Rated power: P_n = 10 kW,
- rated voltage: V_n = 3 x 400 V delta configuration,
- rated power factor: $\cos\varphi_n$ = 0.79,
- rated efficiency: η_n = 87%.

The problem is to calculate the followings:

- Rated current drawn from the mains (I_n);
- rated apparent power drawn from the mains (S_n);
- rated reactive power drawn from the mains (Q_n).

Solution

Rated power available at the axis of the motor is

$$P_n = \sqrt{3} \cdot V \cdot I \cdot \eta \cdot \cos\varphi = 10 \text{ kW} \tag{3.24}$$

and the apparent current drawn from the mains is

$$I = \frac{P_n}{\sqrt{3} \cdot V \cdot \eta \cdot \cos\varphi} = \frac{10000}{\sqrt{3} \cdot 400 \cdot 0.87 \cdot 0.79} = \underline{\underline{21 \text{ A}}} . \tag{3.25}$$

Active power drawn from the mains is

$$P_{nf} = \frac{P_n}{\eta} = \frac{10}{0.87} = 11.49 \text{ kW} . \tag{3.26}$$

Rated apparent power drawn from the mains is

$$S_n = \sqrt{3} \cdot V \cdot I = \sqrt{3} \cdot 400 \cdot 21 = 14550 \text{ VA} = \underline{\underline{14.55 \text{ kVA}}} , \tag{3.27}$$

Rated reactive power drawn from the mains is

$$Q_n = \sqrt{S_n^2 - P_{nf}^2} = \sqrt{14.55^2 - 11.49^2} = \underline{\underline{8.91 \text{ kVar}}} . \tag{3.28}$$

c) Problem

Data of the three-phase synchronous generator with cylindrical rotor and insulated neutral point are:

- Rated power: S_n = 44 MVA,
- rated voltage: U_n = 10.5 kV,
- rated power factor:
  - $\cos\varphi_n$ = 1.0,
  - $\cos\varphi'$ = 0.7 (when overexcited).

The problem is to calculate the apparent, active and reactive powers of the generator with the given power factors.

Solution

Rated value of the armature current is

$$I_{an} = \frac{S_n}{\sqrt{3} \cdot U_n} = \frac{44000}{\sqrt{3} \cdot 10.5} = \underline{\underline{2419.3 \text{ A}}} , \tag{3.29}$$

active component of armature current is

$$I_{anw} = I_{an} \cdot \cos\varphi = 2419.3 \cdot 1.0 = \underline{\underline{2419.3\text{ A}}} \tag{3.30}$$

and its reactive component

$$I_{anm} = I_{an} \cdot \sin\varphi = 2419.3 \cdot 0 = \underline{\underline{0}} \tag{3.31}$$

and the active component of armature current when overexcited is

$$I'_{anw} = I_{an} \cdot \cos\varphi' = 2419.3 \cdot (-0{,}7) = \underline{\underline{-1693{,}51\text{ A}}} \tag{3.32}$$

and the reactive component in overexcited state is

$$I'_{anm} = \sqrt{I_{an}^2 - I'^2_{anw}} = \sqrt{2419.3^2 - (-1693.51^2)} = \underline{\underline{1727.72\text{ A}}}. \tag{3.33}$$

4 Electric energy consumers

Electric energy consumers convert electric energy to the art of the energy required. They can be distinguished according to the sector of economy where they are used:

- Industrial consumers;
- agricultural consumers;
- communal consumers like street lighting;
- electric consumers in buildings like
  - residential buildings,
  - buildings for education,
  - office buildings.

There are other types of buildings as well, however most of them with typical characteristics are covered by the first three items. In all of the mentioned building arts there are household machines used. Electric energy consumers can be distinguished according to their aim of usage as:

1) **Thermal consumers** – producing thermal energy like
   - electric heating,
   - electric furnaces,
   - electric melting units,
   - electric boilers,
   - soldering machines,
   - electric water heaters e.g. for producing domestic hot water (DHW),
   - electric cooking stoves,
   - microwave ovens,
   - washing machines,
   - drying machines,
   - combined washing and drying machines,
   - rinsing machines,
   - ironing machines,
   - coffee machines,
   - toasters,
   - hair dryers,
   - hair curliers,
   - etc.

Thermal consumers are characterized by their power factor near to 1 ($\cos\varphi = 1$) and that they are linear consumers, except those having electronic supply units e.g. for control purposes. Considering the electric energy utilized by them these consumers have an efficiency of 100%, since all the electricity is converted to thermal energy in them. However the equipment using the thermal energy have an efficiency lower than 100% for example in case of a household cooking stove if a part of the heat propagates away without heating the food. If the efficiency of the power plants is taken into account as well than the resultant efficiency can be even lower.

2) **Electric motors**

Most electric motors are characterized by their power factor lower than 1 ($\cos\varphi < 1$) because they need reactive power maintaining the magnetic field required for their operation. In most cases a factory where a number of motors operate require power factor correction realized with static capacitors.

In many cases electric motors have electronic supply units like frequency converters. In this case these power electronic devices ensure a power factor of $\cos\varphi = 1$. There are motors with high power e.g. in locomotives but always supplied by power electronic units.

Efficiency of electric motors is always below 100% because of the waste heat developing in the windings and the iron core. Efficiency can be as low as 55% in case of small motors and as high as 97% in case of motors with powers above 1 MW. It has to be mentioned that the efficiency of a motor depends on its load. It is maximum if the motor drives a machine with its rated power. Thus it is not advisable to over-dimension electric motors, because then their efficiency is lower than the possible maximum. In *Fig. 4.1* an electric motor is shown with a pump driven by it.

Fig. 4.1. Electric motor with a pump

3) **Lighting**

In the past lighting meant incandescent lamps with characteristics similar to the thermal consumers. The efficiency of incandescent lamps was very low. With the appearance of fluorescent lamps the need for a ballast resulted in power factors lower than 1 however in most cases fluorescent lamps ballast contains the necessary capacitor for the power factor correction.

Now LED lightings have electronic ballasts with $\cos\varphi = 1$ in most cases. Efficiency of light sources is expressed by the luminous efficiency, which is highest in case of LEDs and sodium vapor lamps.

In *Fig. 4.2.a* an incandescent lamp of 1000 W is shown and in *Fig. 4.2.b* a LED lamp with the same luminous flux of 24000 lumens. The LED lamp draws a power of 240 W from the mains.

a)　　　　　　　　　　　　*b*)

Fig. 4.2. 1000 W incandescent lamp (a) and a LED reflector (*b*)

4) **Electrolysis**

Consumers of the electrolysis convert electric energy to chemical energy. Hydrogen is produced with electrolysis. Typically countries with excess electric power capacity like France, Norway and Egypt produce and sell hydrogen.

5) **Other electric consumers** like railway, military, etc.

Electric energy consumers can be grouped by the number of phases they are connected to, thus there are
- single phase consumers or
- three phase consumers.

Basically there are two phase consumers as well. For example electric train drives operate with single phase, however this single phase is transformed from two phase at the high voltage level (*Fig. 4.3*). The same can be said on electric melting, etc.

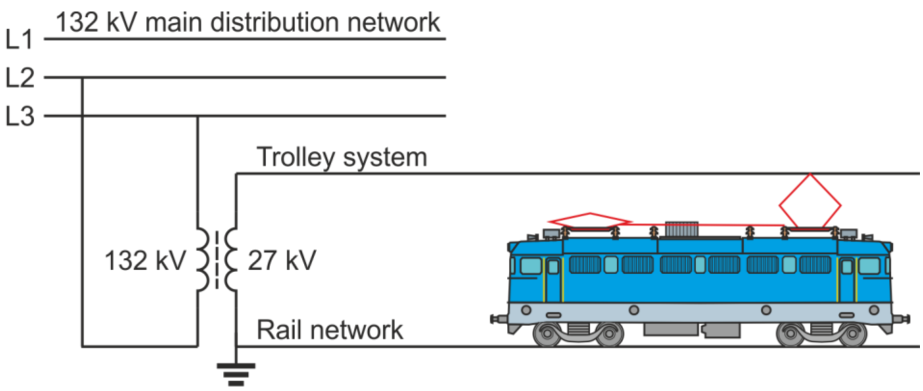


Fig. 4.3. Electricity supply of the electric railway

Single phase consumers have negative impact on the operation of the electrical networks. There symmetrizing circuits for big single phase consumers like the Steinmetz circuit. An electric locomotive can take several megawatts of energy, but the Steinmetz circuit can not be used in for its symmetrization because of the timely variable power of the locomotive.

Electric energy consumers can be grouped by their magnitude of power. In general consumers with power above 1 MW are treated separately. This power can go up to 100 MW, e.g. in case of the Dunaferr iron works. In general these great consumers have own power plants as well.

Electric energy consumers can be grouped by the voltage they are connected to, as
- extreme low voltage (ELV) consumers – up to 50 VAC or 120 VDC;
- low voltage consumers – up to 1000 VAC or 1200 VDC;
- medium voltage consumers – up to 35 kV;
- high voltage consumers – 132 kV.

4.1 Linear and non-linear electric consumers

Electric consumers like those listed under 1) are mainly linear consumers not polluting the public network with disturbances. However more and more of them are coupled with electronic supply with possible negative impacts on the network. With the development of electrical engineering the number of non-linear consumers increases continuously.

According to the standard EN 50160 **Voltage characteristics of electricity supplied by public electricity networks** [4.1] electrical energy, i.e. the voltage has to comply quality requirements. The network operator, namely the utility company has to ensure the good quality of the electric energy supplied through the public system. On the other hand consumers are not allowed to pollute the public network to an extent beyond the levels allowed by the standards.

The point of the network where the quality level of the voltage is measured is regulated in the standard. There is the common coupling point (CCP). It is not so easy to identify the person guilty for the polluted voltage, if it is the utility company or the consumer, but there are methods to find this out.

Quality characteristics of the voltage are:
- Magnitude;
- variance of the magnitude;
- transient over-voltages;
- duration of outages;
- harmonic content;
- symmetry.

In *Fig. 4.4* the phenomenon flat top distortion is shown. As a result of many consumers with electronic supply units drawing current only around voltage peaks the voltage decreases because of voltage drop.

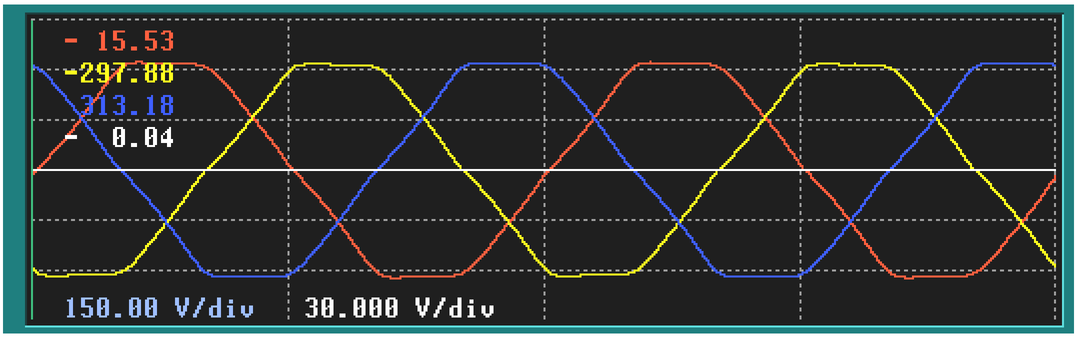


Fig. 4.4. Flat top distortion of the voltage curves

4.2 Need of electric consumers on supply continuity

Some of the electric consumers must have continuous supply in the lack of which serious damages, even explosion, direct risk of life or long term break in production can be the consequence. These consumers belong to category *A* like factories of chemical industry, airports, hospitals or equipment of the telecommunication.

The different categories are as follows:

- Category *A* consumers can tolerate outages with a duration between 0.5 – 5 s. In *Fig. 4.5* the electricity supply of a hospital is shown, with a number of category *A* consumers.

- In case of consumers of category *B* outages with durations between 5 – 15 m are tolerated. E.g. furnaces, arc furnaces, roll trains, etc. belong to this category.

- In case of consumers of category *C* outages with durations between 2 – 4 h are tolerated. E.g. textile factories, freezer houses, etc. belong to this category.

- For consumers of the category *D* the supply of electric energy can stop for longer periods. E.g. service shops, work places with lower reliability need belong to this category.

Some indicators demonstrating the quality level of the electric energy supply and the quality of the electrical network itself relate to the outages of the supply, to their frequency and duration.

Such indicators are:

- System Average Interruption Duration Index (SAIDI);

- System Average Interruption Frequency Index (SAIFI).

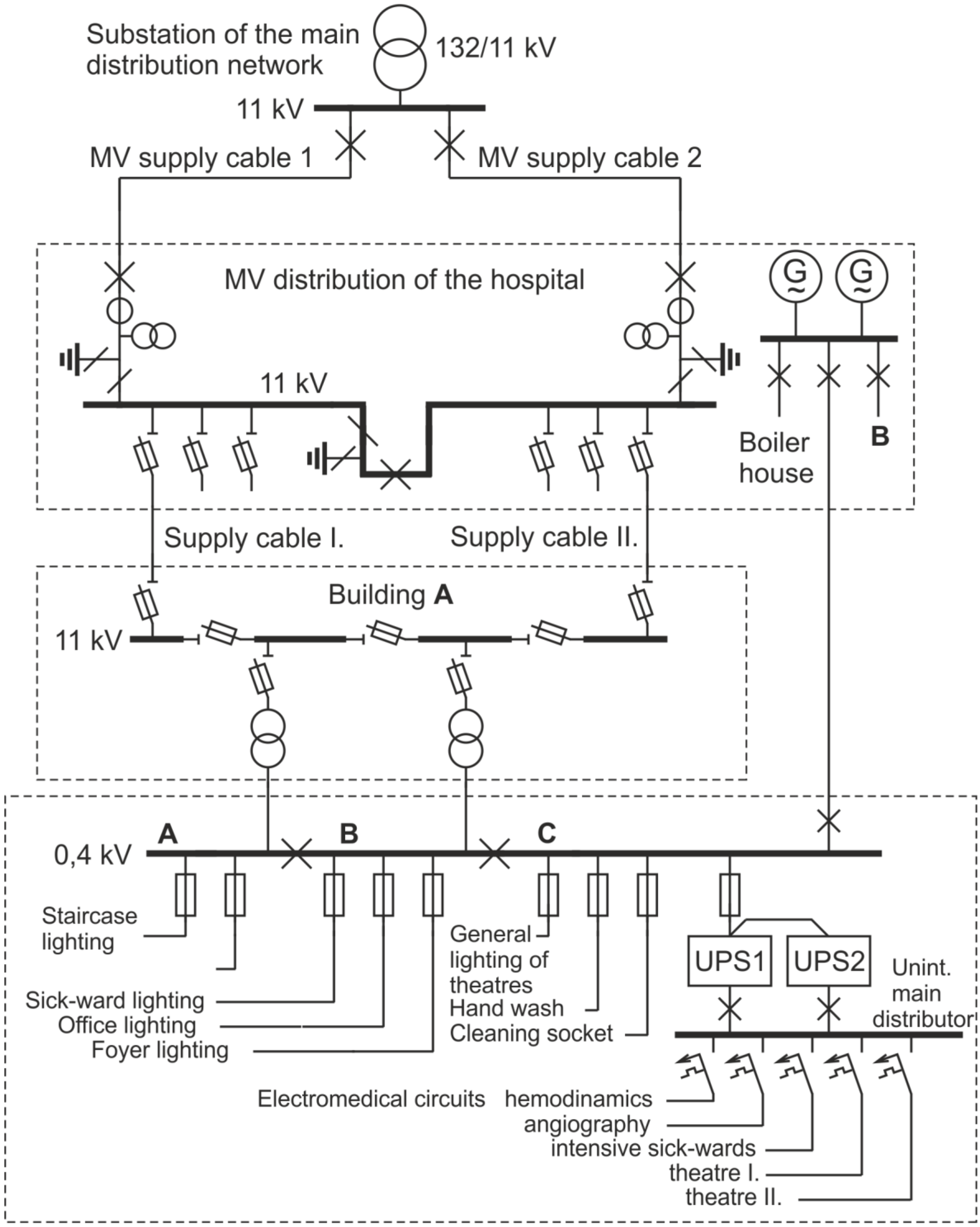


Fig. 4.5. Electricity supply of a hospital

4.3 Variation of the load in time

Minimum installed power could be necessary if the load of the power plants would be constant in time. This is far from reality, the power varies during the day, the week and during the year. The load is minimum during the night and maximum around noon and in the evening. These two periods are called peak hours and the other two periods of the day are non-peak hours.

Fig. 4.6 shows the daily variation of the industrial load on a weekday in Hungary. The industrial load curve has a maximum during the morning, however a factory working 24 hours a day has a much more even load curve as a matter of course.

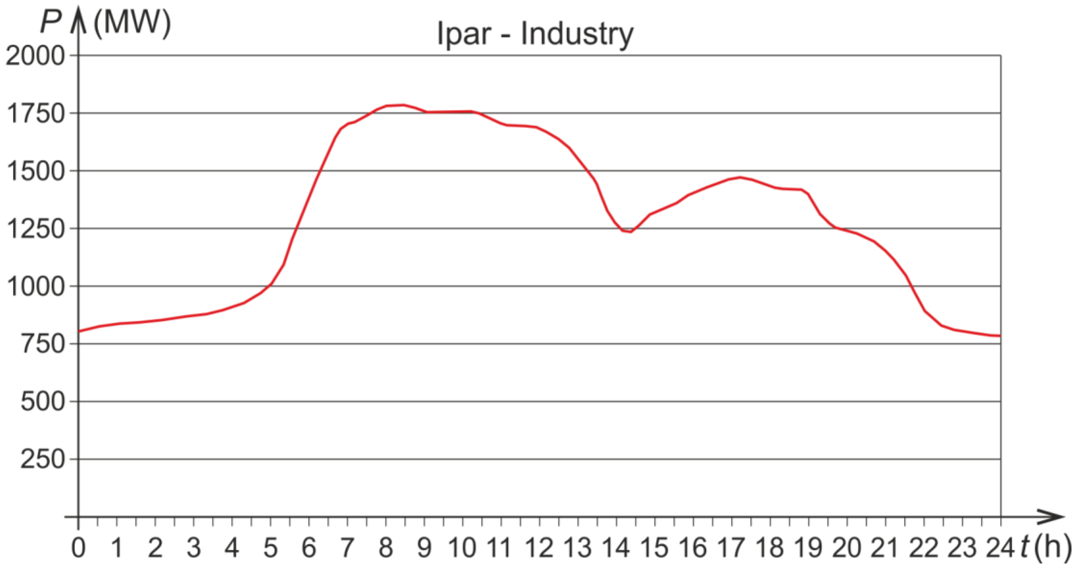


Fig. 4.6. Daily changes in industrial load [4.2]

In *Fig. 4.7* the daily variation of the household load is shown with its peak in the evening. Consumers in some branches of industry can be influenced to a higher extent than household consumers, however there are possibilities to make the household consumption more even. A negative phenomenon from this point of view is that, the proportion of industrial consumption decreases continuously since the middle of the last century.

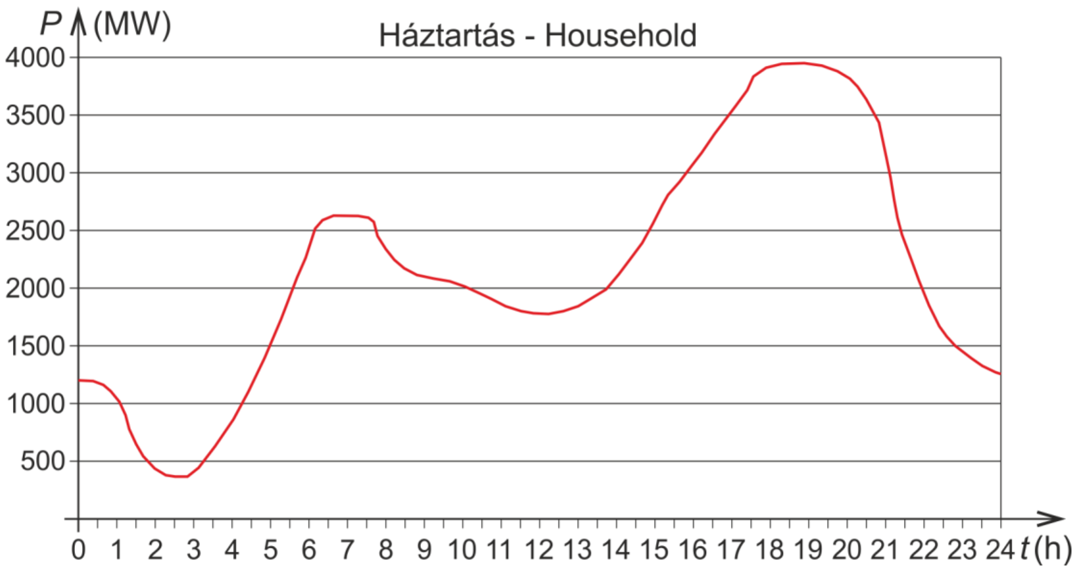


Fig. 4.7. Daily changes in household load [4.2]

The load is higher in weekdays and lower at weekends. In countries closer to the poles the load is maximum in winter and countries closer to the equator the maximum appears in summer. The reason of this is the operation of air conditioners in high number.

An important task nowadays to make the consumption of electric energy more even in time. E.g. in case of households and other consumers "energy management" can help in this field.

4.4 Control of electric energy consumers

Control, i.e. the switching on and off certain electric consumers can have advantages for the operator of the consumers and for the electric utility company as well. A simple example for this is when several machines are not allowed to be switched on simultaneously, but sequentially with a short delay between two starts. This method can prevent a very high initial current and power, which can cause a switch off of the overcurrent protection.

Some consumers, e.g. domestic hot water (DHW) heaters, can be controlled by the electric utility company ensuring the supply of these consumers through e.g. radio frequency signals and other consumers are controlled at site in the facility of an industrial company, office or residential building. In the later cases the artificial intelligence performing the control is called "energy management".

In case of households some consumers can be switched on during off-peak hours, e.g. in the night thus achieving a more flat load curve which is beneficial for the company and for the owner of the consumers since he/she do not have to pay the higher peak hour tariff. In the following considerations are listed for the classification of household consumers:

- Uninterruptible – like security circuits;
- not controllable – like amusement electronic devices which can operate any time however an uninterruptible supply is not inevitable;
- controllable – the electric utility company switches them on and off, e.g. DHW heaters, heating devices;
- schedulable and not interruptible – like washing machines the operation of which can be scheduled during a certain time period, but are not allowed to be switched off before their complete program;
- schedulable and interruptible – like drying machines the operation of which can be scheduled during a certain time period and can have some brake in their operation;
- prohibited in case of absence – like auxiliary heating in the bathroom which can be switched off automatically when the residents leave the flat;
- prohibited during the night – consumers the operation of which has no sense at night.

This control can be made more sophisticated e.g. in case of the presence of a PV unit at the household. When the residents are not present at home and the solar power unit produces a lot of energy during a Summer day which is supplied back into the mains profiting rather low, then the energy management can evaluate the situation involving weather forecast data if available and can begin the washing program preventing a higher payment during the night.

References – 4

[4.1] EN 50160:2011 Voltage characteristics of electricity supplied by public electricity networks.

[4.2] Dr. Morva György, Villamosenergetika (on Hungarian), *EDUTUS Főiskola*, 2012.

5 Electrical conductors and cables

Electrical conductors and cables are key elements of electrical devices, equipment and systems, since mostly they conduct the electric current for power or signal transmission purposes. Essential part(s) of electrical conductors and cables is(are) a conductor or conductors made of conductive materials of first degree, i.e. of metals. Metals most commonly used for current transport are:

- Copper (Cu) – has the most wide-spread application;
- Aluminum (Al) – for the transport of high currents/powers;
- Iron (Fe) – e.g. for grounding and lightning protection;
- Silver (Ag) – is the material with the highest electric conductivity;
- Gold (Au) – mainly for contacts because of its resistance against corrosion.
- Platinum (Pt) – e.g. for high temperatures.

For communication purposes cables exist with non-conductive cores, like in case of fiber-optic cables. However the signal transmitting medium is the electromagnetic field, i.e. the light in this case as well. In a fiber-optic cable, light signals are transmitted through thin fibers of plastic or glass from light-emitting diodes or semiconductor lasers by means of internal reflection. The advantages of fiber-optic cables over conventional coaxial cables include low material cost, high transmission capacity, low signal attenuation, data security, chemical stability, and immunity from electromagnetic interference.

In general a conductor is a single, usually cylindrical, flexible strand or rod of metal. Conductors are used to bear mechanical loads or electricity and telecommunications signals [5.1]. For the field of the present textbook electrical conductors are of interest the definition of which is:

Electrical conductors are single conductors to conduct electrical current for power or signal transmission purposes.

A conductor can have a solid core, or stranded, or braided forms. Although usually circular in cross-section, wire can be made in square, hexagonal, flattened rectangular or other cross-sections [5.1]. An electrical conductor with solid core made of copper and with an insulation of polyvinylchloride (PVC) is shown in *Fig. 5.1*.

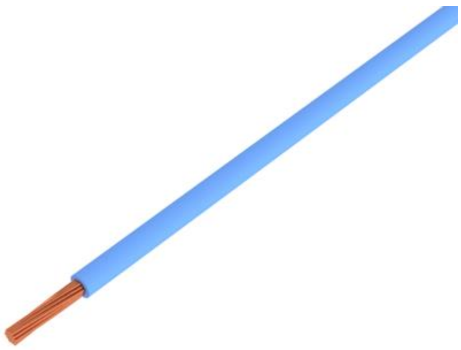


Fig. 5.1. Insulated copper conductor (H05V2-K)

An electrical cable is a conductor or group of conductors for transmitting electric power or telecommunication signals from one place to another [5.1].

Most of the cables have several conductors within a single sheath, however there are single core cables as well. In the near past three-conductor cables has been used as medium voltage (MV) cables, but now single-core cables are manufactured for this voltage level.

Cables can be classified into two main arts: Power cables and communication cables. *Table 5.1* summarizes some differences between power and communication cables.

Table 5.1. Properties of power and communication cables

Property	**Power cables**	**Communication cables**
Voltage	from low to very high voltages	mostly extra low voltages (ELV)
Current	from low to very high currents	mostly very low currents
Diameter	up to high diameters	mostly very low diameters
Frequency	mostly industrial frequencies	from low to very high frequencies
No. of conductors	mostly from 1 to 5	from one to several hundreds
Insulation	from no to very thick ones	mostly simple insulation
Shielding	from no to simple	mostly high efficient shielding

Main arts of cables by their task are shown in *Fig. 5.2*.

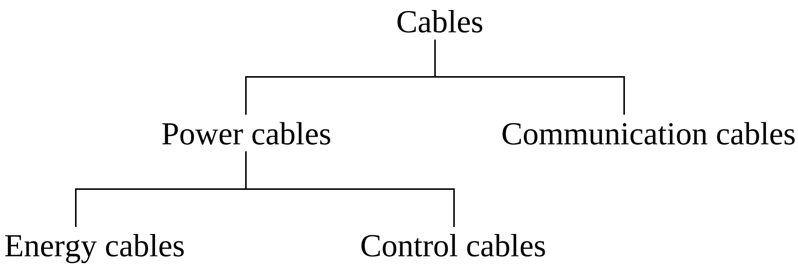


Fig. 5.2. Arts of cables by their task

5.1 Communication cables

Electric communication cables transmit e.g.
- audio signals, e.g. via wired telephones;
- visual images, e.g. to security screens;
- computer data via computers;
- digital signals e.g. on/off signals for control purposes;
- analog signals e.g. temperature values for closed loop control purposes.

In case of communication cables electromagnetic compatibility (EMC) considerations are of high importance. Because of the high frequencies of the transmitted signals radiated disturbances can interfere with these signals deteriorating their integrity.

There are two basic methods for the protection against radiated interferences:
- Shielding;
- twisted pair of conductors.

Coaxial cables

Coaxial cable is a type of electrical cable consisting of an inner conductor surrounded by a concentric (coaxial) conducting shield, with the two separated by a dielectric (insulating) material. Many coaxial cables also have a protective outer sheath (*Fig. 5.3*).

Fig. 5.3. Structure of a coaxial cable

Coaxial cables are used as transmission lines for radio frequency signals. Its applications include
- feedlines connecting radio transmitters and receivers to their antennas;
- computer network (e.g., Ethernet) connections;
- transmission of digital audio signals;
- transmission of cable television signals.

An advantage of coaxial cables over other types of radio transmission line is that in an ideal coaxial cable the electromagnetic field carrying the signal exists only in the space between the inner and outer conductors. This allows coaxial cables to be installed next to metal objects. In order to maintain the EMC protection of coaxial cables their connectors have similar construction as the cable itself (*Fig. 5.4*).

Fig. 5.4. Coaxial cable with BNC connectors

Since the signal propagates within the insulating material as electromagnetic field in the cable, the speed of propagation depends on its material

$$v = \frac{c}{\sqrt{\mu_r \varepsilon_r}}, \tag{5.1}$$

where v is the velocity of the signal propagation;

$c = 2.997992458 \cdot 10^8 \ \frac{\text{m}}{\text{s}}$ the speed of light;

μ_r relative magnetic permeability of the dielectric material and

ε_r relative electric permittivity of the dielectric material.

In case of polyethylene the electromagnetic field propagates with a speed of about 70% of light speed.

Another important property of a coaxial cable is its Z_0 wave impedance

$$Z_0 = \sqrt{\frac{\mu}{\varepsilon}}. \tag{5.2}$$

This wave impedance does not depend on the length of the cable but only on its transversal dimensions and the insulating material. *Fig. 5.5* shows a coaxial like arrangement feeding the signal sending antenna installed in Solt Middle-Hungary. Since the insulating material is the air in this case, the velocity of propagation equals to the light speed and the wave impedance is

$$Z_{00} = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 120\pi \cong 377\Omega, \tag{5.3}$$

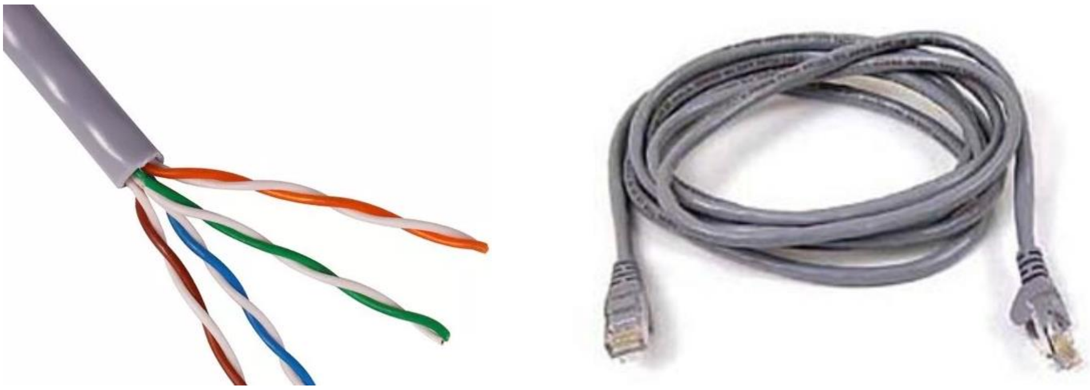
which equals to the wave impedance of vacuum.

Fig. 5.5. Coaxial like arrangement feeding an antenna

UTP cables

UTP Cables containing one or more Unshielded Twisted Pair(s) have PVC sheath but no shielding against radiated electromagnetic interference (EMI). Even though the twisted construction of the conductor pairs ensure a certain protection against radiated electromagnetic interference.

The protection against radiated EMI is essentially important in case of communication cables because of the sensibility of the signals in them. Every solid copper conductor in the cable has a polyethylene (PE) insulation each. *Fig. 5.6.* shows the internal structure of the UTP cable (*Fig. 5.6.a*) and a cable with its connectors ready for installation (*Fig. 5.6.b*).



a) *b*)

Fig. 5.6. UTP cables

A CAT6 UTP 4x2x0,5 type cable can be used e.g. for the broad band internet access and to transport the signal of surveillance cameras and other appliances of the security system. This cable contain four twisted pairs (*Fig. 5.6.a*) with a conductor cross-section of 0,5 mm^2.

Wave impedance and data transmission capability of the UTP cables:
- CAT1 – 2 Mb/s telephone cable (voice transmission, 2 pairs);
- CAT2 – 84-113 Ω, 4 Mbit/s, (Local Talk);
- CAT3 – 100 Ω, 10 Mbit/s, 100 m (Ethernet);
- CAT4 – 100 Ω, 20 Mbit/s, 100 m (16 Mbit/s Token Ring);
- CAT5 – 100 Ω, 100 Mbit/s, 100 m (Fast Ethernet);
- CAT5e – 1000 Mb/s, 100 m;
- CAT6 – 100 Ω, 1000 Mb/s, 100 m;
- CAT7 – 100 Ω, 1200 Mbit/s, 100 m.

The F/UTP (FTP) cables have a metal foil shielding and are used for 10GBaseT applications, while S/UTP (STP) cables have a braid screen shielding. SF/UTP cables have both foil and braid screen shielding and ensure a very good EMI protection.

YCYM cable

The YCYM cable contain twisted pairs as well with solid copper conductor with diameter of 0.8 mm and PVC insulation, aluminum shielding and PVC sheath (*Fig. 5.7*).

The “Y” in the marking of the cable means PVC insulation. One “Y” letter refers to the PVC core insulation of the core and the other “Y” letter refers to the PVC sheath. Letter “C” refers to the coaxial copper conductor.

Fig. 5.7. YCYM cable [5.2]

YCYM cables have application in the system technology (KNX) of buildings for the control of e.g.:
- Lighting;
- heating/cooling;
- ventilating;
- energy management;
- opening/closing doors/windows/shadings;
- transmission of other control signals.

Ribbon cable

The ribbon cable is one of the most simple cable types (*Fig. 5.8*). Because of its simplicity it is not protected against radiated disturbances, however when connecting one or more conductors (or every second) in the cable to the ground, then shielding effect can be achieved.

Fig. 5.8. Ribbon cable

There are more communication cables types, however since this chapter focuses on power cables there is no place for a comprehensive overview of communication cables here.

5.2 Electrical power conductors and cables

In Anglo-Saxon and other countries overhead lines without insulating sheath belong to the group of cables as well. In Hungary only insulated cables are called “cable” in the field of electrical engineering. Overhead cables are suspended overhead between poles or steel towers. These aerial cables consist of a number of conductors, usually of aluminum or copper twisted (stranded) together in concentric layers (*Fig. 5.9*).

Stranding gives the cable flexibility and because aerial cables are frequently subjected to severe environmental stresses, alloys of aluminum or copper are sometimes used to increase the mechanical strength of the cable, although at some detriment to its electrical conductivity. According to the Hungarian terminology power lines can be

- overhead lines, i.e.
  - un-insulated (bare) overhead lines or
  - insulated overhead lines;
- insulated conductors;
- underground cables;
- cable like conductors;
- busbars.

Fig. 5.9. Stranded overhead cables

Now in Hungary only insulated overhead cables are installed in the public low voltage distribution grids. Color marking of three-phase busbars:

- L1 line conductor – green;
- L2 line conductor – yellow;
- L3 line conductor – red.

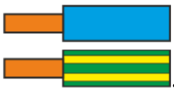
Color marking of power conductors

The international standard **IEC 60446:2007 Basic and safety principles for man-machine interface, marking and identification - Identification of equipment terminals, conductor terminations and conductors**, defines basic safety principles for identifying electrical conductors by colors or numerals [5.3].

Color of the insulation of the conductors in three-phase circuits:

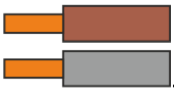
- L1 line conductor – brown
- L2 line conductor – black
- L3 line conductor – grey

- N neutral conductor – blue
- PE conductor – green/yellow



In case of two or three core single-phase cables the line (L) is marked with brown color. PE is the abbreviation of Protective Earth.

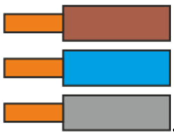
For a two-wire unearthed DC system:
- Positive – brown
- Negative – grey



For a two-wire earthed (of a negative earthed) DC circuit system:
- Positive – brown
- Negative – blue

For a two-wire earthed (of a positive grounded) DC circuit system:
- Positive – blue
- Negative – grey

Three-wire earthed DC circuit system:
- Positive – brown
- Mid-wire – blue
- Negative – grey



The above color marking can be observed in case of the simple power cable shown in *Fig. 5.10* and *Fig. 5.11*.

The standard (Harmonized Document) **HD 361 S3/2000 System for cable designation** specifies the designation system for harmonized power cables and cords, of rated voltage up to and including 450/750 V. This standard gives a lot of technical detail about the cable in a very short code as follows:

Identification of designation
H harmonized type
A recognized, national type.

Rated voltage V_0/V
01 100 / 100 V
03 300 / 300 V
05 300 / 500 V
07 450 / 750 V.

Insulation and sheath materials
B Ethylene-propylene rubber (EPR) +90°C
B2 Ethylene-propylene rubber (EPR) hardened
B3 Butyl rubber
E Polyethylene (PE)
E2 Polyethylene, high density
E4 Poly-tetrafluorethylene

E5 Ethylene propylene rubber
E6 Ethylene tetrafluorethylene
E7 Polypropylene
G Ethylene-vinylacetate copolymer (EVA)
J Glass fiber braiding
J2 Glass fiber wrapping
M Mineral insulations
N Chloroprene rubber
N2 Chloroprene rubber (CR) welding cable
N4 Chlorinated polyethylene
N5 Nitril-rubber
N6 Fluorinated rubber
N7 PVC nitril rubber compound
N8 Polychloroprene rubber, water resistant
P Impregnated paper insulation
Q Polyurethane (PUR)
Q2 Polyethyleneterephthalate
Q3 Polystyrole
Q4 Polyamide
Q5 Polyamide
Q6 Polyvinylidene fluoride
R Natural or synthetic Rubber (NR, SR)
S Silicone rubber (SIR)
T Textile braiding
T2 Textile braiding with flame retardant compound
T3 Textile conductor wrapping or tape
T4 Textile conductor wrapping or tape, flame retardant
T5 Corrosion protection
T6 Textile braiding over individual conductor or cable
V Polyvinyl chloride (PVC)
V2 Polyvinyl chloride soft, heat resistant (PVC+900°C)
V3 Polyvinyl chloride soft, cold resistant (flexible at low temperatures)
V4 Polyvinyl chloride soft (PVC) cross linked
V5 Polyvinyl chloride (PVC) increased oil resistant
X Cross-linked polyethylene (XPE)
Z Halogen-free cross linked compound (LSZH)
Z1 Halogen-free extrudable thermoplastic compound.

Structural elements
- Concentric conductors
A Concentric aluminum conductor
A6 Concentric aluminum conductor, meander shaped
C Concentric copper conductor
C6 Concentric copper conductor, meander shaped
C9 Divided concentric copper conductor.
- Screen
A7 Aluminum screen
A8 Aluminum screen, individual conductors
C4 Copper braid screen
C5 Copper braid screen, individual conductors

C7 Copper tape screen
C8 Copper tape screen, individual conductors
D Screen of one or more thin steel tapes
- Armoring
Z2 Armoring of round steel wires
Z3 Armoring of flat steel wires
Z4 Armoring of steel tape
Z5 Braiding of steel wires
Z6 Supporting braid of steel wires
Z7 Armoring of sectional steel wires
Y2 Armoring of round aluminum wires
Y3 Armoring of flat aluminum wires
Y5 Armoring of special materials
Y6 Armoring of steel wires and/or tape and copper wires.

Conductor material
w/o designation copper
- A Aluminum
- Z Special material and/or special shape.

Special design feature
- Supporting structures
D2 Textile or steel wires over cable conductor
D3 Textile elements stranded in conductor cable
D4 Self-supporting cables and wires
D5 Central conductor element.
- Special versions
w/o designation round cable construction
H Flat types as separable cables with or without jacket
H2 Flat cables not separable
H3 Building cable, flat webbed
H4 Multi conductor flat cable with one plain conductor
H5 Two or more single conductor stranded, non-jacket
H6 Flat cables with 3 or more conductors
H7 Cable with two-jacket extruded insulation
H8 Coil conductor.

Conductor type
- D Fine wire stranded for welding cables
- E Extra fine wire stranded for welding cables.
Cables
- F Fine wire stranded for flexible cables
- H Extra fine wire stranded for flexible cables
- K Fine wire stranded conductor for fixed installation
- M Milliken conductor for fixed installation
- R Conductor of multi stranded wires
- S Sector shaped conductor of multi stranded wires
- U Round conductor of single wire
- W Sector-shaped conductor of single wire
- Y Tinsel conductor

- Z Conductor of special material.

Number of cores

Protective conductor
X Without protective conductor
G With protective conductor green-yellow
U Round single wire.

10 Conductor cross section

Examples

H05V2-K (in *Fig. 5.1*):
H harmonized type
05 rated voltage: 300/500 volt
V2 material of the insulation: polyvinyl chloride soft, heat resistant
round conductor
- copper conductor
K stranded wire.

H03VVH2-F multicore supply cable (in *Fig. 5.10*):
H harmonized type
03 rated voltage: 300/300 volt
V material of the insulation: polyvinyl chloride soft, heat resistant
V non-metallic PVC non-metallic cover
H2 Flat non separable cable
no designation means round conductor
- copper conductor
F fine wire core.

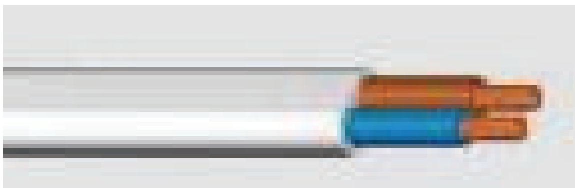


Fig. 5.10. Flat H03VVH2-F (MT) cable

H05RR-F multicore supply cable (in *Fig. 5.11*):
H harmonized type
05 rated voltage: 300/500 volt
R material of the insulation: Ethylene prolypropylene rubber
R non-metallic cover: Ethylene prolypropylene rubber
R non-metallic cover: Ethylene prolypropylene rubber
no designation means round conductor
- copper conductor
F fine wire core.

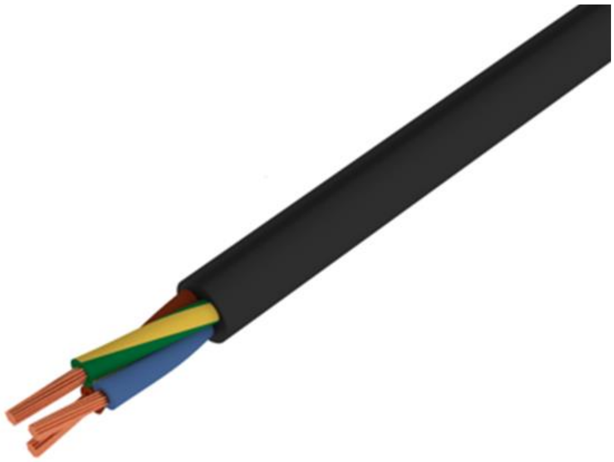


Fig. 5.11. Multi core supply cable (H05RR-F)

Mainly in cities where lack of space or safety considerations preclude the use of overhead lines electric power cables are installed underground. In Hungary the definition of cable is: Cables have one or more insulated conductors and are protected against the intrusion of water by sheath, against mechanical impacts by armor and against corrosion by sheath. *Table 5.2* lists the markings of insulated cables according to the German standard DIN VDE 0289. In Hungary this German marking is widely used.

Table 5.2. Markings of insulated cables according to the standard DIN VDE 0289

N	**„Standard" (Norm) underground cable**
A	**Aluminum conductor (copper is default with no marking)**
Y	**PVC insulation**
2X	**Crosslinked polyethylene (XLPE) insulation**
HX	**Crosslinked, halogen-free polymer insulation**
C	Coaxial copper conductor
CW	Wavy coaxial copper conductor
CE	Coaxial copper conductor on every conductor of the cable with 3 conductors
S	Copper shielding
SE	Copper shielding on every conductor of the cable with 3 conductors
K	Lead sheath
(F)	Longitudinally water-tight shielding
Y	**PVC protective sheath the between shielding or coaxial conductor and armor**
F	**Armor of galvanized flat steel trip**
R	**Armor of galvanized round steel conductor**
Y	**PVC sheath**
2Y	**PE sheath**
H	Thermoplastic, halogen-free polymer sheath
HX	Crosslinked, halogen-free polymer sheath
RE	Single round conductor
RM	Multiple round conductor
SE	Single sector conductor
SM	Multiple sector conductor
-FE	Fire-proof insulation
-J	**With green-yellow insulated conductor**
-O	**Without green-yellow insulated conductor**

Examples

The cable shown in *Fig. 5.12* is installed directly under the plastering on the wall. That is why the Hungarian name of this cable is “MM wall cable”. Letter “M” refers to the PVC insulation in Hungary. The German name of it is YMSteg.

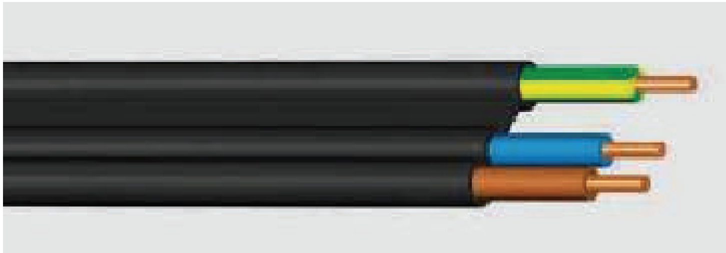


Fig. 5.12. YMSteg cable (MM wall)

Several arts of MT cables have wide-spread application mainly installed outside the wall. The application of this cable types is the supply of low voltage low power portable household appliances excluding toys.

In *Fig. 5.13* a “cable-like conductor” is shown which can already laid underground, however it has no armor. It has five conductors: Three line conductors (L1, L2, L3) with PVC insulation of black, brown and grey colors, the neutral conductor (N) with blue insulation and the protective earth (PE) conductor with green-yellow insulation.

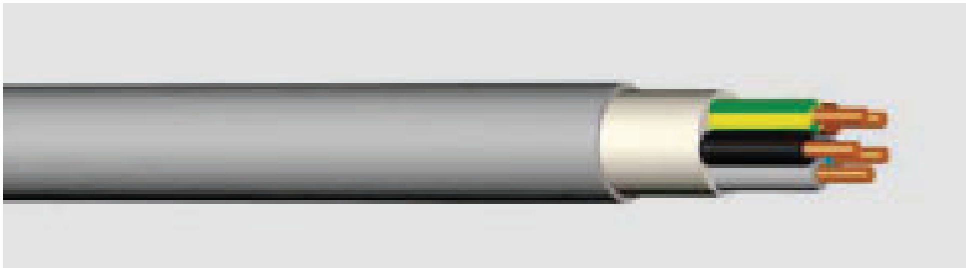


Fig. 5.13. Cable-like conductor (NYM-J)

The cable with the marking **NYY-J 4x35 SM 0,6/1 kV** is a standard (N) low voltage cable with 4 copper sector conductors (SM) with cross-section of 35 mm^2, with PVC insulation (Y) and PVC sheath (Y) with a green-yellow insulated conductor (-J) for voltages of V_0 = 0.6 kV, V = 1 kV.

This cable is shown in *Fig. 5.14* where the layers are:
1 copper conductors with sector cross-section;
2 PVC insulation;
3 PVC filling layer;
4 PVC sheath.

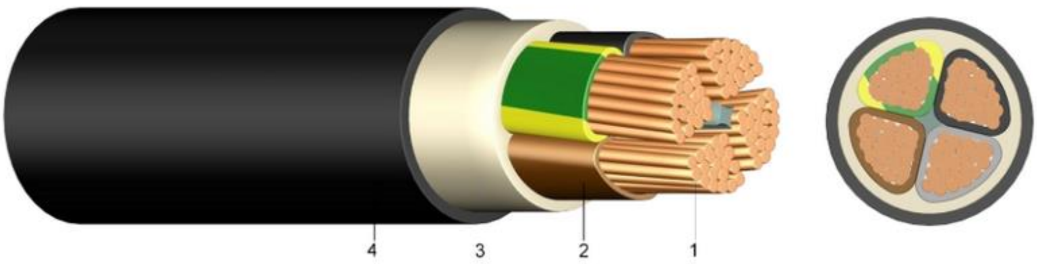


Fig. 5.14. NYY-J 4x35 SM 0.6/1 kV cable (source: Elektrobagoly)

The cable with the marking **NA2XS2Y 1x150 RE/25 12/20 kV** is a standard (N) medium voltage cable (V_0 = 12 kV, V = 20 kV) with a single, round (RE), aluminum (A) conductor with the cross-section of 150 mm^2, with reticulated polyethylene insulation (2X) and PE sheath (2Y).

This cable is shown in *Fig. 5.15* where the layers are:

1 Aluminum conductor with round cross-section;
2 internal semiconductor layer;
3 reticulated polyethylene insulation;
4 external semiconductor layer;
5 copper conductor shielding with copper strip fixing with a total cross-section of 25 mm^2;
6 polyethylene outer sheath.

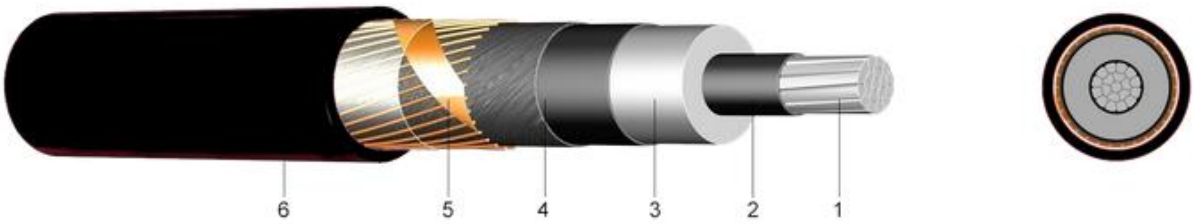


Fig. 5.15. NA2XS2Y 1x150 RE/25 12/20 kV cable [5.4]

It can be seen that, in case of low voltage cables PVC is applied as insulation, but in case of high voltage cable (MV and HV) the crosslinked polyethylene is preferred.

In case of power cables the shielding protects in general not the cable itself, but its environment against the electromagnetic (EM) field of the power cable. It is a general practice to install shielded power cables between frequency converter and the motors controlled by them to protect the sensible electronic devices near to the cable which would radiate high frequency EM disturbances without the shielding.

YSLY cable

The YSLY cable (*Fig. 5.16*) is a power cable type as well, however its main task is to transmit signals for signaling and operating purposes. Thus it is a control cable for general use in industrial systems. It is resistant against oil drops and vibration, thus it is appropriate for being connected to machines.

Fig. 5.16. YSLY cable (source: Kábel Ring Kft.)

Structure of the YSLY cable:
- stranded copper conductor (Class5 DIN EN 60228);
- PVC insulation (marking according to HD 308 S2);
- grey, oil-proof PVC outer sheath.

Solar cable

In case of some application of cables special considerations have to be taken into account related to the construction of the cable, like in case of strong vibration already mentioned above.

One of these special stresses burdening the cable is the radiation of the Sun. Solar radiation can rapidly age some materials, especially artificial materials. Thus when designing a photovoltaic (PV) unit composed by solar cell modules, the cables laid onto the roof of a building or at other sites exposed to direct sunlight cables withstanding ultraviolet (UV) radiation have to be chosen. Such an ultraviolet-proof cable is shown in *Fig. 5.17*.

Fig. 5.17. UV protected solar cable

On the sheath of the cable the following information has to be indicated:
- Type;
- nominal voltage in kV;
- number and cross-section of conductors;
- form and character of conductors;
- cross-section of the shielding or coaxial cable if necessary.

Underground cables have to be laid into a cable trench in a depth between 70 and 80 cm with cable warning tape laid above the cable at a depth of 35 cm as shown in *Fig. 5.18*.

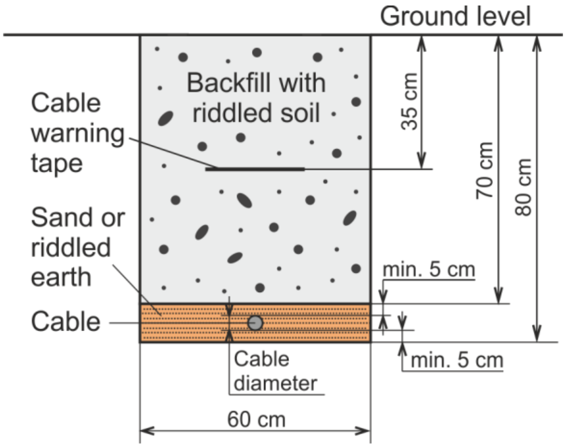


Fig. 5.18. Cross section of a cable trench

5.2.1 Reference methods of installation

Maximum current-carrying capacity of a cable depends on the cooling circumstances of the cable. These circumstances depend on the method of installation of the cable in turn. Standard (reference) cable methods of installation are stipulated by the international standard **IEC 60364-5-52:2009** [5.5] (IEC – International Electrotechnical Committee).

Standard methods of installation are:

A1 Insulated conductors or single-core cables in conduit in a thermally insulated wall (*Fig. 5.19*).

A2 Multi-core cables in conduit in a thermally insulated wall.

B1 Insulated conductors or single-core cables in conduit on a wooden, or masonry wall or spaced less than 0.3 x conduit diameter from it (*Fig. 5.20.a*).

B2 Multi-core cable in conduit on a wooden, or masonry wall or spaced less than 0.3 x conduit diameter from it (*Fig. 5.20.b*).

C Single-core or multi-core cables fixed on, or spaced less than 0.3 x cable diameter from a wooden wall.

D Single or multi-core cables in conduit or in cable ducting in the ground.

E Single-core or multi-core cables in air on perforated tray run horizontally or vertically.

F Several cables or conductors with one conductor with sheath contacting each-other mounted in the air.

G Bare or insulated single conductors with sheath on insulators not contacting each-other (mounted with air-gaps) mounted in the air (apart from the wall).

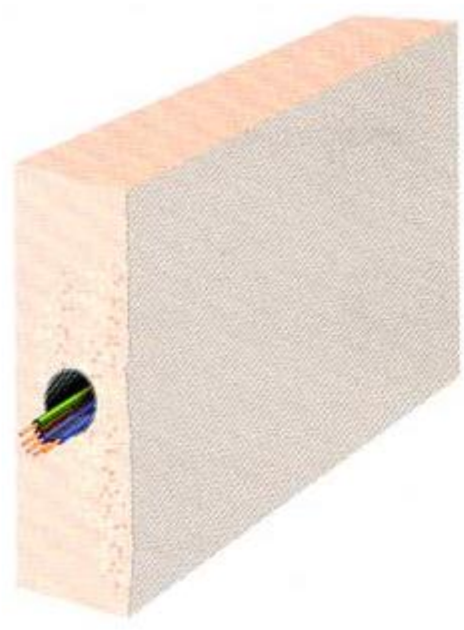
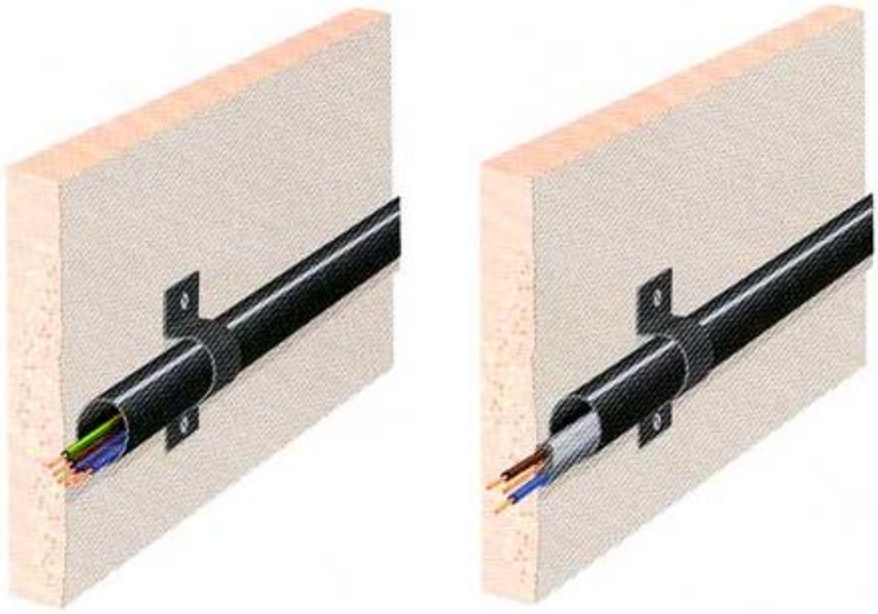


Fig. 5.19. Insulated conductors in conduit in a thermally insulated wall



a) *b*)

Fig. 5.20. Insulated conductors without sheath (*a*) and with sheath (*b*) in conduit on a wooden, or masonry wall

5.2.2 Protective conduits

Protective conduits protect conductors/cables installed into them from mechanical impacts. Conductors/cables in them can be replaced after installation. Material of conduits can be

- metal, e.g.
    - steel tube,
    - iron sheath tubes,

- aluminum tubes;
- synthetic material (*Fig. 5.21.a*).

Material of plastic tubes is hard PVC. Plastic protective tubes are not allowed to be used in rooms containing highly flammable and explosive material and where the temperature is durably below -15°C or above 55°C. Hard PVC is combustible but it does not feed fire, thus it is self-quenching.

Arts of plastic protective tubes in Hungary are
- MÜ I – with thick wall;
- MÜ II – with medium thick wall;
- MÜ III – with thin wall;
- corrugated plastic pipe (*Fig. 5.21.b*).

Hard PVC contains 2-3% softener, resists acids, bases and oils, it decomposes above 200°C. Protective pipes can be installed
- on walls, flush-mounted, on walls, in ceilings, concrete, in lattices;
- in dry rooms;
- in rooms with vaporous, contaminated atmosphere;
- in rooms with intermittently wet, vaporous, steamy atmosphere;
- in warm (≤60°C) environment;
- in caustic environment;
- in rooms containing materials of fire hazard class C.

Internal diameter of plastic protective tubes ranges between 15.4 mm and 48.8 mm. The extension of rigid conduits can be realized by sleeves or bent pipes.

a)

b)

Fig. 5.21. Electric conduits made of PVC

If conductors with a single layer of insulation are installed then in most cases a second insulation layer has to be ensured e.g. in case of installing the conductors into walls (*Fig. 5.22*), sealing (*Fig. 5.23*) or under the ground (*Fig. 5.24*).

Fig. 5.22. Conduits installed into the wall

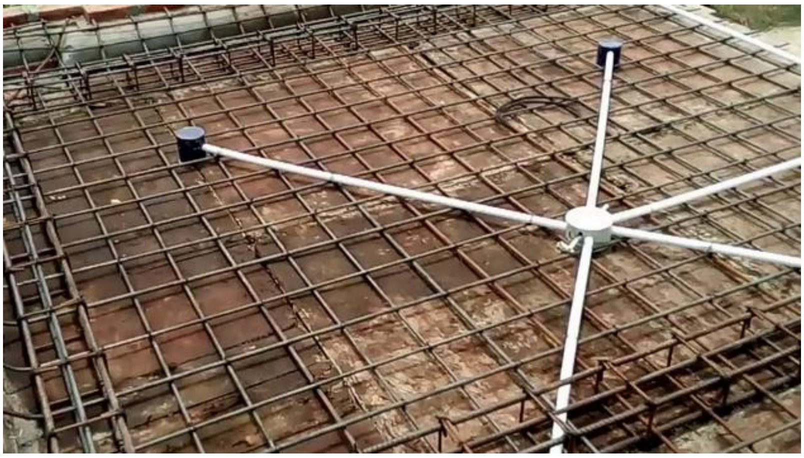


Fig. 5.23. Conduits installed into the concrete sealing

Fig. 5.24. Conduits installed underground

5.2.3 Cable trunkings, ducts, trays

Cable trunkings partly protect the cables installed inside them, however they have the task to make the path of the electric energy supply more decorative, since they are installed outside of the wall e.g. of offices. In *Fig. 5.25* trunkings with white color are shown. *Fig. 5.26* shows a cable trunking with switches and sockets usually installed in offices.

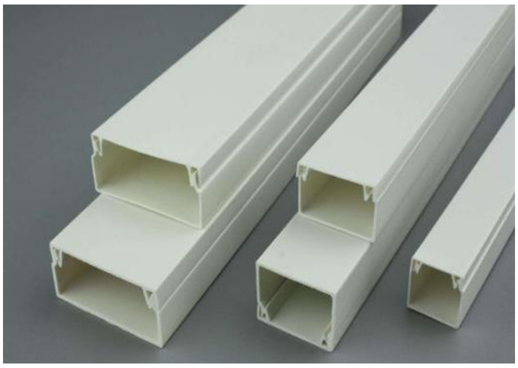
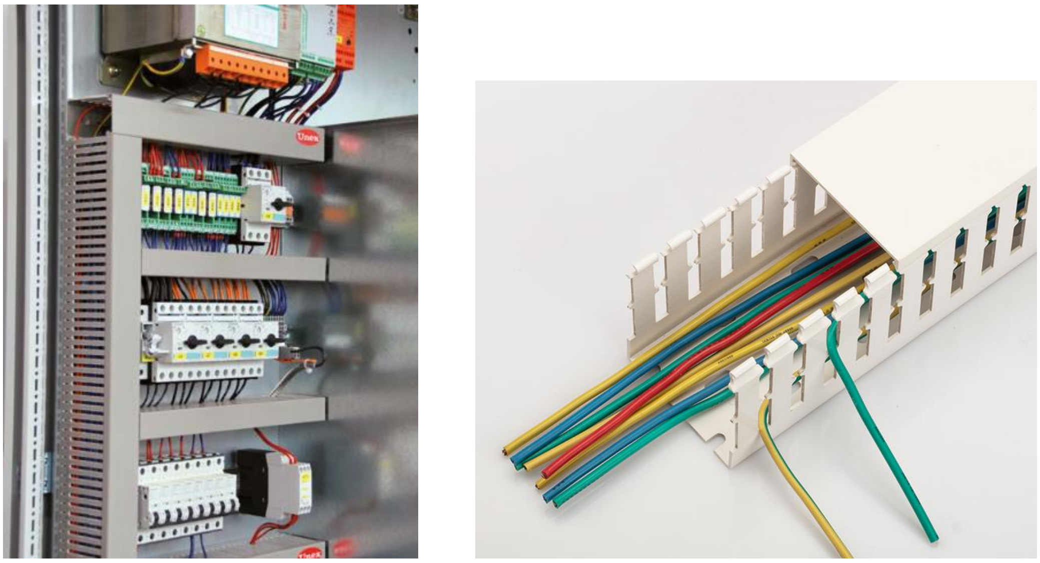


Fig. 5.25. Cable trunkings

Fig. 5.26. Cable trunking with switches and sockets

Inside cabinets slotted cable trunkings are used enables the exiting of the conductors from the trunking (*Fig. 5.27.a* and *b*). In *Fig. 5.28* cable trays are shown under the sealing of an industrial facility supporting cables laid close to each-other.



a) *b*)

Fig. 5.27. Slotted cable trunkings inside a cabinet

Fig. 5.28. Cable trays under the sealing of a facility

5.2.4 Current-carrying capacity of conductors

The current-carrying capacity of copper conductors with different standard cross-sections for the standard methods of installation according to the standard IEC 60364-5-52:2009 [5.5] is listed in *Table 5.3*.

Table 5.3. Current-carrying capacity of copper conductors

A vezető keresztmetszete mm^2	Megengedett terhelés „A” www.novill.hu						Biztosító betétek
	A csoport		B csoport		C csoport		
	Cu	Al	Cu	Al	Cu	Al	
0.5	7	-	10	-	13	-	-
0,75	10	-	13	-	16	-	-
1	12	-	16	-	20	-	6
1.5	16	13	20	17	25	22	10
2.5	21	16	27	21	34	27	16
4	27	21	36	29	45	35	20
6	35	27	47	37	57	45	25
10	48	36	65	51	78	61	35
16	63	51	87	68	104	82	50
25	83	65	115	90	137	107	63
35	110	86	143	112	168	132	80
50	140	110	178	140	210	165	100
70	175	140	220	173	260	205	125
95	215	175	265	210	310	245	160
120	255	205	310	245	365	285	200
150	295	235	355	280	415	330	250
185	340	270	405	320	475	375	315
240	400	300	480	380	560	440	400
300	470	375	555	435	645	510	500
400	570	455	690	540	770	605	630
500	660	530	820	640	880	690	-

Conductor cross section (mm^2)		A1	A2	B1	B2	C	D
0,5	.						
0,75	.						
1	.						

1,5		13,5	13	15,5	15	17,5	18
2,5		18	17,5	21	20	24	24
4		24	23	28	27	32	31
6		31	29	36	34	41	39
10		42	39	50	46	57	52
16		56	52	68	62	76	67
25		73	68	89	80	96	86
35		89	83	110	99	119	103
50		108	99	134	118	144	122
70		136	125	171	149	184	151
95		164	150	207	179	223	279
120		188	172	239	206	259	203
150		216	196	-	-	299	230
185		245	223	-	-	341	256
240		286	261	-	-	403	297
300		328	298	-	-	464	336

American Wire Gauge

In the United States of America and in some other countries standard wire cross sections are given according to the so-called American Wire Gauge (AWG). *Table 5.4* provides a cross-reference between these two standards, showing the closest metric equivalents to each Gauge.

Table 5.4. Certain equivalent AWG and mm^2 values

AWG	**Actual cross-section (mm^2)**	**Closest equivalent metric cable size (mm^2)**
22	0.33	0.35
21	0.41	0.35
20	0.52	0.50
19	0.65	0.75
18	0.82	1.0
17	1.04	1.0
16	1.31	1.5
15	1.65	1.5
14	2.08	2.0
13	2.63	2.5
12	3.31	4
11	4.17	4
10	5.26	6
9	6.63	6
8	8.36	10

7	10.55	10
6	13.29	16
5	16.76	16
4	21.14	25
3	26.65	25
2	33.61	35
1	42.39	50
0 (1/0)	53.46	50
00 (2/0)	67.40	70
000 (3/0)	84.97	95
0000 (4/0)	107.16	120

5.3 Rating of power cables

Rating of a cable means the selection of the optimum and economical size – cross-section – of the conductor(s). Apart from this cable rating can include the selection of other characteristics of the cable, like the art of its insulation and its resistance to certain stresses. This activity is a part of the design.Rating of power conductors is necessary if

- a new electric network or a part of it is built or
- an existing network is extended or renovated.

Considerationsduring this kind of rating are:

1) Technological aspects;
2) personal safety aspects;
3) economic aspects,
4) legal aspects.

1) Technological aspects

Meeting technological aspects meansthat, the electric energy supply at the connection point of the consumer conforms with the quality requirements on one side and with continuity requirements on the other side. Technological considerations are:

- Voltage drop along the supply cable – a voltage quality aspect;
- current-carrying capacity – heating-up of the cable as a result of the sustained current under the given circumstances;
- short circuit current-carrying capacity – heating-up of the cable as a result of the short circuit current;
- mechanical loads as a result of the sustained current, i.e. during normal operation;
- mechanical loads as a result of the short-circuit current.

2) Personal safety aspects

Personal safety aspects include the personal safety, the reliability of the electricity supply and the protection against electric shock.

- Meeting the requirements related to the reliability means choosing the cable type and installation method appropriate for the character and fire class at the given site of application.
- Protection against electric shock includes protective measures preventing accidents resulting from getting into contact with normally live or no-live but exposed parts of electric appliances which can become live in case of faults. Meeting the regulation of the protection against electric shock ensure the protection of people during the operation of the cables.

3) Economic aspects

Meeting economic aspects mean to attempt achieving minimum investment and operation costs at the same time and achieving short installation time and long life-time.

4) Legal aspects

Meeting legal prescriptions, decrees and relevant standards enables the legal judgment of possible legal disputes.

A part of the above requirements has always to be considered, while other requirements will be met automatically in case of the cable type appropriate for the given purpose.

Main part of these requirements relate to the necessary minimum cross-section of the cable, thus the actual cross-section of the cable is that meeting all the requirements arising during the dimensioning.

5.3.1 Voltage drop along a cable

This subject – Electrical Power Engineering I – deals with the cable rating considerations ensuring that, the voltage at the consumer remains within the standard range during the operation of the consumer and with the considerations of the protection against electric shock.

Electric consumers are dimensioned for their rated voltages a deviation from whichcan reduce the performance of the consumer, or can cause its malfunction, damage, crash or consequence damages. The active method of maintaining the voltage within the standard range is voltage regulation and its passive method is the rating of the supply cable for voltage drop. *Table 5.5* lists the behavior of certain consumers at operational voltages (V_o) different from their rated voltage (V_n).

Table 5.5. Behavior of certain consumers at voltages different from their rated voltage

Consumer	$V_o < V_n$	$V_o > V_n$
Fluorescent lamp	Ignition problemsat 0.85 $\cdot V_n$ shorter life-time	
Electric heating	The required temperature will be achieved later	Dangerous overheating
Electronic devices (e.g. TV sets)		Shorter life-time
Asynchronous motors	Reduced torque, speed, higher current, overheated coil	Higher magnetizing current, overheated core

Allowed tolerances in case of the standard voltage:
- On the low voltage network: ± 7.5%,
- on high voltage networks: +15%, -10%.

Electricity consumers are usually installed at a certaindistance from the available electric energy source (or sources). Electric energy is transported over this distance by the supply cable. In most cases the actual length (l) of the supply cable is higher than the real distance between the supply point and the consumer.

This supply cable has series resistance, inductance and parallel capacitance between the conductors and between each conductor and the earth. Current flowing through the cable causes voltage difference along its resistance as well as along its inductance.

In case of short (l < 50 km) conductors/power lines the single-phase equivalent circuit shown in *Fig. 5.31* applies.

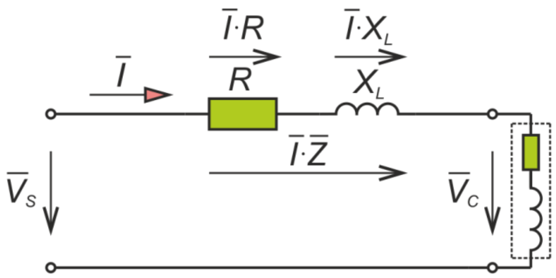


Fig. 5.31. Single-phase equivalent circuit of short conductors

According to its definition voltage drop is the difference between the absolute values of the source voltage $\bar{V}_S$ and the voltage across the load $\bar{V}_C$, source, i.e.

$$\Delta V = \left|\bar{V}_S\right| - \left|\bar{V}_C\right|. \tag{5.4}$$

Voltage drop can be measured on the impedance of the supply cable which impedance is

$$\bar{Z} = R + jX_L. \tag{5.5}$$

Since the impedance $\bar{Z}$ of the cable is not known at the beginning of the cable dimensioning, the current of the circuit is determined by the impedance $\bar{Z}_C$ of the consumer which is much higher than the impedance $\bar{Z}$ of the cable. Thus this is an acceptable negligence with no significant effect on the result. Apart from this the voltage $\bar{V}_C$ of the consumer is not known as well, thus its current is calculated with its rated voltage $\bar{V}_n$ which means an acceptable negligence again.

Applying Kirchhoff's mash rule for the circuit in *Fig. 5.31*

$$\bar{V}_S - \bar{V}_C - \bar{I}(R + jX_L) = 0, \tag{5.6}$$

the voltage drop is

$$\Delta\bar{V} = \bar{V}_S - \bar{V}_C = \bar{I}(R + jX_L). \tag{5.7}$$

The current $\bar{I}$ can be expressed as the sum of its active I_W and reactive I_R components

$$\Delta\bar{V} = (I_W + jI_R)\cdot(R + jX_L), \tag{5.8}$$

after performing the multiplication the voltage drop is

$$\Delta\bar{V} = I_W R + jI_R R + jI_W X_L - I_R X_L \tag{5.9}$$

and after a rearrangement of the equation

$$\Delta\bar{V} = (I_W R - I_R X_L) + j(I_R R + I_W X_L), \tag{5.10}$$

where the real component is

$$I_W R - I_R X_L = \Delta V_{lo} \tag{5.11}$$

of voltage drop is called in the practice **longitudinal voltage drop** and the component

$$I_R R + I_W X_L = \Delta V_{tr} \tag{5.12}$$

is called transversal voltage drop. The phasor diagram visualising the above is shown in *Fig. 5.32*. The phasor diagram is not proportional to the voltages and currents of a typical case for making the components of ΔV more expressive in the figure.

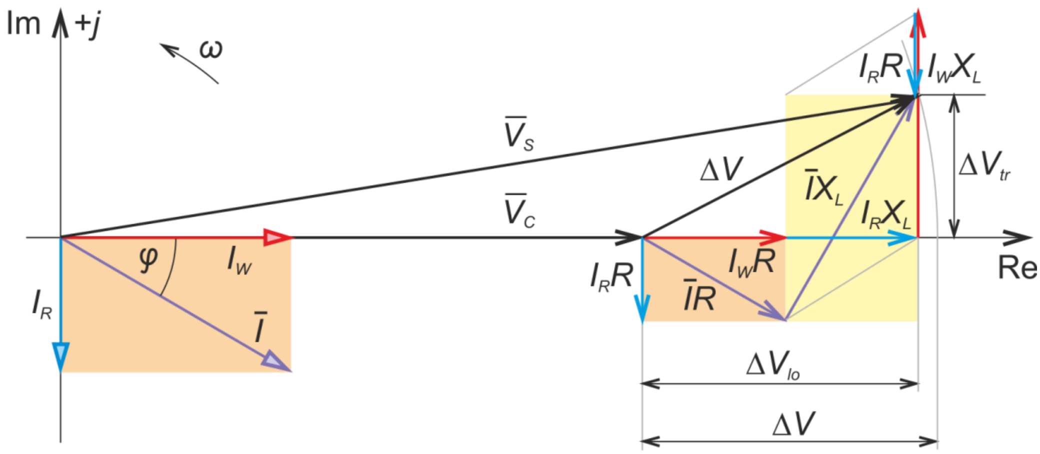


Fig. 5.32. Phasor diagram of the voltage drop

As a general rule φ phase angle between current and voltage of a conductor is low, then

$$\Delta V \approx \Delta V_{lo}, \tag{5.13}$$

i.e. voltage drop taken into account in the practice along the conductor equals tothe longitudinal component of the voltage drop. In the field of power engineering this is a generally applied basic rule when dimensioning internal networks.

In *Fig. 5.32* it can be observed that, the component $I_W R$ appearing in case of direct current (DC) transmission as well as the other component $I_R X_L$ has to be added in case of alternating current (AC) transmission and both add up the longitudinal voltage drop. If the current is lagging when the load has an inductive character and the component I_R is negative, then the two real current components add up and if the current is leading, then the capacitive one has to be subtracted.

In case of rating cables installed in internal grids then X_L can be neglected because of the rather short cables lengths, thus $I_R X_L$ can be neglected as well.Thus since $R/X_L < 1$,

$$\boxed{\Delta V = I_W \cdot R.} \tag{5.14}$$

is used for the calculation of the voltage drop along the supply cables in case of internal networks. In the practice the voltage drop is marked with *e* which equals to

$$e = \left|\overline{V}_S\right| - \left|\overline{V}_C\right| \quad \text{(V)} \tag{5.15}$$

on the basis of (5.4) and expressed in unit volt and its percentage value is

$$\varepsilon = \frac{e}{\left|\overline{V}_S\right|} \cdot 100 \quad (\%). \tag{5.16}$$

In case of direct current (DC) circuits and single-phase alternating current (AC) circuits the current supplying the consumer flows through a path twice as long as the distance between the supply point and the consumer: Once from the supply point to the consumer on the positive or the line (L) conductor, then from the consumer back to the supply point through the negative or neutral (N) conductor. Voltage drop *e* equals two times the voltage on one conductor, thus the relevant voltage drop *e'* on one conductor equals to

$$\boxed{e' = \frac{e}{2} = \frac{\varepsilon}{100} \cdot \frac{V_n}{2} \quad \text{(V)}} \tag{5.17}$$

In case of three-phase alternating current circuits no current flows through the neutral conductor, neither if it exists, if the three currents are symmetrical and no voltage can be measured on it only on the line conductors. The relevant voltage drop *e'* appearing on the line conductorsis

$$\boxed{e' = \frac{e}{\sqrt{3}} = \frac{\varepsilon}{100} \cdot \frac{V_n}{\sqrt{3}} \quad \text{(V)}} \tag{5.18}$$

For three-phasecircuits V_n stands for the line voltage. In case of asymmetrical three-phase circuits, when current flows onthe neutral conductor as well and the extent of the asymmetry is not known the voltage *e'* can be calculated with

$$e' = 0.75 \frac{\varepsilon}{100} \cdot \frac{V_n}{\sqrt{3}} \quad \text{(V)}\,. \tag{5.19}$$

The voltage drop expressed with *e'* is

$$e' = I_w \rho \frac{l}{A} \tag{5.20}$$

and the necessary minimum cross-section of the cable is

$$\boxed{A_{\min} = \frac{\rho}{e'} \cdot I_w l \quad (\text{mm}^2)} \tag{5.21}$$

Table 5.6 contains allowed percentage voltage drop values stipulated by the Hungarian standard MSZ 447 [6.1] for some cases.

Table 5.6. Allowed percentage voltage drop values [5.7]

Part of the grid		Maximum voltage drop allowed in residential buildings and usually applied in industrial facilities (%)
Sum of the voltage drops on the connecting cable and the main supply cable		1
Total on the vertical and horizontal branch cables		1
On the grid beyond the meter	in general	1.5
	in case of motors alone	3

5.3.2 Power loss in a cable

A current flowing through a cable causes power loss in the conductors emitting it to the environment as thermal energy. Considering energy supply this loss has to be minimized.

Apart from the power P_C of the consumer the power P_S put by the source out covers the P power loss of the supply cable as well, as

$$P = P_S - P_C \text{ (W)}. \tag{5.22}$$

Proportion of the power loss compared to the total power consumed is given by the α percentage power loss ratio as

$$\alpha = \frac{P}{\sum_k P_{Ck}} \cdot 100 \quad (\%)\,, \tag{5.23}$$

where $P_{CT} = \sum_k P_{Ck}$ a is the sum of the power values of all of the consumers. In case of direct current grids

$$\varepsilon = \alpha. \tag{5.24}$$

In case of DC circuits and single-phase AC circuits

$$P = I^2(2R)\,, \tag{5.25}$$

where I is the rated current of the consumer and R is the resistance of one conductor.

Relevant power lossv' on a conductor is

$$v' = I^2 R = \frac{P}{2} = \frac{\alpha}{100} \cdot \frac{\sum P_{Ck}}{2} \quad \text{(W)}\,. \tag{5.26}$$

In case of symmetrical three-phase supply the relevant power loss is

$$v' = \frac{P_V}{3} = \frac{\alpha}{100} \cdot \frac{\sum P_{Ck}}{3} \quad (\text{W}) \, . \tag{5.27}$$

Determining the consideration of the cable rating

As preconditions known are the following data of the consumer: V, I, $\cos\varphi$ and the conductor is taken into account with its resistance.

The relevant voltage drop is

$$e' = I_W R_V + I_M X_V = I_W R_V = I R_V \cos\varphi \tag{5.28}$$

and the relevant power loss is

$$v' = I^2 R_V \, . \tag{5.29}$$

In case of single phase supply (I)

$$e' = \frac{\varepsilon}{100} \cdot \frac{V}{2} = I \left(\rho \frac{l}{A} \right) \cos\varphi \tag{5.30}$$

and (II)

$$v' = \frac{\alpha}{100} \cdot \frac{P}{2} = \frac{\alpha}{100} \cdot \frac{VI \cos\varphi}{2} = I^2 \left(\rho \frac{l}{A} \right) . \tag{5.31}$$

How high is the $\cos\varphi$ which results the same cross-section as resulted by the usually applied α? When equation (I) is divided by equation (II) then

$$\frac{\varepsilon}{\alpha} = \cos^2 \varphi \, . \tag{5.32}$$

If taking into account values of $\varepsilon = 3\%$ and $\alpha = 5\%$ then at about a power factor of $\cos\varphi = 0.8$ the cross-sections calculated with the two methods are the same. Thus in case of $\cos\varphi > 0.8$ the cable has to be rated for voltage drop and below it for power loss. The average power factor of public grids is $\cos\varphi \approx 0.95$.

5.3.3 Rating cables according to thermal load

As already mentioned the current flowing through a cable causes power loss on it heating the cable, the conductor itself and the insulation as well. An overheating of the insulation material can destroy the insulation and at higher temperatures the metal conductor can be deteriorated as well. As a consequence damage fire can be the result causing serious damages in lives and objects. In case of bare cables the damage of the more sensitive insulation can be count out that is why bare cables can be loaded with higher currents.

In case of overhead cables current-carrying capacity of cables is limited by the power loss and by the annealing of the conductor material as well. An overheating of cables can be caused by high ambient temperatures as well.If the cable is durably operated in high temperatures then it can be loaded only by lower currents than the current-carrying capacity given for an ambient temperature of 30°C.

Cooling conditions of a cable have significant influence on its current-carrying capacity as well. Cooling conditions depend on the heat conducting ability of the insulation. Current-carrying capacity of cables with thinner insulation or lower cross-section can be loaded with higher current densities. The surface of the cable, which is

$$F = f\left(\sqrt{A}\right) \tag{5.33}$$

composes an important factor, where A is the cross-section of the conductor. Outer surface of the cable increases only with the square root of the cross-section, that is why thinner cables can be loaded more than thick ones. This is the reason why the standard gives the current-carrying capacity values for cross-sections and not for unit area.

Lower cooling surface is available when more conductors conduct current inside a single sheath or more cables are placed next to each-other.

Reference current values given by the standard for every standard cable cross-sections are steady current values composing the initial values of the cable rating for operating thermal load of the conductors.

Thus current-carrying capacity of cables depends on the
- material of the conductor;
- design of the cable;
- method of installation;
- ambient temperature.

If service conditions of the cable deviate from those under which the reference values are valid then the reference values have to be modified by multiplying them with correctionfactors which can be determined with the help of tables, diagramsor equations.

Factors correcting the current-carrying capacity:
- Temperature of the environment (k_1);
- more than 3 loaded conductors in a cable (k_2);
- parallel installation of several cables (k_3);
- harmonic content of the current (k_5).

Ambient temperature

The maximum current-carrying capacity of insulated cables is limited by the maximum temperature allowed for the given insulating material. Maximum temperature values allowed for some insulating materials are listed in *Table 5.7*.

Table 5.7. Maximum temperature values allowed for insulating materials

Type of insulation	**Temperature limit °C**
Polyvinyl-chloride (PVC)	70 at the conductor
Cross-linked polyethylene (XLPE)	90 at the conductor
Ethylene propylene rubber (EPR)	90 at the conductor
Rubber	60 at the sheath
Mineral (PVC covered or bare exposed to touch)	70 at the sheath
Mineral (bare not exposed to touch and not in contact with combustible material)	105 at the sheath

The standard distinguishes between cables of principal and auxiliary circuit, takes the method of installation, the number of conductors and the structure of the cable into account. Reference values are valid under the following conditions:

- Ambient temperature of 30°C;
- maximum three loaded conductors;
- distance not lower than 10 mm between conduits or trunkings.

Correction factork_1 takes the ambient temperatures between 10°C and 80°C into account. This factor has its value of 1 at the reference temperature of 30°C and below this temperature it is higher than 1 and above the reference temperature itis lower than 1.Correction factor values for ambient air temperatures to be applied to the current-carrying capacities for cables in the air are given in *Table 5.8*.

Table 5.8. Correction factors for ambient air temperatures (source: Table B.52.14 of IEC 60364-5-52)[6.2]

Ambient air temperature °C	**Insulation**	
	PVC	**XLPE and EPR**
10	1.22	1.15
15	1.17	1.12
20	1.12	1.08
25	1.06	1.04
30	1	1
35	0.94	0.96
40	0.87	0.91
45	0.79	0.87
50	0.71	0.82
55	0.61	0.76
60	0.50	0.71
65	-	0.65
70	-	0.58
75	-	0.50
80	-	0.41

Number of conductors in a cable

Correction factor k_2 takes into account more than 3 loaded conductors in a cable or several cables touching each-other. Values of this factor are listed in *Table 5.9*.

Table 5.9. Correction factors for numbers of conductors more than three (source: Table B.52.17 of IEC 60364-5-52)

Arrangement (cables touching, on a surface)	**Number of circuits or multicore cables**												**With reference methods**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**12**	**16**	**20**	
Bunched in air, embedded or enclosed in one layer	1	.80	.70	.65	.60	.57	.54	.52	.50	.45	.41	.38	52-C1-52-C14 methods A – F
On wall, floor or unperforated tray in one layer	1	.85	.79	.75	.73	.72	.72	.71	.70	No further reduction factor for more than nine circuits or multicore cables			52-C1-52-C6 method C
Fixed directly under a wooden sealing in one layer	.95	.81	.72	.68	.66	.64	.63	.62	.61				
On horizontal or vertical perforated tray in one layer	1	.88	.82	.77	.75	.73	.73	.72	.72				52-C7-52-C12 methods E – F
In one layer on ladder, support or cleats, etc.	1	.87	.82	.80	.80	.79	.79	.78	.78				

Grouping of cables

Correction factor k_3 takes into account several conduits, ducts or cable bunches closer than 10 mm to each-other. Correction values are listed in table B.52.17 of IEC 60364-5-52.

Harmonic currents

The current-carrying capacity of three-phase, 4-core or 5-core cables is based on the assumption that only 3 conductors are fully loaded, i.e. the three currents compose an ideally symmetrical system. However, when harmonic currents flow as well, the neutral current can be significant, and even higher than the phase currents. This is due to the fact that harmonic currents with multiplication factors being able to be divided by 3 without remainder, do not cancel each other, and sum up in the neutral conductor (*Fig. 5.33*).

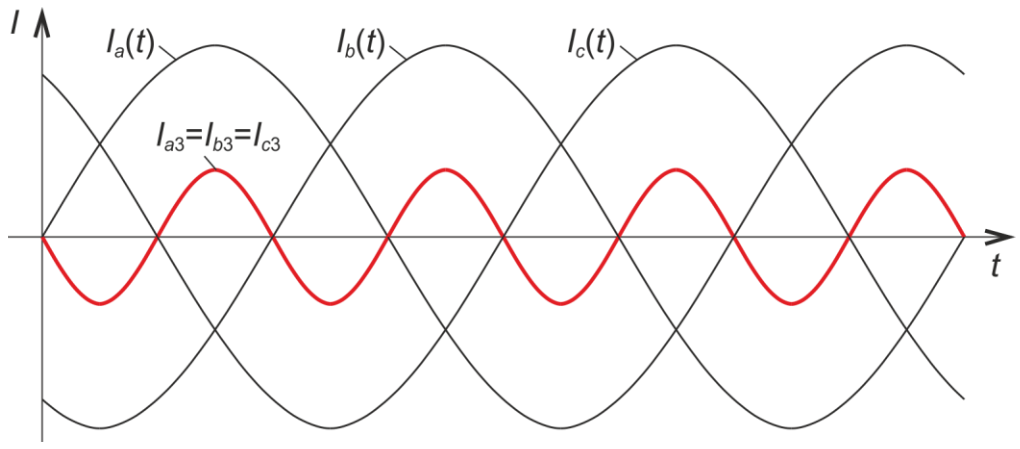


Fig. 5.33. The 3rd harmonic is the same in the three line currents

Among these harmonic currents the 3rd harmonic is usually the highest one. This of course affects the current-carrying capacity of the cable, and a correction factor noted here k_5 shall be applied. In addition, if the 3rd harmonic percentage h_3 is greater than 33%, the neutral current is greater than the phase current and the cable size selection is based on the neutral current (*Fig. 5.34*). The heating effect of harmonic currents in the phase conductors has also to be taken into account.

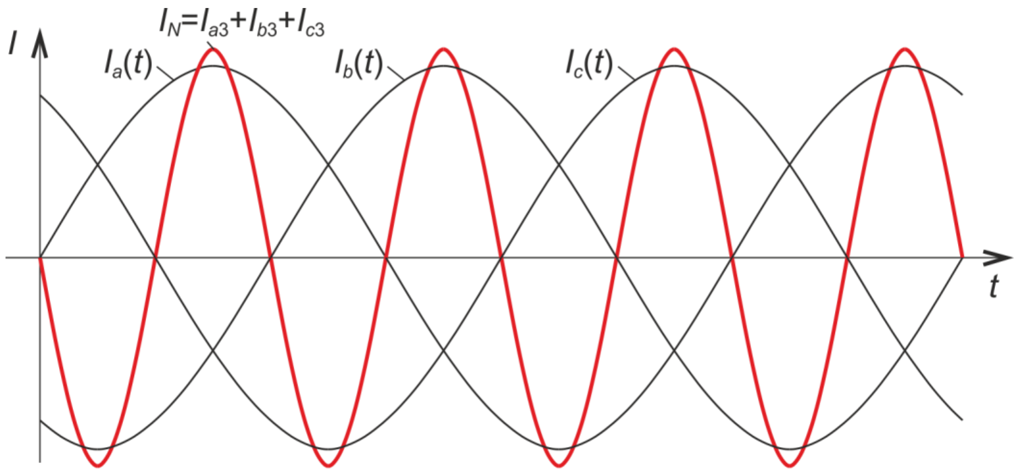


Fig. 5.34. Current I_N of the neutral conductor

The *Table 5.10* lists the correction factors forharmonic currents in four-core and five-core cables.

Table 5.10. Correction factors for harmonic currents (source: Table B.52.19 of IEC 60364-5-52)

Third harmonic content of phase current (%)	**Correction factor**	
	Size selection is based on phase current	**Size selection is based on neutral current**
0 - 15	1.0	
15 - 33	0.86	
33 - 45		0.86
> 45		1.0

Example

If a three-phase circuit supplied by a PVC insulated four-core cable installed with reference method C is loaded with 39 A, then in case of copper conductor the cross-section 6 mm^2 is appropriate with its current-carrying capacity of 41 A if no harmonics are present in the current.In case of a 3rd harmonic content with a percentage of 20% the correction factor 0.86 is valid and the rated load is

$$\frac{39}{0.86} = 45 \text{ A} . \tag{5.34}$$

For the above rated load current a cross-section of 10 mm^2 is appropriate with its current-carrying capacity of 57 A. In case of a 3rd harmonic content with a percentage of 40% the cross-section of the conductor has to be determined on the basis of the neutralcurrent which is

$$39 \cdot 0.4 \cdot 3 = 46.8 \text{ A} \tag{5.35}$$

and applying the correction factor 0.86 valid now the rated load is

$$\frac{46.8}{0.86} = 54.4 \text{ A} . \tag{5.36}$$

For the above rated load current a cross-section of 10 mm^2 is appropriate. However if the 3rd harmonic content is 50%, then the neutral current is

$$39 \cdot 0.5 \cdot 3 = 58.5 \text{ A} \tag{5.37}$$

and the value of the correction factor is 1, the cross-section of 16 mm^2 is necessary with its current-carrying capacity of 76 A.

According to the standard in case of 3rd harmonic content values under 35% of the phase current the cable size has selected on the basis of the phase current and above this value on the basis of the neutral current. Then the three phase conductors will not be fully loaded. The reduction in heat generated by the phase conductors offsets the heat generated by the neutral conductor to the extent that it is not necessary to apply any reduction factor to the current carrying capacity for the three loaded conductors.

Calculation of the resultant rated current

If all relevant correction factors are determined then the I'_Z resultant rated current is

$$\boxed{I'_Z = I_Z \cdot k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot k_5}, \tag{5.38}$$

where I_Z is the reference current-carrying capacity value.

In case of underground power cables the depth of installation of 70 cm and the specific thermal soil resistivity of 70°C/W and the reference ambient temperature of 20°C compose the reference installation condition values for a single cable.

Current-carrying capacity values of overhead cables are determined by the mechanical strength in case of aluminum, tempered aluminum and steel-cored aluminum. The allowed maximum temperature of these materials is 80°C. The reference current-carrying capacity values are valid under 40°C ambient temperature and a wind speed of 0.5 m/s. The allowed value can be determined by the equation

$$I'_Z = I_Z \cdot \left(\frac{v}{5} + 0.9\right) \cdot \sqrt{2 + \frac{\vartheta}{40}} , \tag{5.39}$$

where v is the speed of wind and ϑ is the ambient temperature.

5.3.4 Short circuit rating

In case of a short circuit a much lower impedance than that of the consumer acts as the load of the circuit. This lower impedance in many cases equals to the impedance of the cable supplying the consumer.

We have already seen that, the voltage drop on the cable is much lower than the rated voltage of the consumer and the circuit. Thus if only the cable impedance acts as the load of the circuit then the current flowing during this short circuit condition is higher than the consumer current by order(s) of magnitude(s) and the Joule loss can be a multiple by several hundreds of that in normal case.

The temperature calculated as the steady temperature ϑ_{SC} in short circuit condition would be so high that, the metal core would melt as well not only the insulation thermoplast. Apart from this the current would damage other devices flown through by it. Because of these reasons the short circuit current must be cut as soon as possible. This switching off of the short circuit current is performed by the over-current protection of the given circuit.

From the beginning of the short circuit until its termination by the over-current protection, the short circuit current heats up the cable flown through by this current. Because of the short time period – maximum several seconds – of a short circuit the heat rejection from the cable can be neglected and the consideration can be taken that, the total of this thermal energy heats up the cable itself. Maximum allowed temperatures of the different conductor materials can be found in tables.Thermal energy caused by the current I_{SC} within a time period of t in a cable with a specific resistivity ρ, cross-section A and length l is

$$Q = I_{SC}^2 \cdot t \cdot \rho \frac{l}{A} \quad \text{(J)}, \tag{5.40}$$

which equals to the heat amount heating up the cable which is

$$Q = c \cdot m \cdot (\vartheta_{SC} - \vartheta_O) \quad \text{(J)} \tag{5.41}$$

where $c \left(\frac{\text{J}}{\text{kg} \cdot \text{K}} \right)$ is the specific heat, m is the mass of the cable and ϑ_O is the operational temperature of the cable before the short-circuit. Thus

$$I_{SC}^2 \cdot t \cdot \rho \frac{l}{A} = c \cdot m \cdot \left(\vartheta_{SC} - \vartheta_O \right) \tag{5.42}$$

and

$$A = I_{SC}^2 \cdot t \cdot \frac{\rho \cdot l}{c \cdot m \cdot \left(\vartheta_{SC} - \vartheta_O \right)} \quad \left(\text{mm}^2 \right). \tag{5.43}$$

In most cases this rating calculation can be omitted when the fuse or automatic fuse cuts the short circuit current within a second.

5.3.5 Rating of cables with different layouts

Low voltage consumers are supplied by grids with different layouts from one or two sources. In the followings the determination of the cross-sections of the cables composing these layouts will be discussed from the point of view of the voltage drop on the given cable or cable system.

5.3.5.1 Single supply cable

A simple supply cable with a length of *l* supplying a consumer described by itsuseful power *P*, efficiency η and power factor $\cos\varphi$ supplied with electrical energy by a source with the rated voltage V_n of the consumer is shown in *Fig. 5.35*. In the figure the circle marks the source and the arrow the consumer.

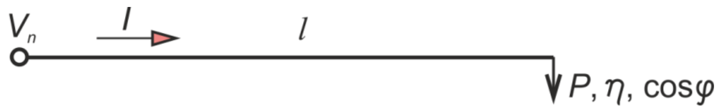


Fig. 5.35. A supply cable

The relationship between the useful power and the current *I* drawn by the consumer is

$$P = V_n \cdot I \cdot \eta \cdot \cos\varphi \ \ \text{(W)} \tag{5.44}$$

and the minimum conductor cross-section required from the point of view of the voltage drop is (5.21)

$$A_{\min} = \frac{\rho}{e'} I_w \cdot l \, .$$

5.3.5.2 Distribution cable

A distribution cable supplies several consumers at different points of the cable. This type of cables can be found e.g. in blocks of freehold flats where the same cable supplies all the flats through branches on the cable and lighting cables inside flat can have the same layout.

A precondition of the rating is that, the cable has the same cross-section along its entire length.A distribution cable supplying *n* consumers with electrical energy by a source with the rated voltage V_n of the consumer is shown in *Fig. 5.36*. In this figure the active components of the currents of the consumers are written lower case (i_{iw}) and the active components of the currents flowing on the sections of the cable are written upper case (I_{iw}).

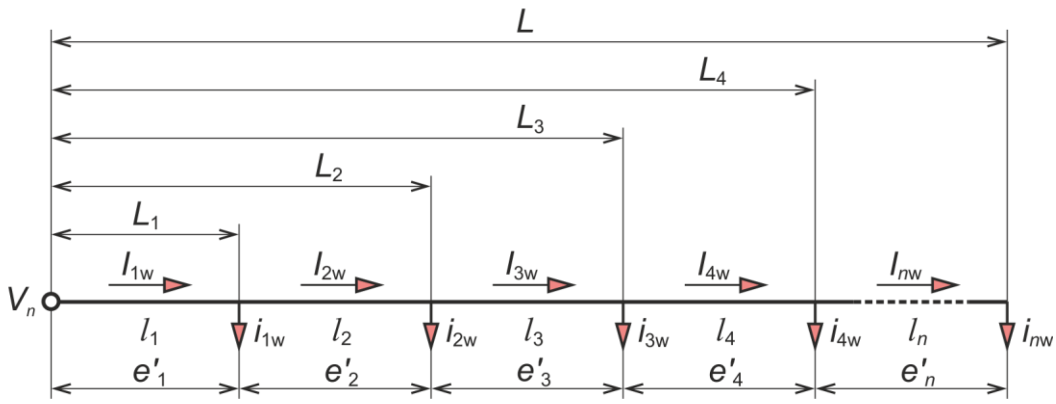


Fig. 5.36. Distribution cable

Since only active current components are dealt with the active current flowing e.g. on the second section of cable can be written as

$$I_{2w} = i_{2w} + i_{3w} + i_{4w} + \cdots + i_{nw}. \tag{5.45}$$

Since the length L of the cable is

$$L = l_1 + l_2 + l_3 + l_4 + \cdots + l_n, \tag{5.46}$$

the voltage drop on one conductor of the cable is

$$e' = e'_1 + e'_2 + e'_3 + e'_4 + \cdots + e'_n \tag{5.47}$$

and after substitution

$$e' = \frac{\rho}{A} I_{1w} \cdot l_1 + \frac{\rho}{A} I_{2w} \cdot l_2 + \frac{\rho}{A} I_{3w} \cdot l_{13} + \frac{\rho}{A} I_{4w} \cdot l_4 + \cdots + \frac{\rho}{A} I_{nw} \cdot l_n . \tag{5.48}$$

Then

$$e' = \frac{\rho}{A}(I_{1w} \cdot l_1 + I_{2w} \cdot l_2 + I_{3w} \cdot l_{13} + I_{4w} \cdot l_4 + \cdots + I_{nw} \cdot l_n), \tag{5.49}$$

the voltage drop on the cable can be calculated with

$$e' = \frac{\rho}{A} \sum_{n}^{i=1} I_{nw} \cdot l_n , \tag{5.50}$$

the minimum cross-section of the cable is

$$\boxed{A = \frac{\rho}{e'} \sum_{n}^{i=1} I_{nw} \cdot l_n}, \tag{5.51}$$

which equals to

$$A = \frac{\rho}{e'} \sum_{n}^{i=1} i_{nw} \cdot L_n. \tag{5.52}$$

The product *Il* is called **current torque**.

5.3.5.3 Radial type distribution cable system

As already written in Chapter 3 in case of radial type networks electric energy have only a single path from the source to a consumer. Theoretically the principle of the same cross-section of the entire cable, respectively the sum of the cross-sections of the cable branches is valid in this case as well, however in the reality this sum does not equal to the cross-section of main cable in the most cases because of the discrete standard cross section values. Thus on the example of *Fig. 5.37*

$$A_1 \approx A_3 + A_4 \tag{5.53}$$

and

$$A_0 \approx A_1 + A_2, \tag{5.54}$$

i.e.

$$A_0 \approx A_2 + A_3 + A_4. \tag{5.55}$$

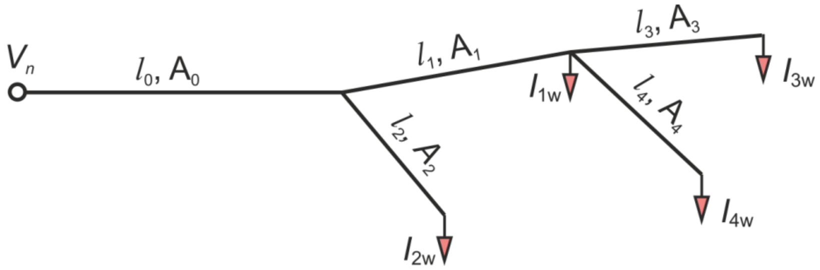


Fig. 5.37. Radial type distribution cable system

The first step in solving this problem, i.e. to find the cross-sections A_0, A_1, A_2, A_3, A_4, is to determine the equivalent supply cable of a consumer being equivalent to the sum of the original consumers (*Fig. 5.38*). Precondition of this transformation is that the voltage drop on the equivalent supply cable must be equal to the maximum voltage drop at the points of the consumers.

Fig. 5.38. The equivalent supply cable

For determining λ the cable branches beginning in one node and ending in consumers have to be replaced by a single cable with a length of λ_{34} at first. The sub-index 34 relates to the example in *Fig. 5.37*. When implementing the equilibrium of the current torques for this example the length of λ_{34} can be calculated with

$$(I_{1w} + I_{3w} + I_{4w}) \cdot \lambda_{34} = I_{1w} \cdot 0 + I_{3w} \cdot l_3 + I_{4w} \cdot l_4 \qquad (5.56)$$

and

$$\lambda_{34} = \frac{I_{3w} l_3 + I_{4w} l_4}{I_{1w} + I_{3w} + I_{4w}} . \qquad (5.57)$$

The cable length supplying consumer I_1 beginning in the node in question is zero (*Fig. 5.39*).

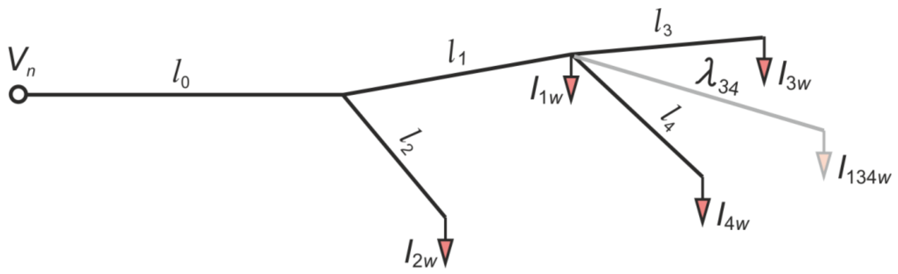


Fig. 5.39. The equivalent of the branches l_3 and l_4

The virtual length for n branches is

$$\lambda_n = \frac{\sum_{n}^{i=1} I_{iw} l_1}{\sum_{n}^{i=1} I_{iw}} . \qquad (5.58)$$

The value of λ for present example is (*Fig. 5.40*)

$$\lambda = \frac{I_{2w} l_2 + I_{134w}(l_1 + \lambda_{34})}{I_{1w} + I_{2w} + I_{3w} + I_{4w}} . \qquad (5.59)$$

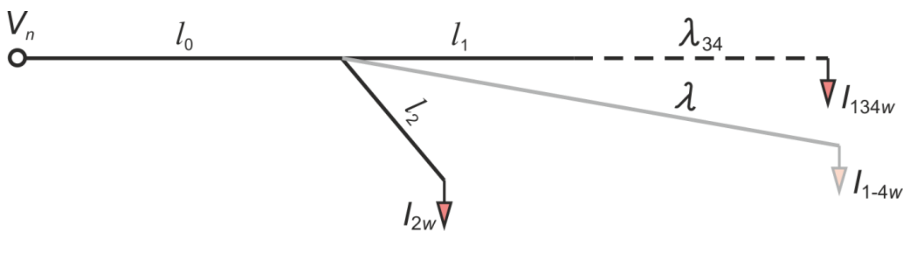


Fig. 5.40. The equivalent of the branches l_1, l_2, l_3 and l_4

At this point the cross-section of l_0 can be calculated with

$$A_0 = \frac{\rho}{e'} I_{1-4w}(l_0 + \lambda) . \qquad (5.60)$$

After choosing the standard cross section A_{0s} next higher than or equal to A_0 and checking it for thermal load the actual voltage drop on l_0 can be calculated with

$$e'_0 = I_{1-4w} \cdot \rho \frac{l_0}{A_{0s}} . \qquad (5.61)$$

This part of the allowed voltage drop *e'* is now used up and the other cable sections have to share on the remaining part of the voltage drop, as

$$e'_{1-4} = e' - e'_0. \qquad (5.62)$$

With the knowledge of this data the cross-sections of l_1 and l_2 can be calculated with

$$A_1 = \frac{\rho}{e'_{1-4}} I_{134w}(l_1 + \lambda_{34}) \qquad (5.63)$$

and

$$A_2 = \frac{\rho}{e'_{1-4}} I_{2w} l_2 . \qquad (5.64)$$

In the present example now the actual voltage drop on l_1 have to be calculated with

$$e'_1 = \rho \frac{l_1}{A_{1s}} \qquad (5.65)$$

and for determining A_3, A_4 the remaining allowed voltage drop have to be calculated with

$$e'_{34} = e'_{1-4} - e'_1. \qquad (5.66)$$

Finally cross-sections of l_3 and l_4 can be calculated with

$$A_3 = \frac{\rho}{e'_{34}} I_{3w} l_3 \qquad (5.67)$$

and

$$A_4 = \frac{\rho}{e'_{34}} I_{4w} l_4 . \qquad (5.68)$$

5.3.5.4 Distribution cable supplied from both sides with the same voltage

Distribution cables supplied from both sides are cables fed by electrical energy at both ends of the cable (*Fig. 5.41*). If e.g. both ends of the cable are connected to the same busbar, then the same voltage (V_S) exists at both ends – at the end “*A*” and “*B*” of the cable.

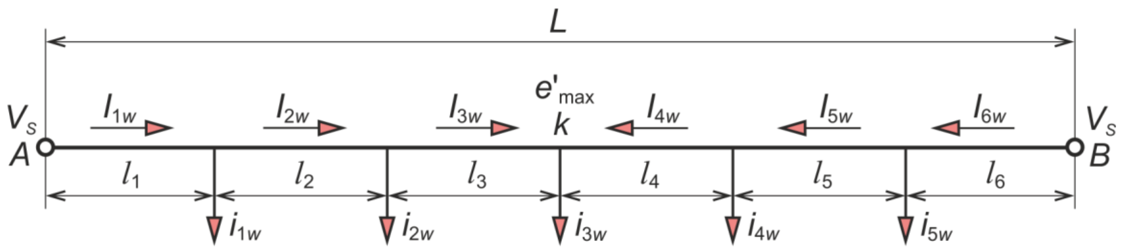


Fig. 5.41. Distribution cable supplied from both side

In this case the maximum actual voltage drop e'_{max} can not be found at either end of the cable but somewhere in the middle of its length L. As a matter of course the voltage drop can develop at an extreme consumer – at the consumer 1 at one end or consumer n at the other end – if it draws a much higher current then the other consumers. Let the number of this consumer be k. This is the consumer fed from both sides of the cable with the current

$$i_{3w} = I_{3w} + I_{4w}. \tag{5.69}$$

in case of the example of *Fig. 5.41* and

$$i_{kw} = I_{kw} + I_{k+1w} \tag{5.70}$$

in general. If this consumer is found then both half of the cable can be considered as simple distribution cables and its cross section can be calculated the same way as by them (*Fig. 5.42*).

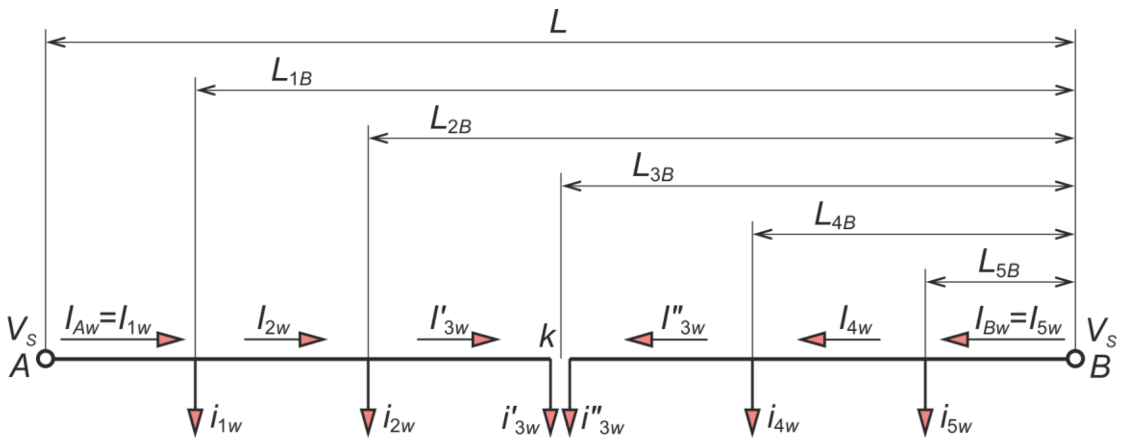


Fig. 5.42. The cable split into two parts

Based on the equation of the equilibrium of the current torques

$$I_{Aw} \cdot L = i_{1w} \cdot L_{1B} + i_{2w} \cdot L_{2B} + i_{3w} \cdot L_{3B} + i_{4w} \cdot L_{4B} + i_{5w} \cdot L_{5B} \tag{5.71}$$

the active current flowing out of supply point "*A*" for this example is

$$I_{Aw} = \frac{i_{1w}L_{1B} + i_{2w}L_{2B} + i_{3w}L_{3B} + i_{4w}L_{4B} + i_{5w}L_{5B}}{L}. \tag{5.72}$$

The equation for the general case is

$$I_{Aw} = \frac{\sum_{n}^{i=1} i_{iw} L_{iB}}{L} \tag{5.73}$$

and active current flowing out from the opposite side is

$$I_{Bw} = \frac{\sum_{n}^{i=1} i_{iw} L_{iA}}{L} \; . \tag{5.74}$$

The consumer fed from both sides can be found with

$$I_{Aw} - i_{1w} - i_{2w} - \ldots < 0. \tag{5.75}$$

When the successive subtracting of the active current of the consumers gives a negative result for the first time the number *k* of the consumer fed from both side is found. At this point the minimum cross-section of the cable can be simply calculated by determining it from one of the half cables parts (*Fig. 5.43*). For the present example it is

$$A = \frac{\rho}{e'}(i_{1w}L_{1A} + i_{2w}L_{2A} + i'_{3w}\,L_{3A}) \; . \tag{5.76}$$

or

$$A = \frac{\rho}{e'}(i_{5w}L_{5B} + i_{4w}L_{4B} + i''_{3w}\,L_{3B}) \; . \tag{5.77}$$

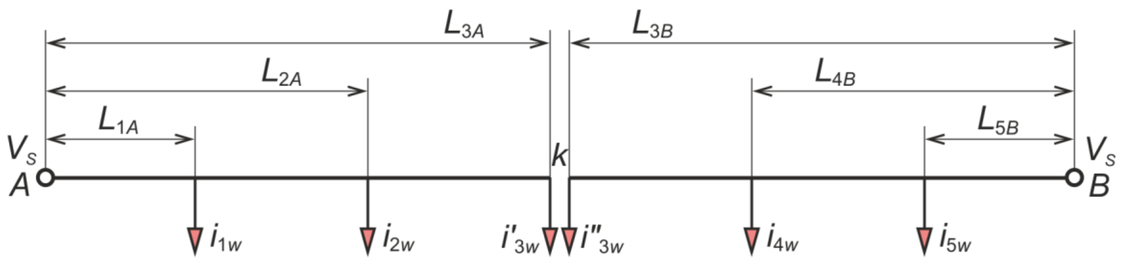


Fig. 5.43. The cable as two simple distribution cables

5.3.5.5 Distribution cable supplied from both sides with different voltages

When a distribution cable is supplied from both sides with different voltages (*Fig. 5.44*) then the minimum cross section of it can be determined with iteration.

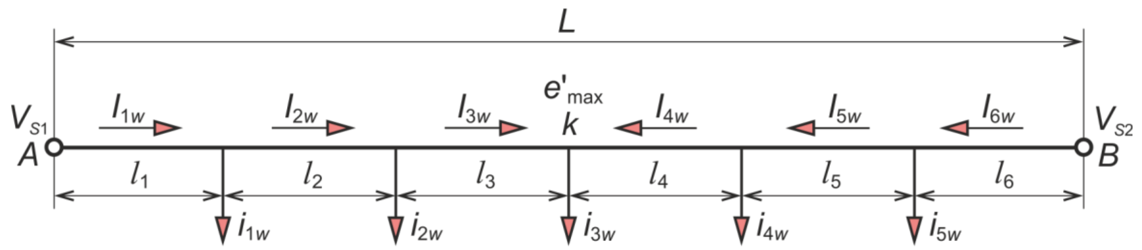


Fig. 5.44. Distribution cable supplied from both side with different voltages

The rating begins the same way as in case of the rating of cables fed at both ends with the same voltage. Active current flowing out of supply point "*A*" for this example is

$$I'_{Aw} = \frac{i_{1w}L_{1B} + i_{2w}L_{2B} + i_{3w}L_{3B} + i_{4w}L_{4B} + i_{5w}L_{5B}}{L}, \tag{5.78}$$

where the apostrophe for I'_{Aw} means that, it surely won't be the correct current value because the equalizing current flowing on the cable as a consequence of the different voltages at its ends is not taken into account. Thisequalizing current can only be determined when the cross-section of the cable is known.

At first the consumer fed from both side have to be found with (5.73). Let the number of this consumer be $k' = 3$. The apostrophe means again the first attempt of the iteration. Then the preliminary value of the cable cross-section has to be calculated with

$$A' = \frac{\rho}{e'}(i_{1w}L_{1A} + i_{2w}L_{2A} + i'_{3wA}L_{3A}). \tag{5.79}$$

At this point the resistance of one cable conductor is calculated with

$$R' = \rho\frac{L}{A'_s} \tag{5.80}$$

and the equalizing current with

$$I'_e = \frac{V_{S1} - V_{S2}}{\sqrt{3}\cdot R'}, \tag{5.81}$$

if $V_{S1} > V_{S2}$, then the equalizing current flows from *A* to *B* and has to be added to the current flowing out from *A* as

$$I''_{Aw} = I'_{Aw} + I'_e. \tag{5.82}$$

Now the consumer fed from both side have to be found again. If

$$k'' = k', \tag{5.83}$$

then the cross-section of the cable is calculated again and if

$$A''_s = A'_s, \tag{5.84}$$

then the cross-section calculated before is correct and the rating for voltage drop is ready. However if

$$A''_s > A'_s, \tag{5.85}$$

then the iteration has to be continued with calculating
- the new resistance value R'' of the thicker conductor;
- the new equalizing current I''_e;
- the new consumer k'' fed from both sides;
- the new cross-section A'''.

The above iteration steps have to be performed until the same cross-section is the result of two subsequent iteration steps.

References – 5

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6 Overcurrent protection

6.1 Overcurrent

Currents beyond the rated current of a circuit are overcurrents. Overcurrent protections can be distinguished as follows:

- Overload protection and
- short-circuit protection.

Overload can appear in sound circuits because e.g. mechanical or load problems at the driven machine and short circuits are electrical faults of the circuit itself. Overload currents can reach values above the rated current by 50-60%, but short circuit currents can be higher than the rated current by orders of magnitude.

An overcurrent is allowed to flow in a circuit so long, until the temperature of the elements in the circuit does not exceed the allowed maximum value. This means that the overcurrent protection has to be the thermal model of the protected device.

Overloads can be remedied even without the operation of the overcurrent protection and without human intervention. However in case of short circuits an immediate, automatic intervention is necessary. This task is performed by the short circuit protection.

> A short circuit current is an overcurrent flowing as a consequence of a failure of an electric circuit when points of the circuit with normally different potentials are connected to each-other through negligible or very low impedance.

Negative impacts of an overcurrent can be

- Overheating;
- mechanical damages.

6.2 Overcurrent protection

Overload currents can be cut by manually of electromagnetically operated switches, however short circuit currents can only be cut by the following devices:

- Fuses;
- automatic fuses;
- circuit breakers.

The highest stress for a switching device is to cut short circuit currents, i.e. to suppress electric arcs. Devices being able to do this are called short circuit protective devices (SCPD).

Rated currents of power-current short circuit protective devices are (A): 0.5, 1, 1.5, 1.6, 2, 2.5, 3, 3.5, 4, 5, 6, 7, 8, 10, 12, 13, 15, 16, 20, 25, 30, 32, 35, 40, 50, 60, 80, 100, 125, 160, 200, 224, 250, 280, 300, 315, 355, 400, 500, 630, 800, 1250, 2500.

6.3 Fuses

Fuses are switching devices as sections of electric circuits intentionally made week and automatically cutting the current (circuit) in case of overload or short circuit.

A fuse has to be able to
1) conduct operational currents continuously and overload and short circuit currents for limited periods;
2) withstand the dynamic stresses of the short circuit currents;
3) automatically switch off overload and short circuit currents.

Fuses have
- two standstill states;
- operating frequency is 1.

Expected features of fuses during normal operation:
- Low losses;
- low price;
- low temperature;
- unlimited lifetime.

Expected features of fuses during overcurrent:
- Most possible fast operation;
- minimum let through energy;
- minimum arc voltage.

Advantages of fuses:
- Small dimensions;
- simple handling;
- low price;
- low power loss;
- reliability;
- low ageing rate;
- high breaking capacity;
- current-limiting at low Joule-integral (I^2t);
- ability for selectivity with small steps.

Disadvantage of fuses:
- The circuit can only be repaired with human intervention after operation.

6.3.1 Working principal of fuses

Most simple fuses are conductors enclosed in glass tubes and with resistance R, heat rejection surface s, heat transfer factor α made for the protection of electronic circuits. Its temperature (τ) versus time (t) function is

$$\tau(t) = \frac{I^2 R}{\alpha \cdot s}\left(1 - e^{-\frac{t}{T}}\right), \tag{6.1}$$

where T is the time constant. Current value at which the fuse would melt during infinite time is the thermal limit current I_{lim}, and the melting over-temperature expressed with it is

$$\tau_{melt} = \frac{I_{lim}^2 \cdot R_{melt}}{\alpha_{melt} \cdot s}, \tag{6.2}$$

where R_{melt} is the resistance of the melting wire at melting temperature, since the resistance increases with the temperature as well as the heat transfer factor α_{melt}. If a current higher than I_{lim} flows through the fuse, then the melting, i.e. the operating period is

$$t_{melt} = -T \cdot \ln\left(1 - \frac{I_{\mathrm{lim}}^2}{I^2}\right). \tag{6.3}$$

In case of high power fuses the melting wire is surrounded with filling material, mainly SiO_2 siliceous sand. This sand plays main role in the operation character of the fuse. During arc extinguishing this sand melts and extracts heat from the arc as a secondary conductor.

Cross section of the melting element defines the rated current of the fuse. Arc voltage is defined by the number of the sections with reduced cross section (perforations).

During the pre-arcing and arcing period, i.e. between the beginning of overcurrent arcing and its switch off the energy ensured by the source and the energy stored in the circuit – mainly $½LI^2$ – dissipate in the fuse. Joule-heat is given as a characteristic instead of the actual energy.

Material of the melting element can be

- silver;
- copper;
- silver and copper connected in series to each-other (thrulay).

6.3.2 Structure of fuses

Fuses exist in extremely wide range of size. Their rated currents cover four orders of magnitudes and some constructions can cut the highest short circuit currents.

Tube fuses are built for the protection of electronic circuits with low power. The melting wire is placed into glass of ceramic tubes. Soundness of the melting wire can be checked visually through the glass tube (*Fig. 6.1.a*).

Neozed (N) fuses are in general for industrial application. A fuse link of this construction is shown in *Fig. 6.1.b*.

Diazed (D) fuses are used in general for household application. A fuse link of this construction is shown in *Fig. 6.1.c*. Its rated current of 63 A and the maximum voltage level of 500 A can be read on the link. The snail house refers to the sluggish character of the fuse link.

Knife type fuses are built for high power use. A knife type fuse link with rated current of 100 A is shown in *Fig. 6.1.d*. Scale of the fuse links shown is not proportional to each-other.

a) *b*) *c*) *d*)

Fig. 6.1. Fuse links

Diazed fuses

In *Fig. 6.2* the structure of a Diazed type (D) fuse is shown. The contact at phase voltage is on the bottom of the casing and the contact at neutral potential is the Edison thread itself. Cross-section of the contact of the fuse link is proportional to the rated current of it and for making unable to insert a link with higher rated current an adapter ring is placed on the bottom of the casing.

Color of the adapter ring fits to the color marking of the rated current (*Table 6.1*). The same color has the signaling disk at the other end of the fuse link which is pushed out by a small spring when the melting wire and the fixing wire melt, thus signaling the melting of the link. Melting wire is surrounded by siliceous sand which extinguishes the arc effectively.

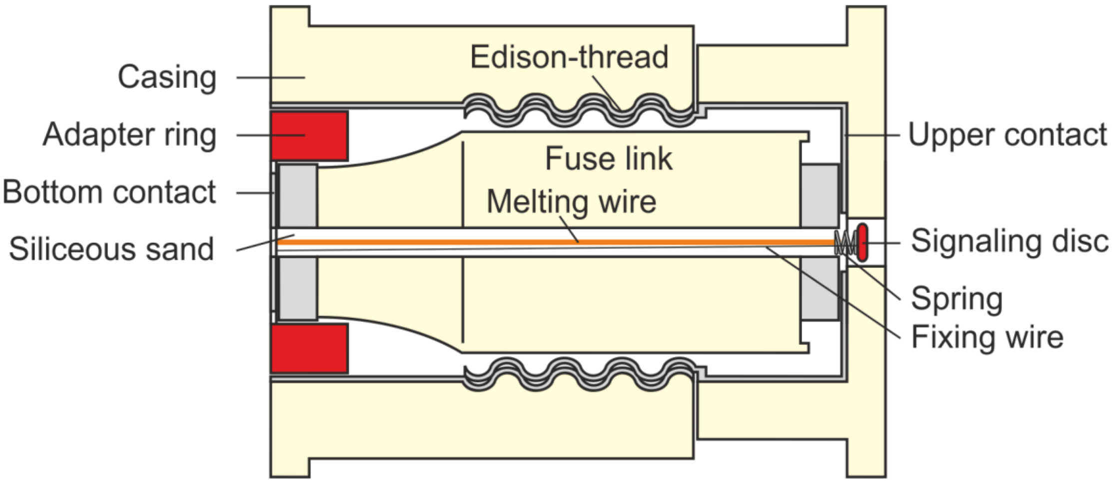


Fig. 6.2. Construction of Diazed type fuses

Table 6.1. Rated currents and their color markings

I_e	Color	I_e	Color	I_e	Color	I_e	Color
2A		13 A		35 A		100 A	
4 A		16 A		50 A		125 A	
6 A		20 A		63 A		160 A	
10 A		25 A		80 A		200 A	

Knife type fuses

In *Fig. 6.3* construction of a fuse ling of knife type fuses of the NH system is shown.

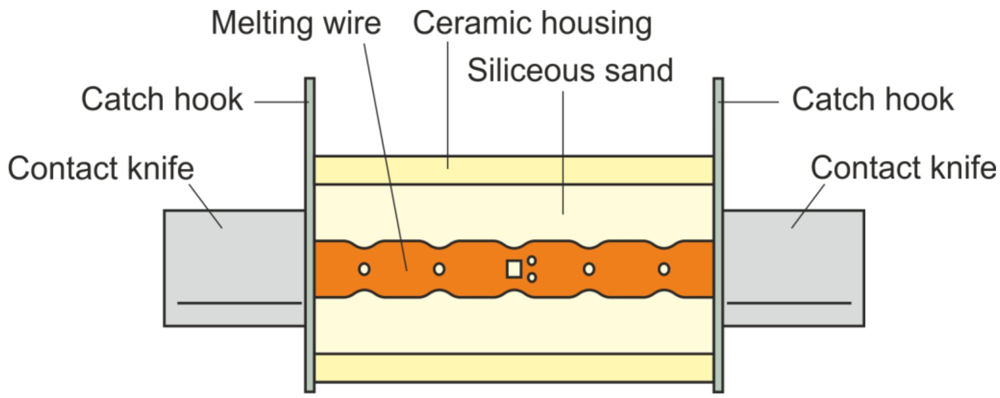


Fig. 6.3. Construction of a fuse ling of knife type fuses

6.3.3 Characteristics of fuse links

The application field of fuses is basically defined by their melting time–overcurrent characteristic. Depending on the time during which the link melts as an effect of the same current the fuse link can be

- super fast (FF);
- fast (F);
- medium sluggish (M);
- sluggish (T);
- super sluggish (TT).

Marking characters used in German speaking countries are shown in parenthesis (F – flink, M – medium, t – träg). A fast link switches the current off within 20 ms if this current is ten times higher than the rated current of the link, however the medium sluggish type switches it off within 50-90 ms and sluggish type during 100-300 ms.

In case of sluggish type links not melting during the starting (locked rotor) overcurrent of squirrel cage induction motors a solder drop is placed onto the melting wire.

International marking of fuse links with different purpose:
G General purpose;
L line/cable protecting links;
M motor protecting link;
Tr transformer protecting link;
R rectifier protecting link;
S cable/conductor and semiconductor protecting link;
B link for mining purposes.

Operating time–current characteristic series of general purpose links is shown in *Fig. 6.4.* The higher is the overcurrent the shorter is the time period during which the fuse melts. In case of very high currents the operating time can be a few milliseconds.

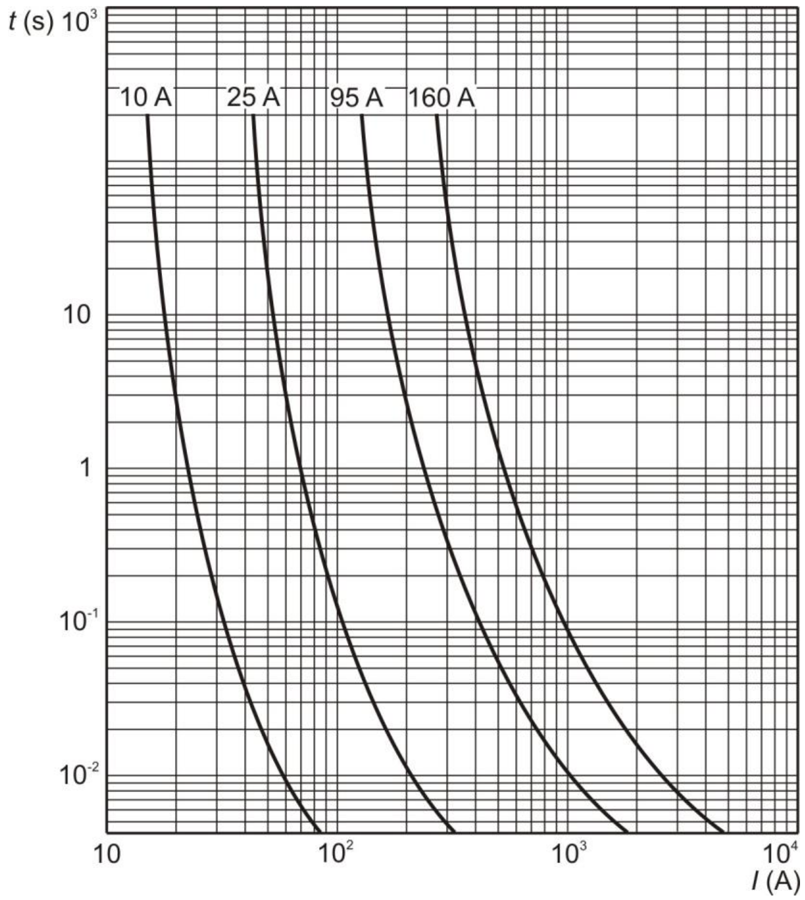


Fig. 6.4. Operating time–current characteristic series of general purpose links

In *Fig. 6.5* operating time–current characteristic of a motor protecting fuse link can be seen. For the protection of squirrel cage asynchronous motors sluggish fuse links have to be applied for preventing the melting of the fuse during the start of the motor with is multiple locked rotor current. This is the reason of the shape of this characteristic curve.

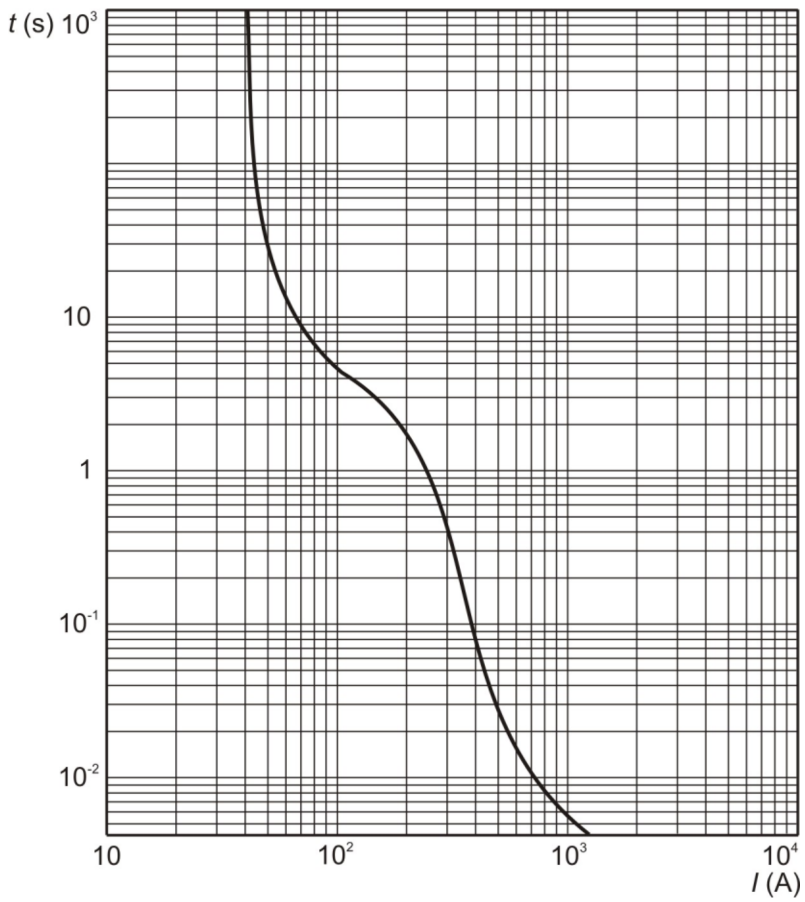


Fig. 6.5. Operating time–current characteristic of motor protecting links

Most of the short circuit protective devices are able for current limiting which means, that in case of high short circuit currents neither the first current peak can develop before cutting the current (*Fig. 6.6*).

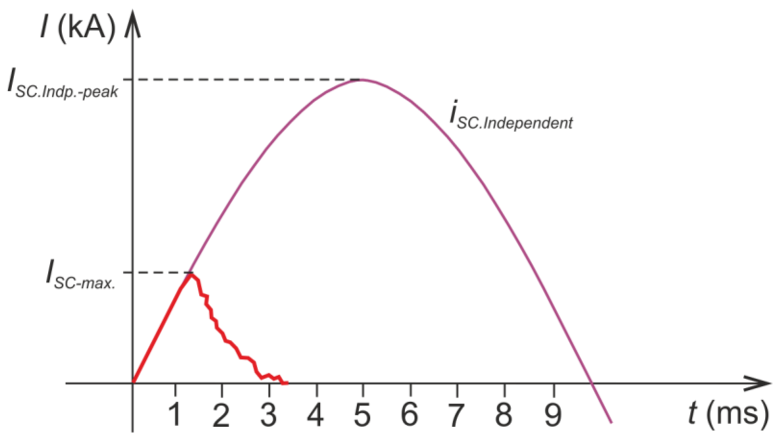


Fig. 6.6. Arc extinguishing in case of current limiting

The $i_{SC.Independent}$ independent short circuit current would flow in the circuit suffering short circuit, if there was no short circuit protection in the circuit. Typical current limiting characteristic series can be seen in *Fig. 6.7*.

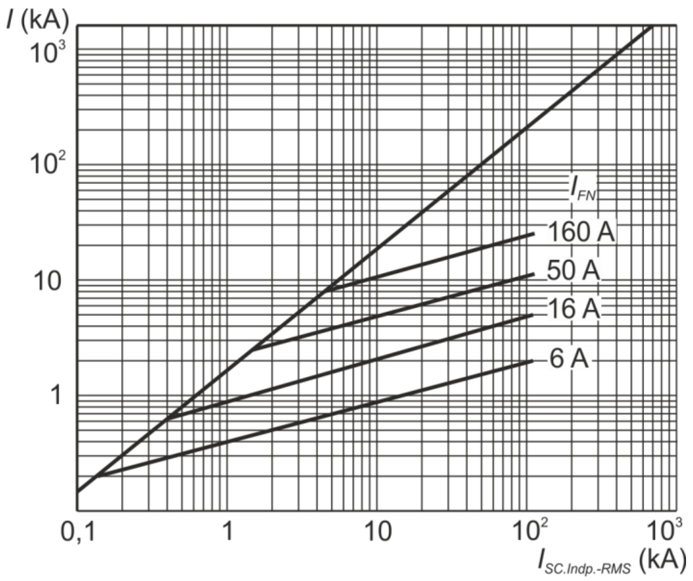


Fig. 6.7. Current limiting characteristic of fuses (cut-off characteristics)

In *Fig. 6.7* it can be seen that a fuse link with a rated current of 6 A begins to cut off the short circuit current at 300 A current, however the link with 160 A begins this only at a current of 8000 A.

6.4 Automatic fuses

Automatic fuses compose a separate category among short circuit protective devices and within the category of circuit breakers itself. Actually automatic fuses are simple circuit breakers.

Automatic fuses have the following descriptive data:

- Rated voltage: V_e = 230 VAC / 400 VAC, max. 48 VDC;
- rated current: I_e = 0.5 A - 125 A;
- independent breaking current: I_{cu} = 1.5 kA - 50 kA;
- lifetime: 500 - 20000 switching cycles;
- arc extinguishing medium: air;
- construction: open;
- number of built-in releases: 2;
- selectivity class: 3;
- protection: IP20;
- clamped wire cross section: 1 - 25 mm^2;
- clamping mode: fixed;
- operating mode: independent manual operation;
- mounting mode: TS35 rail;
- isolating ability: no;
- ability for time selectivity: no;
- maintenance need: maintenance free.

Rated current values of automatic fuses: 0.5 A, 1 A, 1.5 A, 1.6 A, 2 A, 2.5 A, 3 A, 3.5 A, 4 A, 5 A, 6 A, 7 A, 8 A, 10 A, 12 A, 13 A, 15 A, 16 A, 20 A, 25 A, 30 A, 32 A, 35 A, 40 A, 50 A, 63 A, 80 A, 100 A, 125 A.

6.4.1 Operation of automatic fuses

Automatic fuses have two releases being effective in the lower and higher ranges of over-currents:

1) Thermal release for lower over-currents, its time constant has values in the order of magnitude of minute.

2) Magnetic rapid release for short circuit currents, its time constant has values in the order of magnitude of 1-10 milliseconds.

In *Fig. 6.8* construction of an automatic fuse is shown with its construction elements.

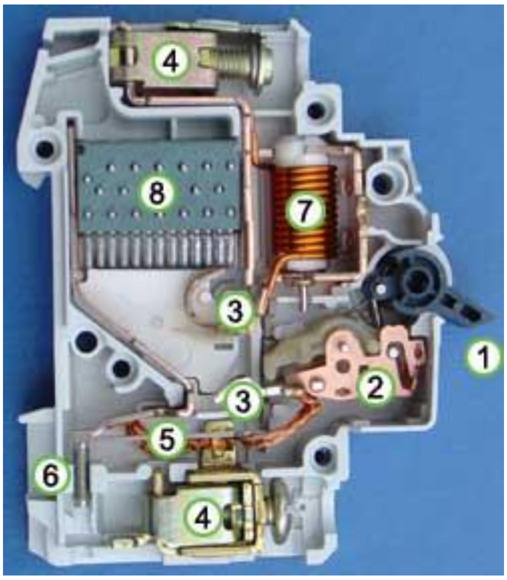


Fig. 6.8. Construction of an automatic fuse

Parts of an automatic fuse are

1 Actuator lever for the manual switching on and off of the automatic fuse showing the status of the fuse at the same time. The majority of the circuit breakers are of independent release, which means that the fuse switches off even if the actuator lever is held on;
2 actuator mechanism;
3 contacts;
4 terminals, in general the phase wire remaining live at switched off fuse is connected on the top and the switched wire is connected at the bottom of the device;
5 thermal release (bimetallic strip);
6 calibration screw;
7 magnetic rapid release (solenoid);
8 arc extinguisher.

As a reaction of an over-current, e.g. because of the overload of the protected circuit the bimetallic strip built into the thermal release warms up and after a certain time period it bends and operates the actuator mechanism and switches the circuit off. The thermal release has a calibration screw, the help of which the manufacturer calibrates the device to the appropriate accuracy.

In case of a short circuit of the protected circuit this current flowing through the solenoid of the magnetic release builds a magnetic field with an intensity effecting a force onto the iron core it operates, thus switching off the device. This release cuts the current quicker by orders of magnitudes than the thermal release protecting so the circuit from the thermal effect of the short circuit current. The arc extinguisher has a harder job in this case.

Circuit symbol and design marking (F) of automatic fuses are shown in *Fig. 6.9*. The symbol of the bimetallic strip is drawn at the top and the arrow drawn at the bottom symbols the magnetic rapid release.

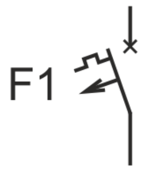
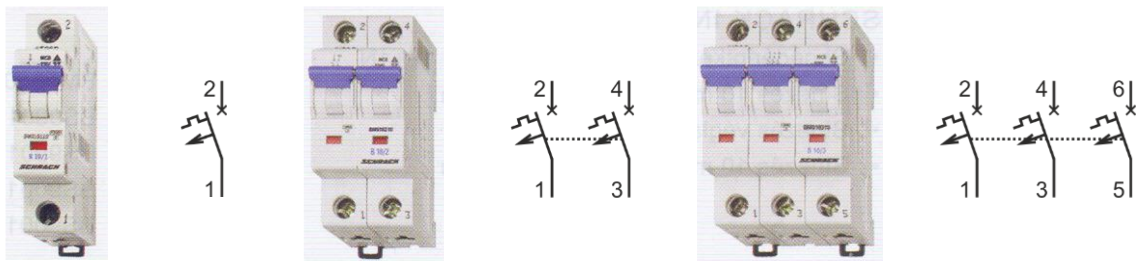


Fig. 6.9. Circuit symbol of the contact of automatic fuses

6.4.2 Poles and releases of automatic fuses

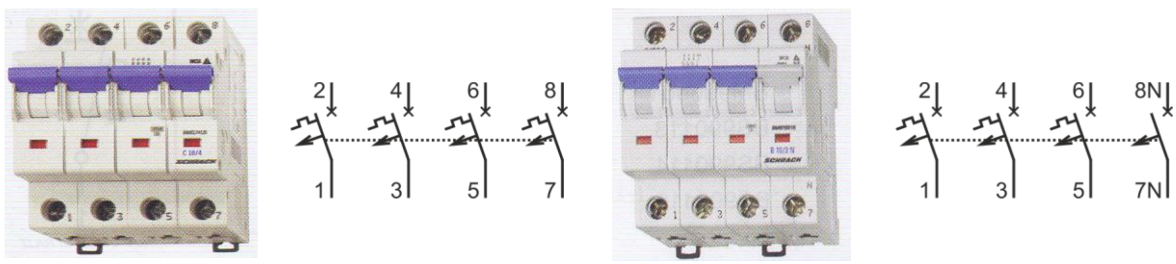
Figures *6.10.a*, *6.10.c* and *6.10.e* show photos of automatic fuses with one, two and three poles. Actuator lever of the devices with several poles operate commonly in their original state, which means that the device cuts all poles (phases) even in case of the short circuit of a single phase. *Figures 6.10.b, 6.10.d* and *6.10.f* show the symbols of the certain constructions.



a) *b*) *c*) *d*) *e*) *f*)

Fig. 6.10. Photos and circuit symbols of automatic fuses with one, two and three poles (*source*: SCHRACK)

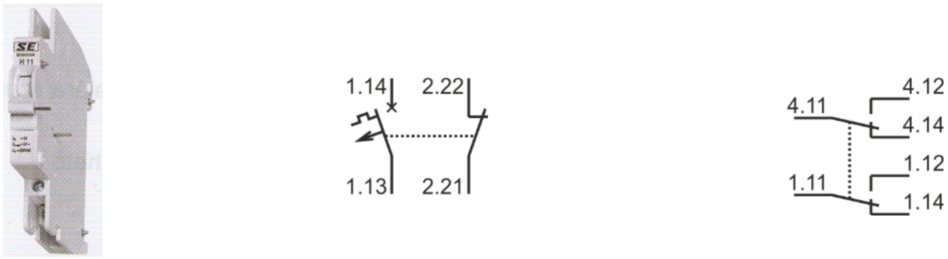
Fig. 6.11.a show the photo of a fuse with a pole for the neutral wire. This kind of automatic fuses is necessary if the current in the neutral wire is of the same order of magnitude or higher than that in the phases. *Fig. 6.11.b* shows its circuit symbol. *Fig. 6.11.c* shows the photo of a three-pole automatic fuse with switched neutral wire and *Fig. 6.11.d* its circuit symbol.



a) *b*) *c*) *d*)

Fig. 6.11. Fuse with 4 poles and with switched neutral wire (*source*: SCHRACK)

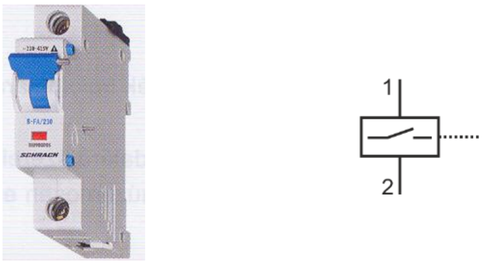
In *Fig. 6.12.a* the photo of an auxiliary contact e.g. for position signaling is shown and in *Fig. 6.12.b* its circuit symbol. This unit contains a normally open (NO) and a normally closed (NC) contact. In *Fig. 6.12.c* the circuit diagram of an auxiliary unit containing two Morse contacts can be seen.



a) *b*) *c*)

Fig. 6.12. Auxiliary contacts (*source*: SCHRACK)

Automatic fuses are always equipped with two overcurrent releases, but fuse manufacturers offer further releases as well which can be attached to the fuses mechanically similarly to the auxiliary contacts. In *Fig. 6.13.a* the photo of a working release can be seen and in *Fig. 6.13.b* its circuit symbol.



a) *b*)

Fig. 6.13. Working release (*source*: SCHRACK)

With the help of a working release an automatic fuse can be operated remotely as well. In *Fig. 6.13.a* a pin protruding from the blue actuator lever can be seen which tap opens the automatic fuse connected to its side.

6.4.3 Characteristics of automatic fuses

Current–opening time characteristics of different automatic fuses differ from each-other in the time period how long the short-circuit current has to flow through the device for releasing the magnetic fast release of the fuse. Characteristic curve of an automatic fuse is shown in *Fig. 6.14*. Because of manufacturing dispersion this characteristic curve is actually a characteristic band. Operating time of a certain device belonging to a certain current is inside the characteristic band. In *Fig. 6.15* the four different characteristics of automatic fuses are shown.

Characteristic current factors shown in *Fig. 6.14* are as follows:

- I_1 Thermal non-release current (flowing through the device it does not triggers operation within 1 hour);
- I_2 thermal release current (causes the operation of the device within an hour if it flows through it);
- I_3 short-circuit non-release current;
- I_4 short-circuit release current.

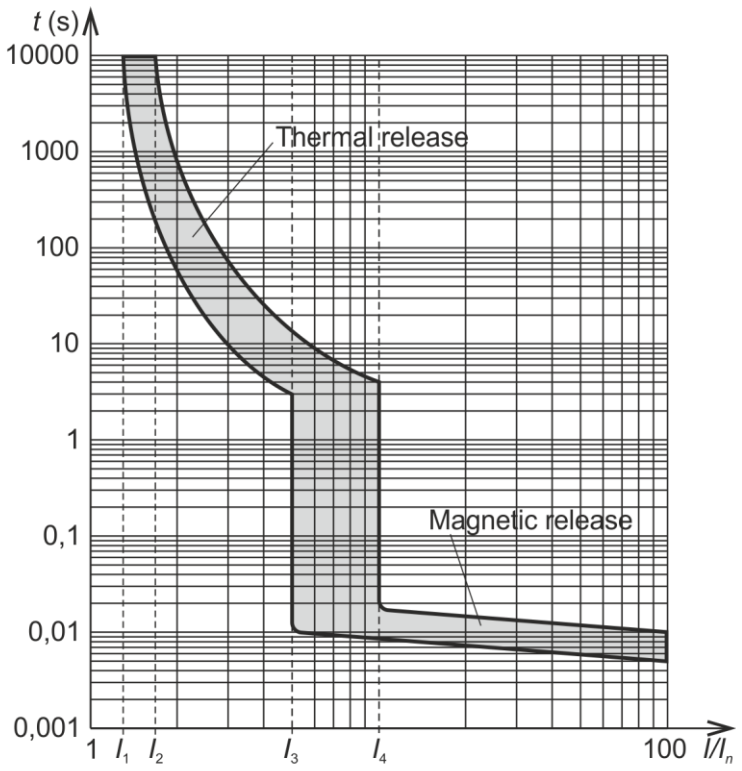


Fig. 6.14. Characteristic curve (band) of an automatic fuse

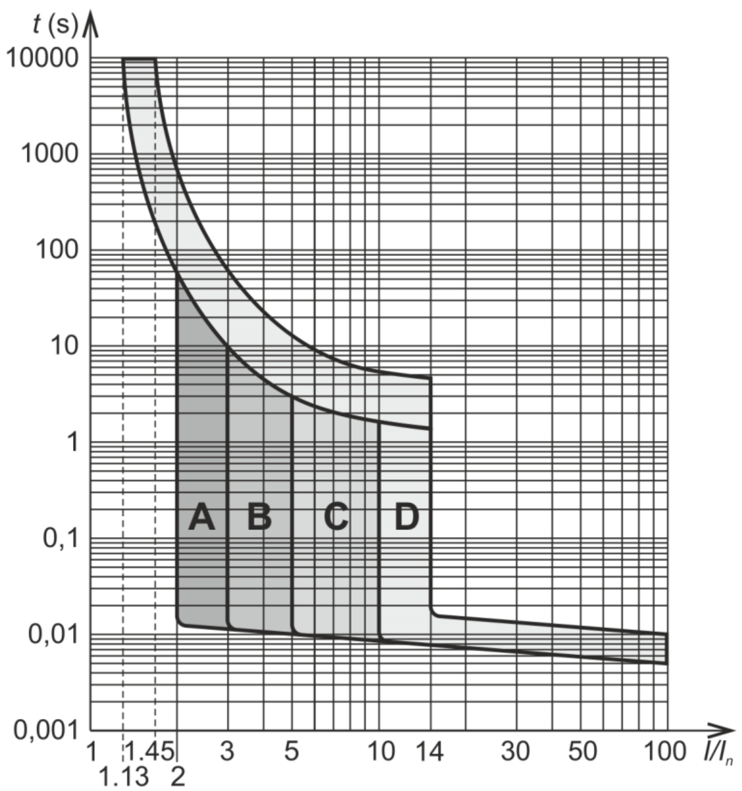


Fig. 6.15. Characteristic curves of automatic fuses

In *Figures 6.14* and *6.15* not absolute current values given in Amperes but values normalized according to the rated current are shown as multiplication factors without dimension on the horizontal axis of the diagram.

A value of I_1/I_n = 1.13 for the thermal non-release current and a value of I_1/I_n = 1.45 for the thermal release current is valid for every characteristics, only the values of I_3/I_n and I_4/I_n are different. The *Table 6.2* lists the key-letters, objective and multiplication factors of the short-circuit non-release and release current of the different automatic fuse characteristics.

Table 6.2. Standard characteristics of automatic fuses

Characteristic		**Short-circuit**	
Key-letter	**Denomination**	**non-release current**	**release current**
A	**Semiconductor protection**, for the protection of electronic circuitries	2	3
B	**Cable protection**, for the protection of cables, sockets, lighting and thermal devices	3	5
C	**Motor protection**, for the protection of circuitries containing normal motors	5	10
D	For the protection of circuitries with high starting current (motors, transformers)	10	14

Circuitries containing motors with powers lower than 3 kW can be protected with automatic fuses with characteristic „B". In *Table 6.3* non-standard automatic fuse characteristics are listed in the case of which I_1 = 1.05 and I_2 = 1.2.

Table 6.3. Non-standard automatic fuse characteristics

Characteristic		**Short-circuit**	
Key-letter	**Denomination**	**non-release current**	**release current**
E	**Exakt**, enables selective delay	5	6.25
Z	**Rapid semiconductor protection**, in case of low network impedance	2	3
K	**Kraft**, high switch-on current, sensitive overload operation	8	14

In general semiconductor manufacturers give the product $I_2 \cdot t$ (Joule integral) allowed for a given semiconductor device. This value is important for the installation of a selective protection as well as in case of intermittent operation.

If a load current load varying in time is

#	Period (minutes)	Current (A)
1	2	15
2	1.5	25
3	3	40

then the thermally equivalent current is

$$I = \sqrt{\frac{t_1 \cdot I_1^2 + t_2 \cdot I_2^2 + t_3 \cdot I_3^2}{t_1 + t_2 + t_3}} = \sqrt{\frac{2 \cdot 15^2 + 1.5 \cdot 25^2 + 3 \cdot 40^2}{6.5}} = 30.85\ \mathrm{A} \tag{6.4}$$

and the Joule integral is

$$I^2 \cdot t = 2{,}6^2 \cdot 10^6 \cdot 15 \cdot 10^{-3} = 101.4\ \mathrm{kA^2 s}\ . \tag{6.5}$$

If the preset time of a short-circuit protection differs from that given by the device/cable manufacturer then the actually allowed short-circuit current and the time delay can be derived from

$$I_{th}^2 \cdot t_{th} = I_{zeff}^2 \cdot t_z\ . \tag{6.6}$$

Then the allowed delay period is

$$t_z = t_h \frac{I_{th}^2}{I_{zeff}^2}\ , \tag{6.7}$$

and the allowed short-circuit current is

$$I_{zeff} = I_{\mathrm{th}} \sqrt{\frac{t_h}{t_z}}\ . \tag{6.8}$$

6.5 Circuit breakers

Circuit breakers are able to switch off short circuit currents, they are the most expensive switching devices installed in the grids. In high voltage stations the high voltage circuit breakers are the second most expensive elements. In *Fig. 6.16* low voltage circuit breakers are shown.

Fig. 6.16. Low voltage circuit breakers (source: SCHRACK)

Prescriptions related the construction, inspection and rated data of circuit breakers are stipulated by the standard **EN 60947-2:2007 Low voltage switching equipment. Part 2. Circuit breakers**. The symbol and design marking of circuit breakers on electric drafts is shown in *Fig. 6.17*.

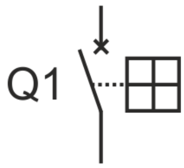


Fig. 6.17. Symbol of circuit breakers

Fig. 6.17 shows a single pole circuit breaker however it is a very rare variant, but it is drawn frequently on single line diagrams. The standard EN 60947-2 mentions the following data related to this topic:

- number of poles (1 – 4),
- type of current
  - direct current,
  - alternating current,
    - number of phases,
    - f_n rated frequency.

Fig. 6.18 shows the current and switching off time setting possibilities in case of low voltage circuit breakers.

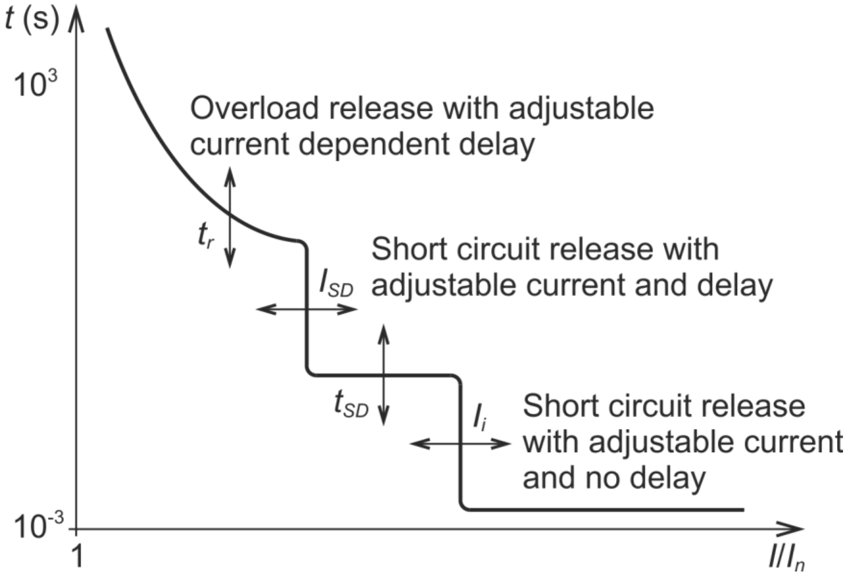


Fig. 6.18. Current and switching off time setting possibilities of low voltage circuit breakers

7 Electrical safety

Majority of electric circuitries and devices – even low voltage ones – operate on voltages dangerous for humans and for other living things. Getting into contact with live parts of low voltage networks, circuitries, i.e. with conductive parts being on rated voltage or even lower voltage levels, can result in fatal accidents. A contact of this kind results in an electric shock. Electric shocks on humans can lead to permanent disabilities or death.

The voltage itself as the line integral of the electric field strength does not cause direct danger. The harmful effect of electricity is caused by the current flowing through the human body – a conductive body – as a result of the voltage between different points of this body. Electric shock occurs if a human body becomes a part of an electric circuit.

Significantly different effects can caused by the
- electric current;
- electric arc;
- electromagnetic fields;
- static electricity.

> Electrical safety is a system of organizational measures and technical means to prevent harmful and dangerous effects of getting into contact with electric circuitries.

According to the standard 2004 NFPA 70E [7.1] the definition of electrical safety is as follows: “Electrical Safety – Recognizing hazards associated with the use of electrical energy and taking precautions so that hazards do not cause injury or death.”

Since electricity can cause fire or even explosion in several ways, electrical safety has fire protection considerations as well. For this reason the decree 54/2014 (XII.5) of the Ministry of the Interior on the Regulation of Fire Protection [7.2] has references to the electrical safety.

7.1 Physiological effects of electromagnetic fields

This section deals with the physiological effects of non-ionizing electromagnetic fields. These effects depend on several factors of the exposition of these fields onto human or other living beings. Physiological effects of an electromagnetic field depend on
- its intensity;
- frequency;
- duration of exposition.

It is well-known that if somebody is charged with static electricity his/her hair begins to stand apart because of the repulsion force of charges with the same sign. In electric fields of low frequency the hair begins to vibrate.

Bio-currents

There are electric currents in living bodies. These currents are called bio-currents and serve for the control of several functions of the life. For example the hart has an electrical control system.

Magnitude of bio-currents are expressed as current densities, which can be
- 0.1 μA/cm^2 in case of idle state and
- 1 μA/cm^2 as a result of in case of stimulus.

Since the majority of living bodies are conductive, also electromagnetic fields can induce current is them. For example an electric field with a field strength of 1 kV/m can induce a current density of 2.5 nA/cm^2. As a reference it is worthy to mention that a magnetic resonance imaging device (MRI) can induce current densities between 0.1 - 1 μA/cm^2 with its magnetic flux density of 0.5 – 5 T.

Ranges of induced current densities by biological effects up to 30 kHz:
- 0.1 - 1 μA/cm^2 – no biological effect observed;
- 1 - 10 μA/cm^2 – stimulus of the eyes, week muscle stimuli;
- 10 - 100 μA/cm^2 – significant muscle stimuli;
- > 100 μA/cm^2 ventricular fibrillation.

Exposition to electromagnetic fields

The directive 2013/35/EU of the European Parliament and of the Council on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields) [7.3] defines maximum electric field strength (*E*) and magnetic flux density (*B*) values for workers.

It has to be mentioned that much lower values are valid for the residential area. E.g. $B = 1000$ μT is the maximum value for workers but only 100 μT for the residents in the European Union.

In *Fig. 7.1* electric field strength values measured under overhead lines are shown. Only under the transmission line with the voltage of 400 kV can be measured electric field strength values above the residential exposure limit.

Frequencies above 30 kHz majority of the radiated energy is absorbed by the body. Depth of penetration is 10 cm in this case. Four ranges of the absorption spectrum are
- < 20 MHz – the sub-resonant range;
- 20 MHz - 300 MHz – the resonant range;
- 300 MHz - 2 GHz – range of inhomogeneous local absorption;
- > 2 GHz – superficial absorption.

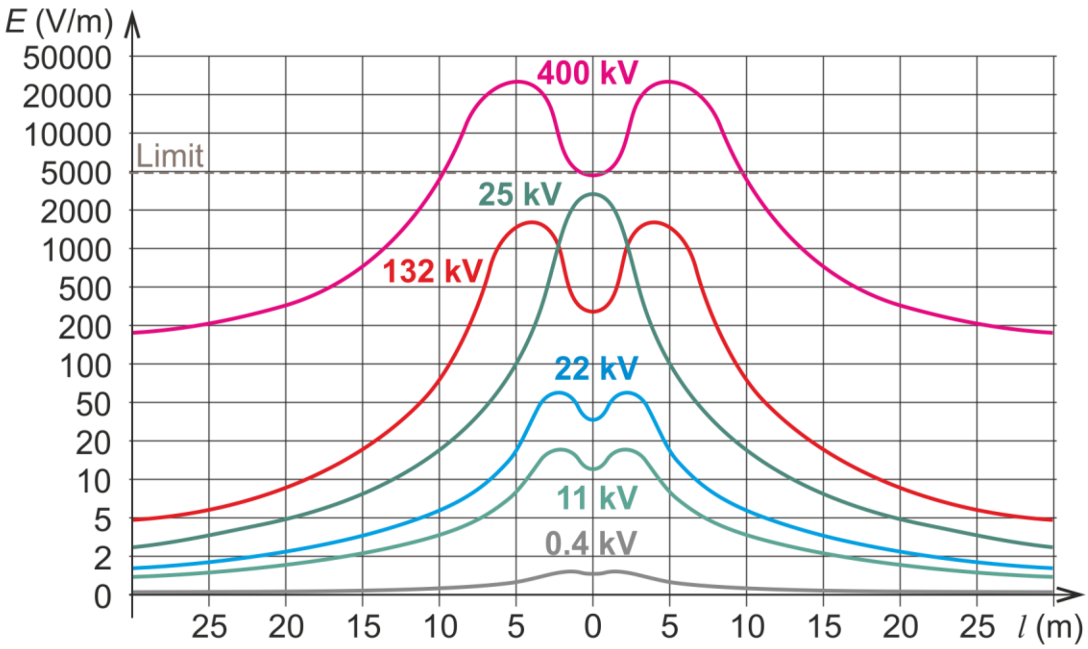


Fig. 7.1. Electric field strengths of overhead lines

7.1.1 Physiological effects of the electric current

This subchapter deals only with alternating electric currents of industrial frequencies (50 – 60 Hz). Effects of the current depend on several factors like

- art of the current, i.e. direct current (DC) or alternating current (AC);
- magnitude of the current;
- frequency of the current;
- state of the skin, i.e. wet, dry or damaged;
- current path.

Effects of currents of this kind are as follows:

- **1 – 2 mA** is the so called perception limit, i.e. the lowest noticeable current value;
- **3 – 5 mA** cause light shock;
- **6 – 10 mA** cause strong shock, strong vibration of the muscles;
- **25 – 40 mA** is the „let to go" range, if the living part (under voltage) is grabbed then the victim can not release it, respiratory arrest, severe muscular contractions can occur;
- **50 mA** cause ventricular fibrillation since electric current has effects on the electric control system of the heart;
- above **80 mA** cardiac arrest can occur, i.e. the heart stops beating and the victim becomes clinically dead.

7.1.2 Measures to do in case of electric shock

The person having been shocked has to be removed from the electric circuit by switching off the electric circuit/equipment. If this is not possible the victim has to be removed from the circuit by a mean made of insulating material. If the respiratory system or the heart of the victim has stopped the recovery of the respiration and the operation of the heart have to be started without delay.

The magnitude of the current flowing through the human body is determined by the magnitude of the voltage on the body and the resistance of the body part between the contact points. In case of dry skin the resistance can go up to several ten thousands ohm. The resultant resistance of the circuit can be further increased by the resistance of the shoes on the victim.

With sweat, wet or damaged skin the resistance of the body can be lower by orders of magnitudes. From electrical safety point of view the resistance of the human body has to be taken into account with a value of **800 ohm**.

Those written above are typical for relatively low currents. If the current flowing through the human body is higher than 1 A, then other physiological effect appear. If average humans becoming parts of high voltage circuits – with voltages of 11, 22, 35 kV – they do not die promptly, their death occurs one or two weeks later because of the arrest of the operation of one or more internal organs, typically of the kidney.

If somebody is stroked by a lightning, then the majority of its current with a peak value of several ten thousand amperes flows at the surface of the body because of its high frequency content. In most cases the heart of the victim stops and the parts of the cloths with high resistance of the victim can burst into flames. The revivification of the victim has to be started without delay, which has an average success factor of 50%.

7.2 Arts of environments

Several characteristics of the environment where an electric circuitry operates have impact on the measures and technical means applied for the safety of this circuitry. For example in wet environments other means are necessary for achieving appropriate safety than in dry rooms.

The standard HD 60364-5-54:2012 Low-voltage electrical installation. Part 5-54. Selection and erection of electrical equipment [7.4] defines the appropriate methods of installation of electrical equipment. Environments defined by this standard and their characteristics are listed below.

Dry environment

In dry rooms the relative humidity does not exceed 75% and in general no condensation of vapor, steam or humidity occurs in case of proper use of the room.

Dry rooms are for example:
- Residential rooms;
- offices;
- air intake stations;
- engineering shops;
- compressor station.

Intermittently wet environment

In intermittently wet rooms the relative humidity exceeds 75% only for short periods and condensation of vapor, steam or humidity appears only intermittently followed by a quick desiccation of the room in case of proper use of the room.

Intermittently wet rooms are for example:
- Kitchens in flats, residential houses;
- bath-rooms and shower rooms of flats;
- certain chemical laboratories;
- similar rooms of kitchens of factories.

Wet environment

In wet rooms the relative humidity exceeds 75% durably and condensation of vapor, steam or humidity occurs durably also in case of proper use of the room.

Wet rooms are for example:
- Cellars with poor ventilation;
- community wash-houses;
- shower rooms;
- baths;
- certain boiler-rooms;
- wells;
- public kitchens;
- laundries;
- factory dressing rooms;
- cold-storage plants;
- certain parts of canning factories;
- meat processing factories;
- dairy plants;
- leather factories;
- dye-houses;
- water pump stations;
- ore-washers, coal-washers;
- traditional rooms for keeping and feeding animals.

Dusty environment

In dusty rooms suspended dust or other contamination can deteriorate the insulation state, cooling circumstances or the operation of the electric circuitry/device when depositing on it.

Dusty rooms are for example:
- Brickworks;
- cement factories;
- grinding factories;
- foundries;
- mills;
- factories processing minerals or ores;
- certain rooms of chemical factories.

Caustic environment

In rooms with caustic atmosphere (with caustic vapor or steam) aggressive steam, vapor or liquid are always or durably present and or sediments or molds develops which can have harmful effect on insulating and/or conductive parts of the electric circuitry/device.

Rooms with caustic atmosphere are for example:
- Rooms of acidic batteries;
- certain rooms of chemical factories;
- certain rooms of paper and textile factories;
- electroplating rooms;
- souring rooms of food factories.

Warm environment

In warm rooms the temperature exceeds 35°C in general and separately 40°C at places not exposed to direct sunlight, independently from the season in case of proper use of the room. Warm rooms are for example:
- Boiler rooms;
- baking rooms of bakeries;
- parts of factories where thermal processing of metals takes place;
- smitheries;
- metal casting and melting factories;
- hot-rolling mills.

Free space

In free space electric equipment placed there is exposed to precipitates and/or other climatic effects like sunshine, ultra-violet radiation, wind, etc.

7.3 Inflammability classes

Inflammability classes relate to substances, compositions characterizing their behavior and danger posed by them on the basis of the physical and chemical character of the substance, composition [7.2].

Class of substances, compositions posing explosion risk

Following substances, compositions belong to this class:
a) Detonating, highly inflammable, inflammable, slightly inflammable substances and compositions according to the law on chemical safety;
b) liquids or melts with closed area flash points below 21°C, or with open area flash points up to 55°C, or the operation temperature of which is higher than the value of its open area flash point lowered by 20°C;
c) combustible gases, steams or fogs;
d) dusts composing explosive composition with the air;
e) substances, compositions of the inflammability classes “A” or “B” before this regulation came into force.

Class of inflammable substances, compositions

Following substances, compositions belong to this class:

a) Solid combustible materials if they do not belong to the class of explosives;
b) gas oils, fuel oils, petroleum with open area flash points above 50°C;
c) liquids, melts, petroleum with open area flash points above 55°C or with operating temperatures lower by at least 20°C than its open area flash point;
d) gases not combustible alone but feed the combustion except air;
e) building materials with ignition points above 150°C belonging to fire protection classes B-F determined according to related technical requirements;
f) watery dispersion systems the flash point of which can not be determined with standard methods and the combustible part is higher than 25% and water content is lower than 50%;
g) substances, compositions of the inflammability classes “C” or “D” before this regulation came into force.

Class of non-inflammable substances, compositions

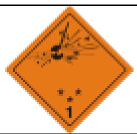
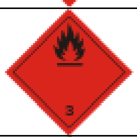
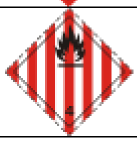
Following substances, compositions belong to this class:

a) Non-combustible materials;
b) building materials belonging to fire protection classes A1 or A2;
c) substances, compositions of the inflammability class “E” before this regulation came into force.

Symbols of dangerous substances, compositions

Warning symbols of some substances, compositions are shown in *Table 7.1*.

Table 7.1. Warning symbols of some substances, compositions

	Detonating substances, compositions and objects containing them.
	Inflammable gases.
	Inflammable liquids.
	Inflammable solid materials.

7.3.1 Environment with the risk of explosion

In environments with the risk of explosion only equipment can be kept in operation which has been designed, manufactured, installed and maintained according to the relevant legal regulations. Relevant regulations are:

- Directive 2014/34/EU (ATEX) [7.5];
- Decree 35/2016 (IX. 27.) of the ministry NGM on the testing and certification of equipment intended for application in environments with the risk of explosion (H) [7.6].
- Decree 22/2009 (VII. 23.) of the ministry ÖM on the regulations related to obtaining the fire protection certificate (H) [7.7].
- Decree 40/2017 (XII. 4.) of the ministry NGM onthe interconnecting and user equipment and on electrical equipment and protective systems operating in potentially explosive environment (H) [7.8].
- Standard EN 1127-1 Explosive atmospheres. Explosion prevention and protection. Part 1: Basic concepts and methodology [7.9].
- Standard EN 60079 [7.10].
- Standard EN ISO 80079 Explosive atmospheres. Part 37: Non-electrical equipment for explosive atmospheres. Non-electrical type of protection constructional safety "c", control of ignition sources "b", liquid immersion "k" (ISO 80079-37:2016) [7.11].
- Law 1996/XXXI on the protection against fire (H) [7.12].

An explosion can be

- physical explosion or
- chemical explosion.

Physical explosion occurs for example when a coffee machine or a boiler explodes. In these cases a transformation in the physical properties of the material occurs accompanying by a rapid energy change. If the temperature of the water under pressure inside a container increases above 100°C and an opening appears on this container then the water transforms suddenly to steam and its volume increases significantly.

In case of **chemical explosions** an extremely rapid combustion, i.e. oxidation occurs accompanied by heat releasing with a fire propagation velocity of higher than 100 m/s. Chemical explosions belong to the topic of explosion safety technology. The simultaneous presence of three factors is necessary for a chemical explosion. These three factors are:

- Explosive material;
- oxidizing material (e.g. air);
- effective ignition source.

According to the standard EN 1127-1:2012 [7.9] ignition source can be

- open flame;
- hot surface;
- exothermal reaction;
- mechanical spark;
- electrical spark;
- ultrahigh frequency radiation;
- radiofrequency radiation.

In the general industrial practice, i.e. in every industrial facilities except those of deep mining three risk categories are valid for explosive areas as follows:

- **Zone 0** (in case of risk of dust explosion Zone 20): continuous, long term presence of explosive atmosphere at normal operation (>1000 hours/annum).

- **Zone 1** (in case of risk of dust explosion Zone 21): non-continuous, but frequent, possible or log-term presence of explosive atmosphere at normal operation (10 - 1000 hours/annum or workers spend more than 50% of their work time in explosive atmosphere).
- **Zone 2** (in case of risk of dust explosion Zone 22): rare, short-term occurrence of explosive atmosphere typically not at normal operation (< 10 hours/annum).

Three categories of devices allowed to be operated in explosive zones are:
- **Category II 1GD** – the device must not become an ignition source according to the standard EN 1127-1 in case of two independently and simultaneously occurring malfunction. The risk assessment is performed by the notified body.
- **Category II 2GD** – the devices ensure an appropriate protection in case of frequent malfunctions or failures. The risk assessment is performed by the notified body.
- **Category II 3GD** – the device must not become an ignition source during its operation. The risk assessment can be comprehensively performed by the manufacturer.

Machines, equipment or devices intended for the production, processing, usage, storage or dosage of inflammable or explosive substances or compounds are allowed to be installed, sell exclusively in the case when they have a fire protection compliance certificate or an equivalent compliance certificate e.g. for being explosion proof issued by a notified body. Zone characteristics are listed in *Table 7.2* and Ignition temperature and energy of certain inflammable and explosive materials in *Table 7.3*.

Table 7.2. Characteristics of zones with risk of explosion

Occurence frequency of risk of explosion	Medium causing risk of explosion	
	Gas or fog	Dust
Continuous	Zone 0	Zone 20
Frequent, long-term or periodic	Zone 1	Zone 21
Rare, short-term or non-periodic	Zone 1	Zone 21

Table 7.3. Ignition temperature and energy of certain inflammable and explosive materials

Material	**Ignition temperature (°C)**	**Ignition energy (mJ)**
Flour	380	30
Wood	410	100
Brown coal	380	100
Black coal	500	1000
PVC	530	5
Al	560	5
S	240	10
Methane	595	0m28
H	560	0,016
Carbon bisulfide	95	0,009

Only non-flammable materials of the fire protection class A1 are allowed to be used as thermal insulating materials of buildings.

Harmful effects of explosions can be prevented by the followings:

- preventive measures:
  - preventing the build-up of explosive atmosphere;
    - filling up the container containing the explosive material with inert gas (e.g. with nitrogen),
    - continuous measurement of concentration of the explosive gas and signaling in case of dangerous level;
  - eliminating ignition sources;
  - minimization of the impacts of the explosion.

7.4 Protection against electric shock

Requirements of the protection of humans and the animal stock against electric shock are defined by the standard HD 60364-4-41:2007 Low voltage electrical installation. Part 4-41. Protection for safety. Protection against electric shock [7.13].

People and animals can become in contact with dangerous voltages by two ways:

- **Direct Contact**: Electric contact of persons or animals with **live parts** which are under dangerous voltage under normal, faultless conditions. Protection against direct contacts is called Basic Protection.

- **Indirect Contact**: Electric contact of persons or animals with an **exposed conductive part** which have become live under fault conditions. Then the person is subject to an indirect contact when touching a conductive part that can become live due to a single fault. Protection against direct contacts is called Fault Protection**.**

Live parts of electrical appliances are conductive parts of the appliances being under voltage in normal condition, i.e. during the operation or switched on state of the appliances.

The most important terms of this topic are defined by the standard IEC 61140 [7.14] as follows.
- **Exposed-conductive-part** is a conductive part of the electrical equipment, which can be touched and which is not normally live, but which **can become live when basic insulation fails.**

- **Extraneous-conductive-part** is a conductive part not forming part of the electrical installation and liable **to introduce an electric potential**, generally the electric potential of a local earth.

Fig. 7.2 shows an example of live, exposed and extraneous conductive parts of an electric motor. The winding live during operation of the motor is illustrated simplified. Live parts are drawn red in the figure, however the wires of the supply cable outside the motor are not parts of the machine. Exposed conductive parts of the motor are e.g. the housing the support, etc. Extraneous conductive part is the protective earth (PE) wire in the figure. *Fig. 7.3* shows an example of direct and indirect contact.

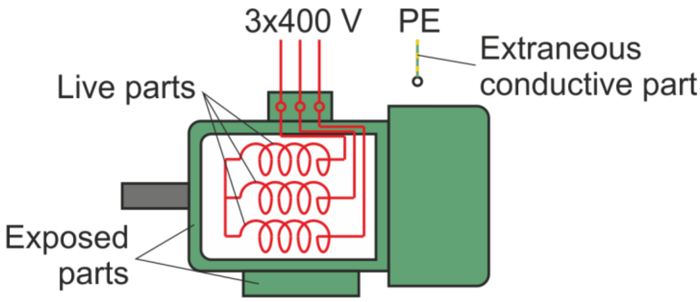


Fig. 7.2. Live, exposed and extraneous parts of an electrical appliance

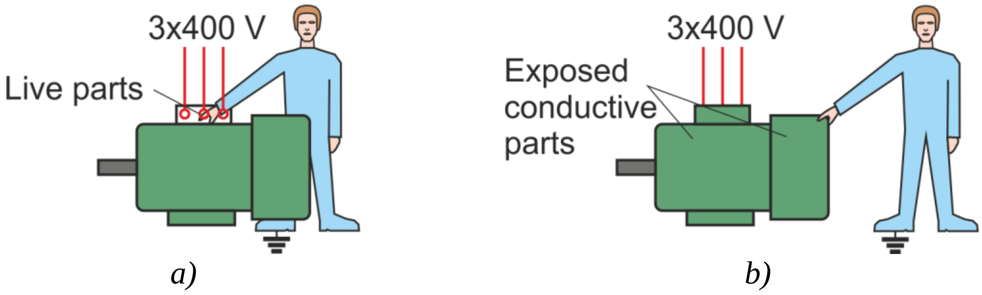


Fig. 7.3. Direct (*a*) and indirect contact (*b*)

Protection against electric shock is composed by two main parts which are as follows:

- **Basic protection** – protection from shock under normal – faultless – conditions is provided by basic protective provisions referred to as 'basic protection'.

- **Fault protection** – when the installation is in a single fault condition the shock protection is provided by fault protective provisions referred to as 'fault protection'.

Basic protection serves for protection against accidents caused by electric shock when getting into contact with normally live parts of electric equipment. Fault protection serves for protection against accidents caused by electric shock when getting into contact with normally not live parts of electric equipment normally however which can become live in case of a single fault – line-to-earth fault – of the equipment.

Protective measure shall consist of:

- An appropriate combination of a provision for basic protection and an independent provision for fault protection, or

- an enhanced protective provision which provides both basic protection and fault protection, like e.g. reinforced insulation.

7.4.1 Basic protection

According to the standard IEC 61140 [7.14] Basic Protection is the protection against electric shock under fault-free conditions. Basic protection can be formularized as protection against electric shock in case of normal – faultless – state of the electrical equipment.

Basic protection separates the normally live parts of the electric equipment from the normally not live parts of it and prevents live – dangerous – parts to be touched by unauthorized persons by applying one of the following measures:
- Basic – working – insulation of active parts;
- protective earthing (US: grounding);
- protective enclosure.

7.4.2 IP protection level

Requirements of degrees of the basic protection is defined by the standard EN IEC 60529:2015 Degrees of protection provided by enclosures [7.15] (MSZ 806-1:1976).

The IP degree of protection informs about the level of protection of the electrical equipment against intrusion of body part like hands and fingers, dust, accidental contact and water.

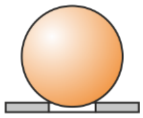
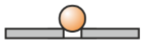
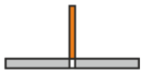
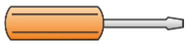
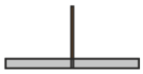
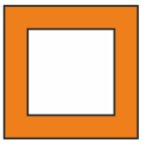
Degree of protection of an electrical equipment is marked with IP xy. IP is the abbreviation of International Protection followed by two digits. The first digit (marked with ‘x’ above) indicates the level of protection against access to hazardous parts and intrusion of foreign material like dust. The second digit (marked with ‘y’ above) indicates the level of protection against the intrusion of water.

Detailed description of the first digit (protection against intrusion of solid bodies):
0 - No protection, live parts can be touched freely and foreign bodies can get into contact with them;
1 - live parts can not be touched with the back of the hand;
2 - live parts can not be touched with fingers;
3 - live parts are not accessible with wires with diameters up to 2.5 mm;
4 - live parts are not accessible with wires with diameters up to 1 mm;
5 - ingress of dust is not entirely prevented, but it do not interfere with the operation of the equipment;
6 - no ingress of dust.

Detailed description of the second digit (protection against intrusion of solid bodies):
0 - no protection against the intrusion of water;
1 - protection against water dripping vertically;
2 - protection against water dripping at an angle of 15° to the vertical;
3 - protection against water dripping at an angle of 60° to the vertical;
4 - protection against water splashing at any angle;
5 - protection against water jet at any angle;
6 - protection against powerful water jet at any angle (or against water wave);
7 - protection against intermittent immersion into water;
8 - protection against durable immersion into water.

Meaning of the first digit is illustrated in *Table 7.4*.

Table 7.4. Illustration of the first digit of the IP protection code

Degree of protection	**Dimension**	**Intrusion of foreign bodies**	**Access of humans**	
IP1X	∅ ≥ 50 mm			back of the hand
IP2X	50 > ∅ ≥ 12.5 mm			finger
IP3X	12.5 > ∅ ≥ 2.5 mm			tool
IP4X	2.5 > ∅ ≥ 1.0 mm			wire
IP5X	protected against dust			wire
IP6X	protected against dust			wire

Meaning of the second digit is illustrated in *Figures 7.4* to *7.8*.

a) *b*)

Fig. 7.4. Equipment protected against the intrusion of water drops dripping vertically (*a*) and at an angle of 15° to the vertical (*b*)

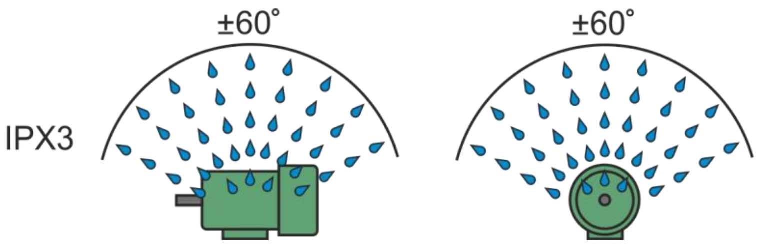


Fig. 7.5. Equipment protected against the intrusion of water drops dripping at an angle of 60° to the vertical

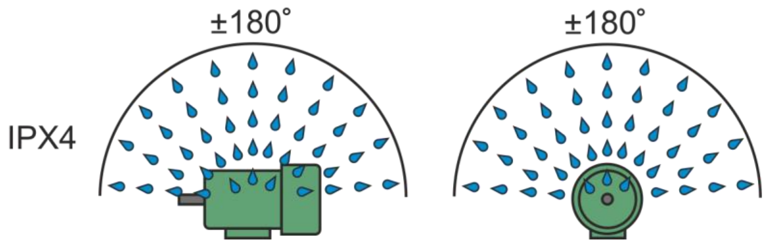
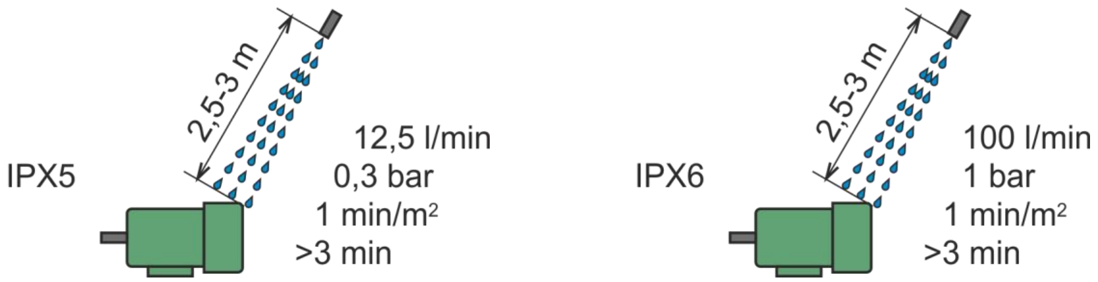
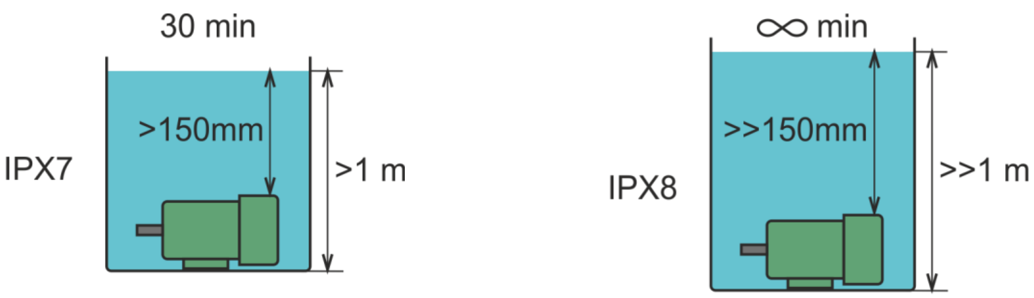


Fig. 7.6. Equipment protected against the intrusion of water splashing at any angle



a) *b*)

Fig. 7.7. Equipment protected against water jet at any angle (*a*) protection against powerful water jet at any angle (or against water wave) (*b*)



a) *b*)

Fig. 7.8. Equipment protected against intermittent (*a*) and durable immersion into water (*b*)

Symbols marking the second digit are illustrated in *Table 7.5*.

Table 7.5. Symbols illustrating the second digit

Degree of protection	Dimension	Intrusion of water
IPX1	Protected against dripping water	
IPX2	Protected against water dripping at an angle of 15°	
IPX3	Protected against water dripping at an angle of 60°	
IPX4	Protected against splashing water	
IPX5	Protected against water jet	
IPX6	Protected against powerful water jet (water wave)	
IPX7	Protected against intermittent immersion into water	
IPX8	Protected against durable immersion into water	

Electrical equipment with degree 6 are intended for the use on boards of ships. In case of degree 7 the equipment can be immersed into water e.g. for cleaning.

The protection of contactors and many other devices mounted into switch or control cupboards is in general IP 20. This means that their live parts can not be touched with fingers but water can intrude into them.

As a mater of course some pairs of numbers are excluded, like IP18 can not exist and some pairs of numbers are obvious, like IP 68 the degree of protection of a plunger pump. If the degree of protection of one of the two kinds is not identifiable or indifferent, than it is marked with X, e.g. IP X2. Further letters can be appended to provide additional information related to the protection of the device:

f - oil resistant;
H - high voltage equipment;
M - device moving during water test (e.g. its rotor);
S - device standing still during water test (e.g. its stator);
W - needs extra protection in case of certain weather conditions.

A part of the basic protection is the enclosure of the equipment. According to the standard EN 60529:2001 the enclosure is the part of the equipment which protects the equipment against certain external impacts and direct access to live parts of it, i.e. it composes a part of the basic protection. Tasks of the enclosure are

- the protection of humans, living things against access to the dangerous parts within the enclosure;
- the protection of the equipment inside the enclosure against

- the intrusion of foreign bodies, materials;
- the harmful effects of water;
- mechanical shocks;
- corrosion, corrosive solutions;
- living things, like molds, worms, rodents, etc.;
- sunshine;
- frost;
- explosive media.

7.4.3 Protection against external mechanical impacts

In this case the electrical equipment is protected, namely against external mechanical impacts. The standard IEC 62262:2002 Degrees of protection provided by enclosures for electrical equipment against external mechanical impacts (IK code) [7.16] defines the IK code system describing the level of protection of the electrical equipment against external mechanical impacts. The IK code and the energy of the impacts are listed in *Table 7.6*.

Table 7.6. IK code and the corresponding impact energy

IK code	Energy of the impact (joule)
01	0,14
02	0,2
03	0,35
04	0,5
05	0,7
06	1
07	2
08	5
09	10
10	20

7.5 Fault protection

According to the standard IEC 61140 [7.14] fault Protection is the Protection against electric shock under single fault conditions. More detailed the fault protection covers measures taken for the prevention of accidents resulted by touching exposed conductive parts of electrical equipment normally – in faultless condition – not under voltage, however which can become live in case of a fault. Fault protection covers the protection against step voltage as well.

According to IEC 61140 single fault condition is the condition under which either the basic protection against electric shock is defective or a single fault is present which could cause a hazard. Single fault condition can develop when a line-to-exposed-part fault appears in the electrical equipment.

Not all parts made of conductive materials normally not under voltage are exposed parts of the equipment. E.g. metal parts inside wall switches are not exposed parts in this sense. According to the relevant standard other metal parts of electrical equipment not considered as exposed parts are

- metal supports of insulators overhead lines fixed to buildings if they are out of the reach of humans;
- steel parts of the reinforcement of overhead line poles if they are not accessible;
- small parts (below about 50 mm x 50 mm), which can not be touched with the hand because of their dimensions or position or can not get in contact with a significant part of the human body if their connection to the protective conductor would be too complicated or not enough reliable. Such parts are e.g.:
    - Screws,
    - rivets,
    - data plates,
    - cable clamps;
- metal tubes protecting constructions with double or reinforced insulation or similar metal enclosures.

On exposed parts of electrical equipment can appear only voltages not exceeding the maximum allowed touchable voltage. Maximum allowed touchable voltages are:

- In case of industrial frequency (50 - 60 Hz) alternating currents 50 V;
- in case of direct currents 120 V.

According to the standard IEC 61140:2016 Protection against electrical shock. Common aspects for installation and equipment [7.14] the following protection classes are defined:

Class 0

No fault protection. Electrical appliances of Class 0 have only basic protection against electric shock and no fault protection.

Class I

“Protective earth”. Electrical appliances of Class I must have their exposed parts connected to electrical earth (US: ground) by a separate earth conductor (colored green/yellow in most countries, green in the US, Canada and Japan).

The basic requirement is that no single fault can result in dangerous voltage becoming exposed so that it might cause an electric shock and that if a fault occurs the supply will be removed automatically.

Protective earth means that an earth (ground) connection of the exposed conductive parts of electrical equipment helps protect from electric shock by keeping the exposed conductive surface of connected devices close to earth potential, when a failure of electrical insulation occurs.

When a fault occurs, current flows from the power system to the earth. The current may be high enough to operate the overcurrent protective fuse or circuit-breaker of the faulty circuit, which will then disconnect this circuit. To ensure the voltage on exposed surfaces is not too high, the impedance of the connection to earth must be kept low relative to the normal circuit impedance. Symbol of Class I protection is shown in *Fig. 7.9*.

Fig. 7.9. Symbol of Class I protection

Class II

Double insulated electrical appliances or those having reinforced insulation designed in such a way that they do not require a safety connection to the electrical earth. The basic requirement is that no single fault can result in dangerous voltages becoming exposed so that it might cause an electric shock and that this is achieved without relying on an earthed metal casing.

This is usually achieved at least in part by having at least two layers of insulating material between live parts and exposed parts, i.e. the user, or by using reinforced insulation. Double or reinforced insulation is marked with a double square shown in *Fig. 7.10*.

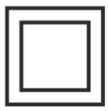


Fig. 7.10. Symbol of Class II protection

Class III

Appliances of Class III are designed to be supplied from a separated/safety extra-low voltage (SELV) power source. The voltage from a SELV supply is low enough that under normal conditions a person can safely come into contact with it without risk of electrical shock. The extra safety features built into Class I and Class II appliances are therefore not required. For medical devices, compliance with Class III is not considered sufficient protection, and further more-stringent regulations apply to such equipment. Symbol of Class I protection is shown in *Fig. 7.11*.

Fig. 7.11. Symbol of Class III protection

7.5.1 Automatic disconnection of supply

Automatic disconnection of the supply (ADS) of the faulty circuit belongs to the protection Class I and is an active fault protection method because it includes the operation of a switching device. If a dangerous voltage, i.e. voltage above the allowed maximum touch voltage appears on the exposed part of the electrical equipment, then the circuit protective device operates within the required time period for a given supply system.

In *Fig. 7.12* a simplified illustration is shown why dangerous voltages can appear on the exposed parts of electrical devices in case of earth faults. Neglecting the details of the faulty circuit behind the supply cable of the equipment half of the voltage of 230 V at the supply end of the cable drops on the line conductor with length of l, cross section of A and specific resistance of ρ and the other half of the voltage drops on the protective earth (PE) conductor with the length, cross section and material.

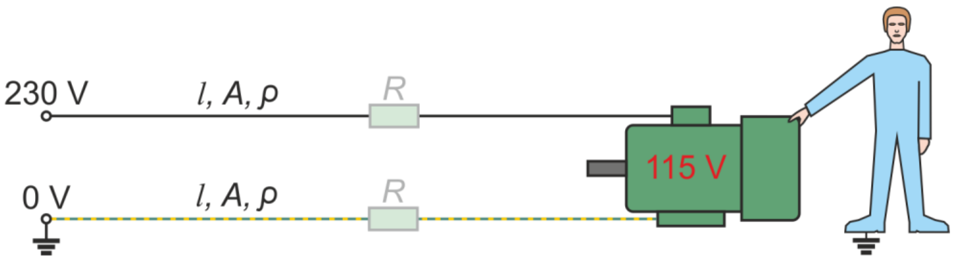


Fig. 7.12. Dangerous voltage on the exposed part of the electrical appliance

A circuit protective device can be a
- fuse;
- automatic fuse;
- circuit breaker;
- residual current device (RCD).

ADS can be realized in case of
- TN systems,
- TT systems,
- IT systems and
- systems with functional extra-low voltage (FELV).

In case of TN and TT systems an operational conductor of the supplying low voltage network is connected directly to the earth. This operational conductor is the neutral conductor (N). Star points of the low voltage winding of medium/low voltage transformers of the normal networks, e.g. public networks, are connected directly to the earth. The neutral conductor as an operational conductor of the network is connected to this star point (*Fig. 7.13*).

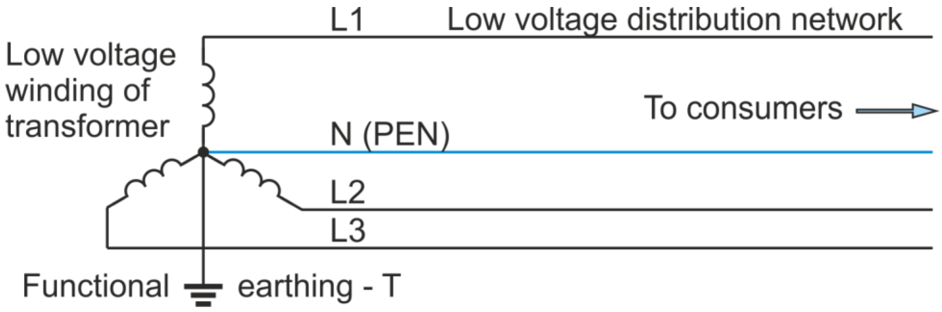
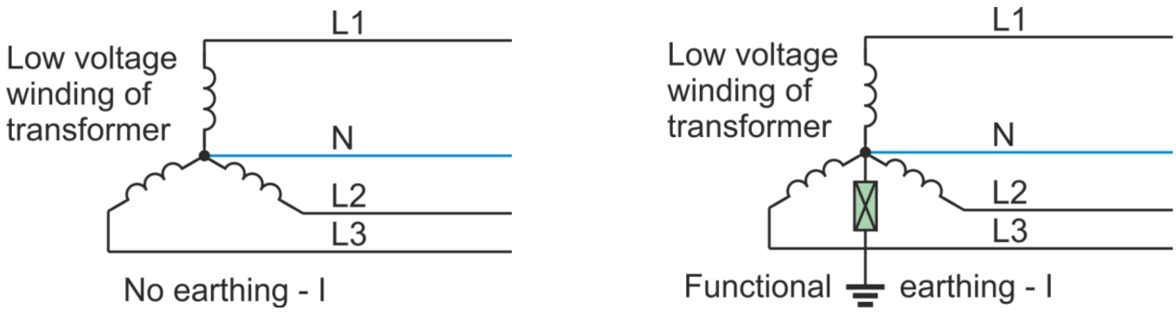


Fig. 7.13. Directly earthed network enabling TN or TT systems

In case of IT systems the star point of the supplying low voltage network is not connected directly to the earth, i.e. it can be insulated from the earth as shown in *Fig. 7.14.a* or connected to it through an impedance as shown in *Fig. 7.14.b*.



(*a*) (*b*)

Fig. 7.14. Insulated network (*a*) and network earthed through impedance (*b*)

The disconnection time period has to be short enough not to allow fibrillation to start if a person is in contact with the exposed part at the time.

If a line-to-exposed-part, i.e. line-to-PE contact with negligible impedance occurs in the electric circuit or structure, e.g. in case of a contact between a live part and an exposed part, then the circuit protective device has to disconnect the supply of the faulty circuit within a prescribed time period.

For the different cases the prescribed time periods are:

1) For end circuits up to 32 A the longest periods listed in *Table 7.7* have to be applied.
2) For distribution circuits and circuits in TN systems not belonging to 1) a disconnection period of maximum 5 s is allowed.
3) For distribution circuits and circuits in TT systems not belonging to 1) a disconnection period of maximum 5 s is allowed.
4) Meeting the above disconnection periods is not necessary if in systems with nominal voltage values higher than V_0 = 50 V in case of alternating current and V_0 = 120 V in case of direct current the output voltage of the supply source decreases to 50 VAC or 120 VDC or lower within the prescribed period listed in *Table 7.7* or within 5 s in case of a line-to-PE or line-to-earth contact. Cause of a disconnection can be other.

5) If the above automatic disconnection periods can not be realized, then auxiliary equipotential bonding has to be applied.

Table 7.7. Maximum disconnection periods

System	**50 V < V_0 ≤ 120 V** (s)		**120 V < V_0 ≤ 230 V** (s)		**230 V < V_0 ≤ 400 V** (s)		**> 400 V** (s)	
	AC	DC	AC	DC	AC	DC	AC	DC
TN	0,8	*	0,4	5	0,2	0,4	0,1	0,1
TT	0,3	*	0,2	0,04	0,07	0,2	0,04	0,1
If in TT systems the disconnection is realized by an over-current protection device and all foreign conductive parts in the equipment are connected to the EP bonding system, then the longest values valid for the TN system can be applied.								
* A disconnection can have other causes than the protection against electric shock.								

In case of fuses applied as disconnecting devices the disconnection multiplicators listed in *Table 7.8* can be applied in Hungary instead of the disconnection periods listed in *Table 7.7.*

Table 7.8. Multiplication factors to be applied in case of stationary equipment

Type of fuse	**I_n (I_{ch}) A**	**TN system (5 s)**	**TT system (1 s)**	**Portable equipment**
		α		
gG, gM (fast and delayed)	≤ 25 ≥ 32	3 4	5 7	6 8
gR (NOR, NOSi, NOGe)		2,5	4	6

Characteristic of the thermal releases of automatic fuses which currently meet the standards does not depend on type, thus a value of $\alpha = 5$ can be taken into account for all types corresponding to the disconnection period of 5 s prescribed for stationary equipment.

In case of portable equipment following α multiplication values can be applied:
- In case of automatic fuses type A: α = 3,
- in case of automatic fuses type B: α = 5,
- in case of automatic fuses type C: α = 10,
- in case of automatic fuses type D: α = 14.

TN system

TN system is the most commonly applied fault protection method. This is the preferred method, which means that the standard MSZ HD 60364 prescribes the application of this fault protection method in all cases where its preconditions are met and no other more severe method is prescribed for the given application.

In the abbreviation TN the letter T stands for the direct earthing (Terra - Earth in latin) of the network, i.e. the star point of it and the letter N stands for the Neutral conductor, because this conductor is a part of the short circuit path in case of line-to-exposed-part contact. TN system has three different cases as follows:

- TN-C system with common (C) neutral and protective earth conductors;
- TN-S system with separated (S) neutral and protective earth conductors;
- TN-C-S system with partly common, partly separated (C-S) neutral and protective earth conductors.

In TN-C systems a combined protective earth and neutral PEN conductor fulfills the functions of both a PE and an N conductor. In 3x400/230 V systems normally it is only used for distribution networks. Circuit of the TN-C system is shown in *Fig. 7.15* and the current path in case of PN contact in *Fig. 7.16*.

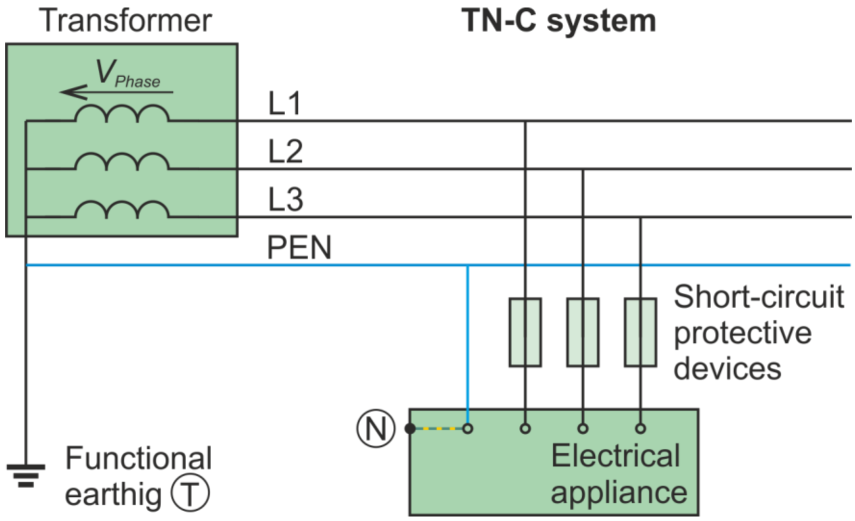


Fig. 7.15. Circuit of the TN-C system

The neutral (N) wire including the function of the protective earth (PE) wire has the marking **PEN**. According to the standard the cross section of the PEN conductor must be at least 10 mm^2.

In case of an earth fault, when a phase voltage – in *Fig. 7.16* phase voltage of L1 – becomes in contact with the exposed part of the electrical appliance, current flows on the PEN conductor connected to the exposed part of the appliance. The PEN conductor conducts the current to the star point of the low voltage transformer winding where it follows to flow to the line conductor of the supply cable of the consumer.

The voltage supplying this short circuit is a phase voltage of the system, in *Fig. 7.16* the phase voltage of L1. If the fault current is large enough, then it will trip the over-current device – in *Fig. 7.16* the fuse cartridge in L1 – and disconnect the supply.

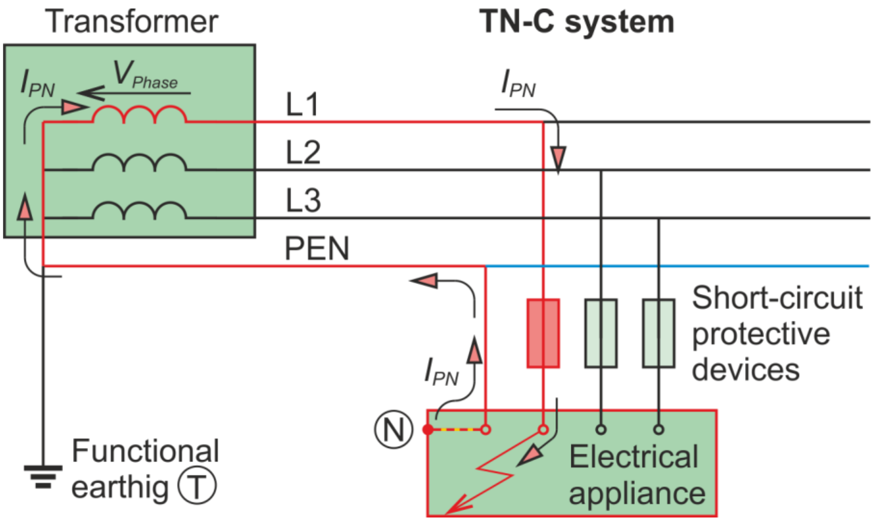


Fig. 7.16. Current path in the TN-C system in case of an earth fault

The TN system can be applied if the external preconditions of its application are met. The external preconditions can be fulfilled by the electric network operator (electric utility company).

These external preconditions are as follows:

1. The star point of the network is connected directly to the earth and is earthed in case of over-head lines at the end point and in every 350 m of the line.
2. The line-neutral loop impedance meets the tripping requirements at every electric construction of the network.
3. Neutral conductor – PEN conductor – at the connection point of the consumer has a cross-section of at least 10 mm^2.
4. At consumers connected to the network through an over-current protection higher than 25 A (at the kilowatt-hour meter) there is no protective earthing installed instead of ADS without RCD.

If external preconditions of the TN system are not met, it can still be applied for electrical consumers if the internal preconditions are met.

Internal preconditions are:

1. At the connection point to the public network a directly earthed, neutral wire with a cross-section of at least 10 mm^2 of the network is available.
2. The equipotential bonding network has been built on the whole area of the consumer cable network and a foundation earthing or other earthing with an earthing resistance not higher than 10 Ω – proven by measurement – is connected to it.
3. All consumers in free space to be connected to the TN system and all those consumers supplied from it are connected to the TN system (including those protected with RCD).

TN-S: PE and N are separate conductors that are connected together only near the power source. Circuit of the TN-S system is shown in *Fig. 7.17* and the current path in case of phase-PE contact in *Fig. 7.18*.

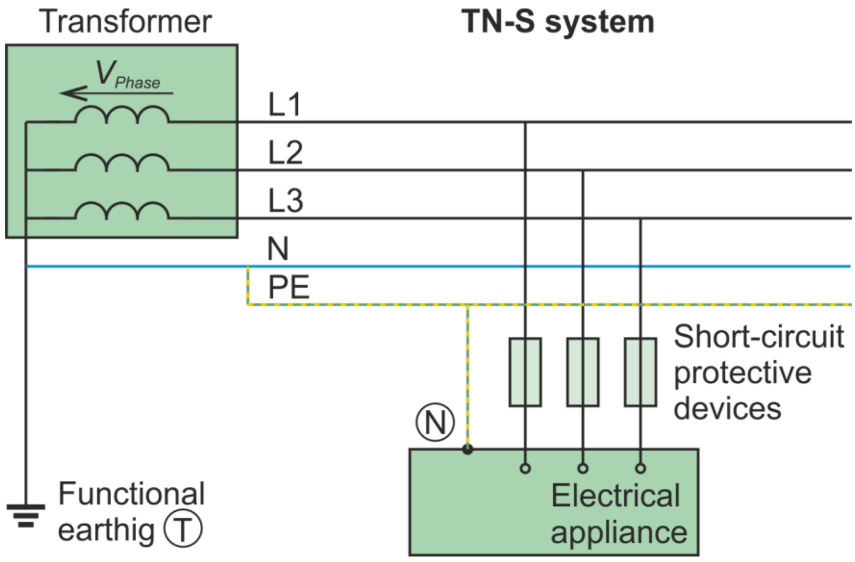


Fig. 7.17. Circuit of the TN-S system

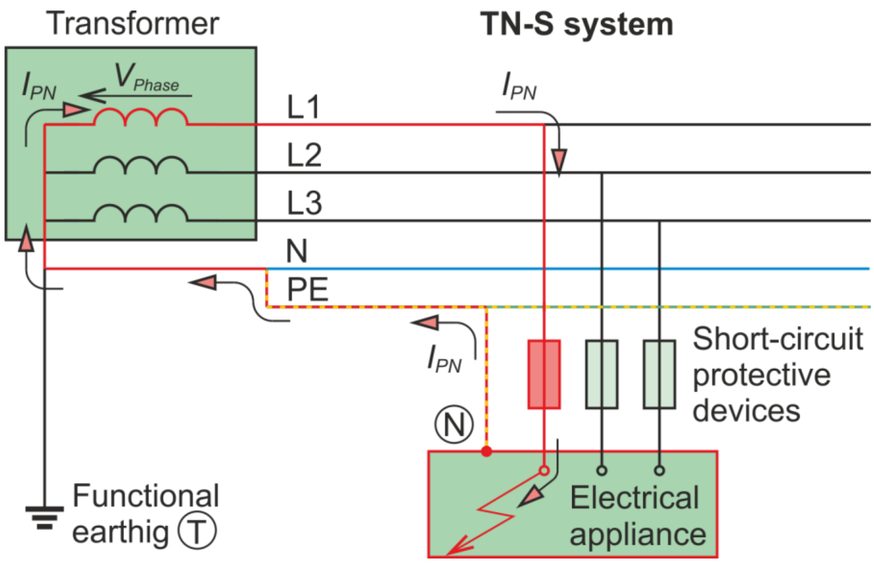


Fig. 7.18. Current path in the TN-S system in case of chassis contact

In TN-C-S systems a part of the system has a combined PEN conductor, which is at some point split up into separate PE and N conductors. The combined PEN conductor typically occurs between the substation and the entry point into the building and the protective earth and neutral are separated in the service head. Circuit of the TN-C-S system is shown in *Fig. 7.19*.

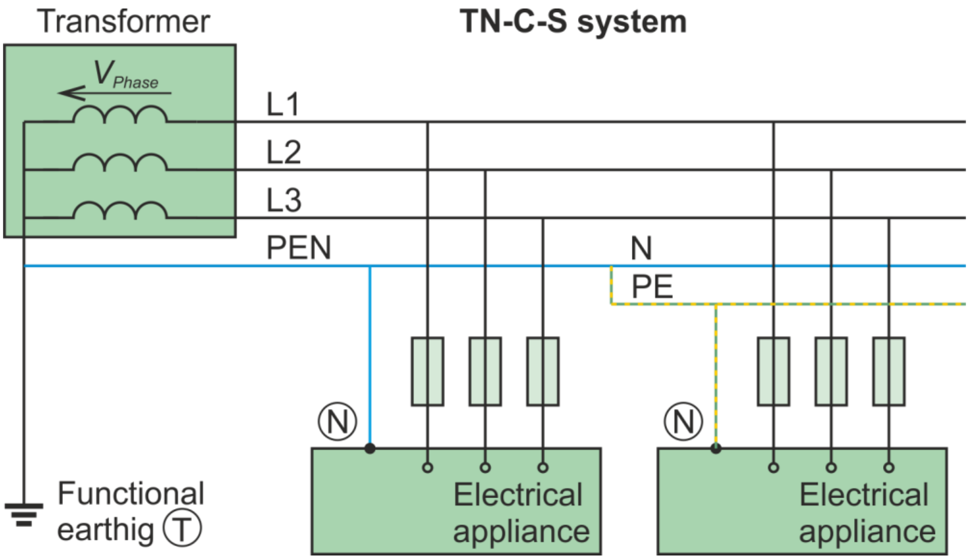


Fig. 7.19. Circuit of the TN-C-S system

In most cases the circuit protective device is the short-circuit protective device of the consumer, i.e. fuse or an automatic fuse. Precondition of the proper operation of the fault protection is that the short-circuit protective device disconnects the supply from the faulty circuit within the prescribed time period, e.g. within 5 s in case of stationary electric appliances.

Thus the loop impedance of the short-circuit path has to be lower than that allowing a current enough high to operate the protective device within 5 s. This means that

$$Z_s \cdot I_a \leq V_0, \tag{7.1}$$

where Z_s is the loop impedance in Ω;
I_a is the current in case of which the disconnecting device cuts the circuit within the prescribed period;
V_0 is the nominal voltage to the earth.

The current loop contains the

- supply source, typically the inductive reactance of the transformer is considered;
- line conductor from the supply source to the point of the fault, its resistance is considered;
- protective conductor from the point of the fault to the supply source, its resistance is considered.

If the circuit protective device is the short-circuit protective device, then the tripping current is

$$I_a = \alpha \cdot I_B \tag{7.2}$$

where α is the melting / operating multiplicator and
I_B is the nominal current of the fuse / automatic fuse.

Multiplicating factors for the protection of different appliances are listed in *Table 7.9*.

Table 7.9. Multiplicating factors for the operation within the prescribed period

Type of the fuse / automatic fuse	Value of the multiplicating factor in case of the protection of		
	Portable or during operation displaceable appliances	Equipment of the utility co.	Other appliances
NOR, NOSi, NOGe cartridges	-	2	2
Cartridges with delayed melting	-	3	4
Cartridges with fast melting	-	2,5	3
Autom. fuses of motor protection (U, G, C)	10	-	4
All other Automatic fuses	5	-	4

TT system

In a TT system, the protective earth connection for the consumer is provided by a local earth electrode and there is an other earthing at the star point of the network. There is no earth wire between the two. The fault loop impedance is higher, because the short circuit path contains the R_A earthing resistance. Circuit of the TT system is shown in *Fig. 7.20* and the current path in case of phase-PE contact in *Fig. 7.21*.

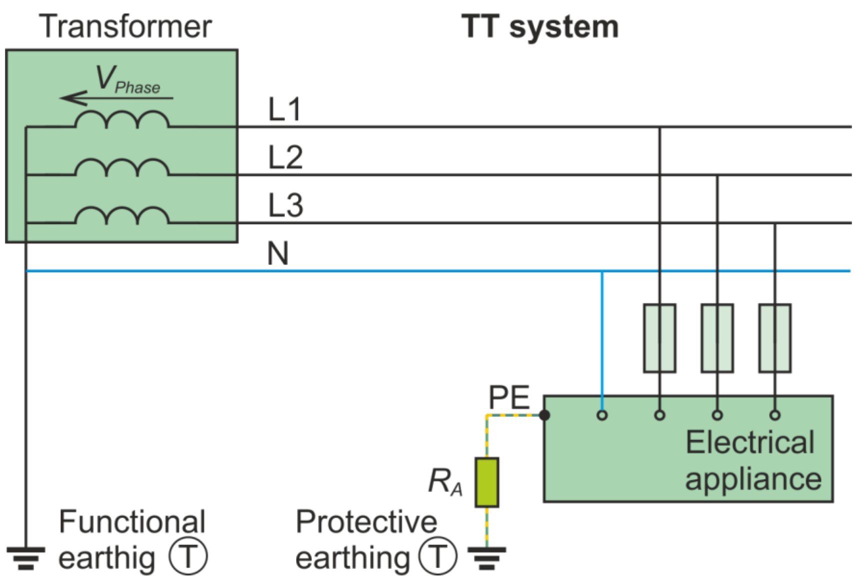


Fig. 7.20. Circuit of the TT system

In the abbreviation TT the letter T stands for the direct earthing of the network, i.e. the star point of it and the second T stands for the protective earthing at the consumer.

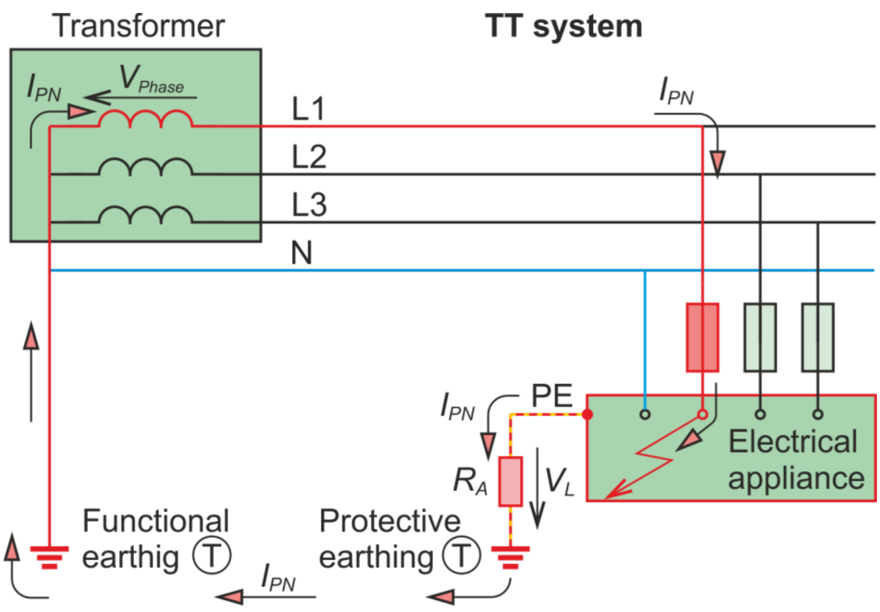


Fig. 7.21. Current path in the TT system in case of phase-to-exposed-part contact

In *Fig. 7.21* it can be seen that in case of TT the voltage appearing on the exposed of the electric appliance is determined by the R_A earthing resistance and the I_a short-circuit current. Thus the dimensioning equation of the TT system is

$$R_A \cdot I_a \leq V_L \tag{7.3}$$

where R_A is the earthing resistance of the exposed part of the protected appliance,
I_a is the current in case of which the disconnecting device cuts the circuit within the prescribed period calculated the same way as in case of TN;
V_L allowed maximum touch voltage (50 V).

This prescribed time and the current rating in turn sets a permissible maximum earth resistance. In case of TN the short-circuit current closes on cables conductors, thus the resistance of the short-circuit path can be rather easily controlled by selecting the appropriate cross-section of the cable. However in case of a TT system the short-circuit path contains the earthing resistance R_A which cannot be controlled easily, an earthing resistance of few tenth of ohms is very complicated and costly to realize.

It is obvious, that if an earthing resistance of 1 Ω is present, which value cannot be rationally realized at family houses at all locations, the phase-to-exposed part short-circuit current resulting 50 V on the earthing resistance is

$$I_{PN} = \frac{V_L}{R_A} = \frac{50}{1} = 50 \text{ A} . \tag{7.4}$$

If the protected consumer is a motor, then its nominal current must not exceed the value of

$$I_B = \frac{I_{PN}}{\alpha} = \frac{50}{10} = 5 \text{ A} \tag{7.5}$$

in case of portable or during operation displaceable appliances. To provide supplementary protection against high-impedance faults in case of high power consumers it is common to recommend a residual-current device (RCD).

IT system

In case of an IT system star point of the network is not connected directly to the earth. It can be either completely isolated from the earth, or connected to the earth through an impedance. Circuit of the IT system is shown in *Fig. 7.22* and the current path in case of phase-to-exposed-part contact in *Fig. 7.23*.

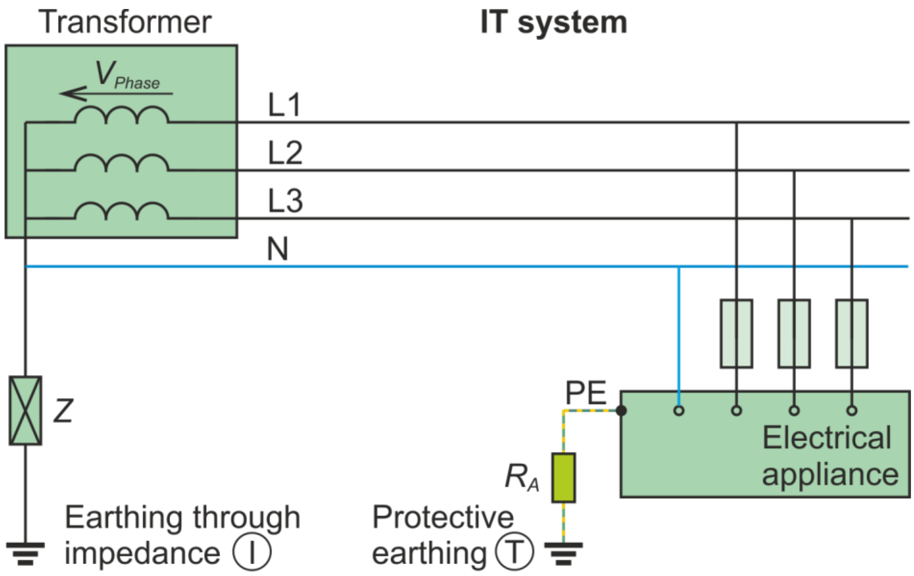


Fig. 7.22. Circuit of the IT system

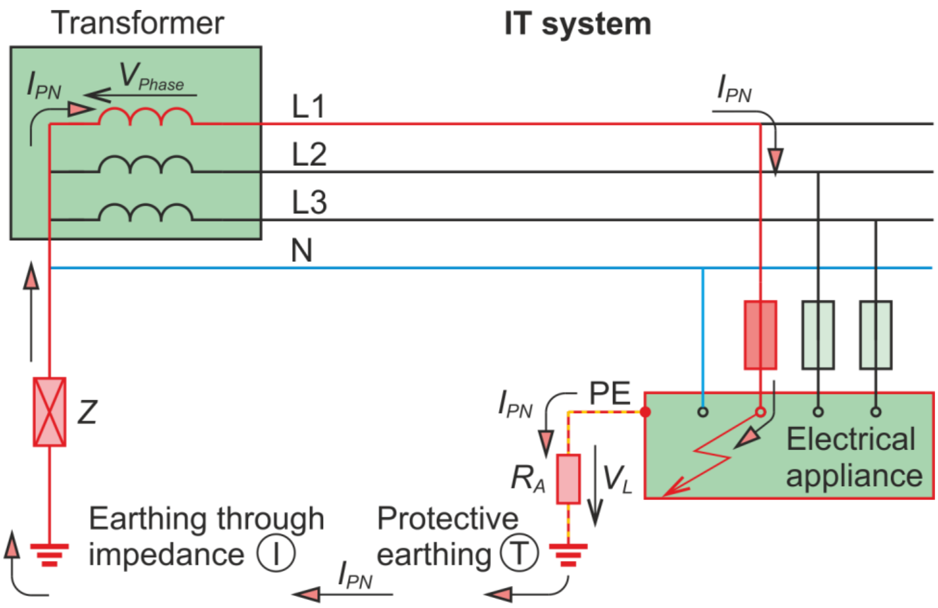


Fig. 7.23. Current path in the IT system in case of chassis contact

The problem with the short-circuit protecting device exist in the case of IT systems as well. A residual-current device (RCD) is necessary for the operation of the protection against electric shock.

Auxiliary protection

Auxiliary protective measures can be necessary for a certain method of protection under special circumstances or environments. If one or more conditions of the given method of protection can not be ensured, then auxiliary measures have to be done to guarantee the required level of safety. In case the fault protection art automatic disconnection of the supply (ADS) auxiliary protection can be a

- residual-current device (RCD) or
- supplementary equipotential bonding.

7.5.2 Double or reinforced insulation

Double or reinforced insulation composes the Class II fault protection. An alternative to protective earthing of exposed parts is a design with double or reinforced insulation, such that a single fault or highly probable combination of faults cannot result in contact between live circuits and the exposed parts (*Fig. 7.24*).

In case of this fault protection method exposed parts of the electrical equipment are separated from the live parts of the equipment with an insulation composing the basic protection and with a supplementary insulation as well.

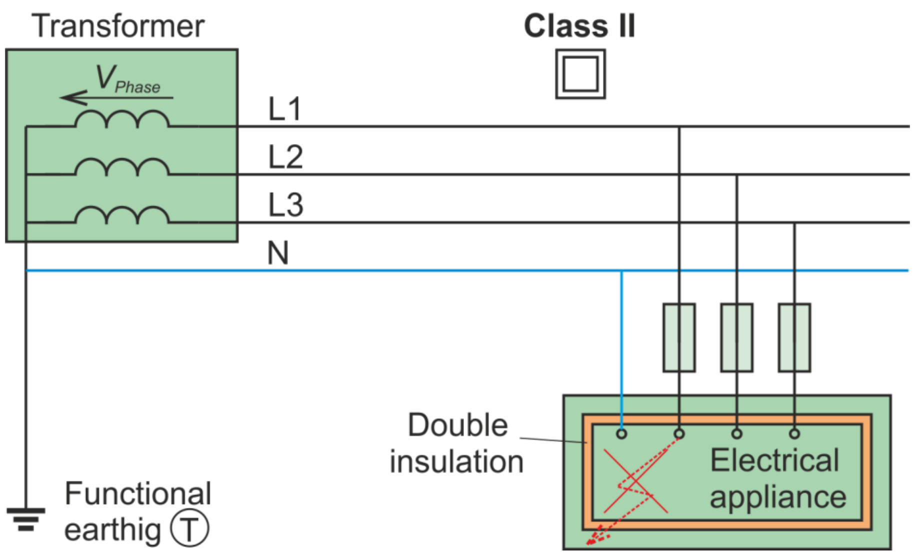


Fig. 7.24. Protection with double insulation

In most cases portable electrical equipment held by the user and those which can be displaced during operation are provided with this fault protection method. For example, a hand-held power tool might have an extra system of electrical insulation between internal components and the case of the tool, so that even if the insulation of the motor or the switch fails, the tool case is not energized.

The reinforced insulation is an improved basic insulation with such mechanical and electrical properties that, in itself, the insulation provides the same degree of protection against electrical shock as a double insulation. The reinforced insulation has two separate levels of protection which provide basic as well as the extra insulation.

Insulated AC/DC power supplies (such as cell-phone chargers) are typically designated as Class II, meaning that the DC output wires are isolated from the AC input. Typical components that are constructed with a reinforced insulation include optocoupler and power transformers. These will usually have a minimum insulation thickness of 0.4 mm. Others include reinforced insulation cables, reinforced insulation transformers, reinforced insulated meters, reinforced insulation tapes, etc.

Other than the protection against electric shocks, the reinforced insulation may provide a fail-safe operation that terminates the system activities when there is a failure. This helps in securing the components from damage by some of the faults. The level of insulation is very critical and affects the form factor, performance, reliability and cost of equipment such as transformers.

7.5.3 Extra-low voltage

Extra-low voltage (ELV) is an electricity supply voltage in a range which carries a low risk of dangerous electrical shock. There are various standards that define extra-low voltage.

The International Electrotechnical Commission member organizations define an ELV device or circuit as one in which the electrical potential between conductor or electrical conductor and earth (ground) does not exceed 50 V AC or 120 V DC (ripple free).

Extra-low voltages can be divided to
- functional extra-low voltage (FELV) – unearthed;
- separated or safety extra-low voltage (SELV) – unearthed;
- protected extra-low voltage (PELV) – earthed or unearthed.

Basically the second type of extra-low voltage (SELV) composes the Class III fault protection method, as this is indicated by its name: Safety. Aim of the application of functional extra-low voltage is not the protection against electric shocks. Its use has technological reasons.

Functional extra-low voltage (FELV)

The term functional extra-low voltage describes any other extra-low-voltage circuit that does not fulfill the requirements for an SELV or PELV circuit. Although the FELV part of a circuit uses an extra-low voltage, it is not adequately protected from accidental contact with higher voltages in other parts of the circuit.

Examples for FELV circuits include those that generate an extra low voltage through a semiconductor device or a potentiometer or a transformer. A typical example is the old door-bell circuit fed from a transformer. This kind of ELV is applied widely in the industry.

Separated or safety extra-low voltage (SELV)

IEC 61140 defines a SELV system as "an electrical system in which the voltage cannot exceed ELV under normal conditions, and under single-fault conditions, including earth faults in other circuits". Protection by SELV is used in high risk situations where the operation of electrical equipment presents a serious hazard to safety.

A SELV circuit must have:

- Electrical protective-separation (i.e. double insulation, reinforced insulation or protective screening) from all circuits other than SELV and PELV (i.e. all circuits that might carry higher voltages).
- Simple separation from other SELV systems, from PELV systems and from earth (ground).

The safety of a SELV circuit is provided by

- the extra-low voltage;
- the low risk of accidental contact with a higher voltage;
- the lack of a return path through earth (ground) that electric current could take in case of contact with a human body.

Fig. 7.25 illustrates the protection with separated extra low voltage. However line-to-exposed-part fault can occur within the SELV system but without electric shock to the person touching this part and without any current flowing through the person. The transformer symbol on the shield below the transformer refers to the insulating (separation) transformer.

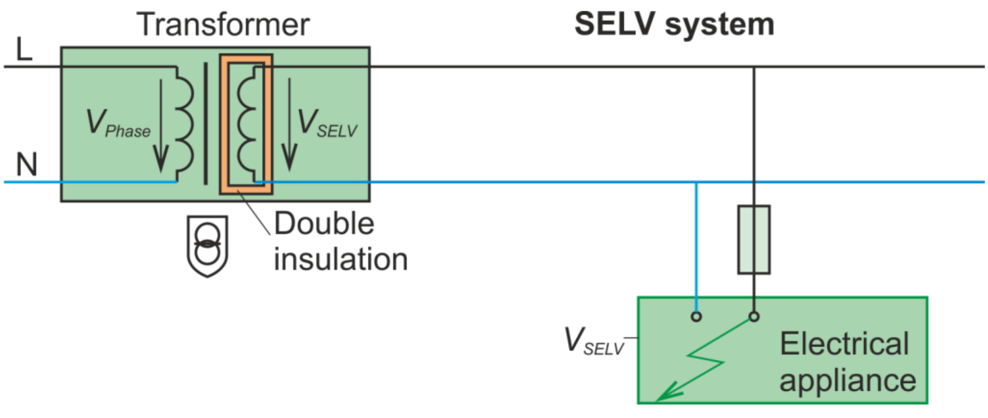


Fig. 7.25. Protection with separated extra low voltage

This part of the standard applies to plugs, fixed or portable socket-outlets, and to socket-outlets for appliances from 6 V up to and including 48 V DC or AC (50/60 Hz) SELV with rated current of 16 A, intended for household and similar purposes, either indoors or outdoors.

The design of a SELV circuit typically involves an isolating transformer, guaranteed minimum distances between conductors and electrical insulation barriers. According to the standard IEC 60884-2-4 Plugs and socket-outlets for household and similar purposes – Part 2-4: Particular requirements for plugs and socket-outlets for SELV the electrical connectors of SELV circuits should be designed such that they do not mate with connectors commonly used for non-SELV circuits (*Fig. 7.26*).

Fig. 7.26. ELV plug and socket

A very important application field of SELV are the circuits in contact with the patients of medical electrical appliances. Voltage applied in the circuits in contact with the body of the patients must not exceed 12 V (AC).

Other typical applications of SELV are
- Modern cordless hand tools;
- Class III battery charger, fed from a Class II power supply;
- Decorative out-door lighting;
- Pool lighting;
- Spa lighting;
- Sauna lighting;
- Bathroom lighting.

Protected extra-low voltage (PELV)

The standard IEC 61140 defines a PELV system as "an electrical system in which the voltage cannot exceed ELV under normal conditions, and under single-fault conditions, except earth faults in other circuits".

A PELV circuit only requires protective-separation from all circuits other than SELV and PELV (i.e., all circuits that might carry higher voltages), but it may have connections to other PELV systems and earth (ground).

In contrast to a SELV circuit, a PELV circuit can have a protective earth connection (*Fig. 7.27*). A PELV circuit, just as with SELV, requires a design that guarantees a low risk of accidental contact with a higher voltage. For a transformer, this can mean that the primary and secondary windings must be separated by an extra insulation barrier, or by a conductive shield with a protective earth connection.

A typical example for a PELV circuit is a computer with a Class I power supply. Some types of landscape lighting use SELV/PELV (extra-low voltage) systems. Modern battery operated hand tools fall in the SELV category. In more arduous conditions 25 volts RMS alternating current / 60 volts (ripple-free) direct current can be specified to further reduce hazard. Lower voltage can apply in wet or conductive conditions where there is even greater potential for electric shock. These systems should still fall under the SELV/PELV (ELV) safety specifications.

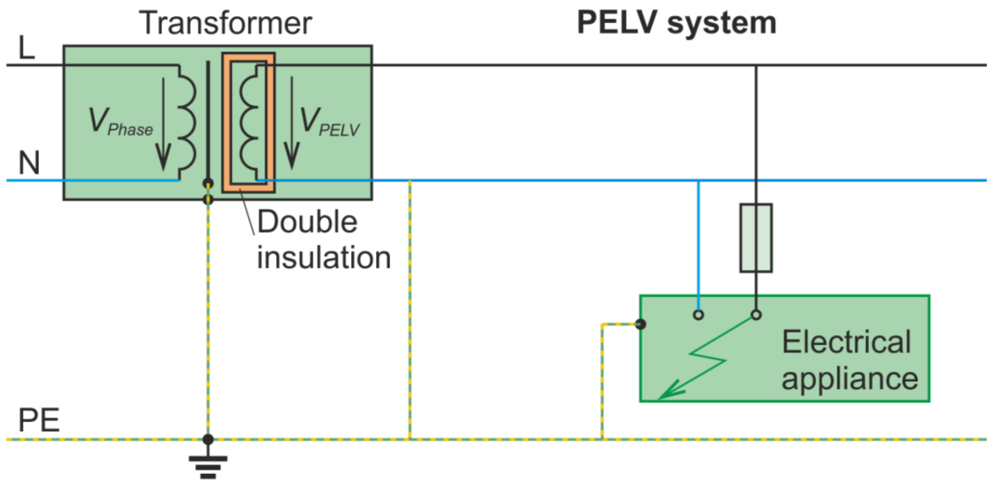


Fig. 7.27. Protection with protected extra low voltage

In *Fig. 7.28* an example is shown when an earth fault of another circuit can cause dangerous voltage on the earthed exposed part of the PELV consumer. The dangerous voltage is coupled by the PE conductor from the faulty consumer connected to a normal TN-S system.

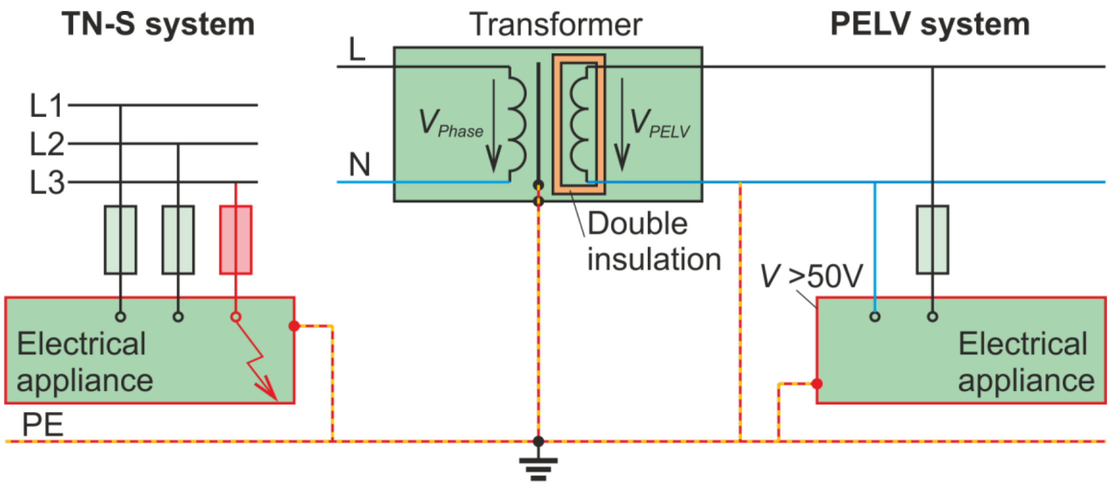


Fig. 7.28. Possible dangerous potential caused by an earth fault in another circuit

7.5.4 Electrical separation of the supply to one item

Electrical separation of the supply to one item of current-using equipment. In case of this fault protection method no earthing is present and if on the exposed part of the protected consumer dangerous voltage appears because of a fault, it does not cause accident if being touched (*Fig. 7.29*). The separation is realized with a transformer with a ratio of 1. No safety transformer required.

If the exposed part of the separated electric appliance is touched, then no current flows through the person touching the appliance because of the lack of closed circuit. The supply cable of a separated appliance must remain short because the longer is the cable, the higher is its capacitance to the earth and the higher current flows through the person.

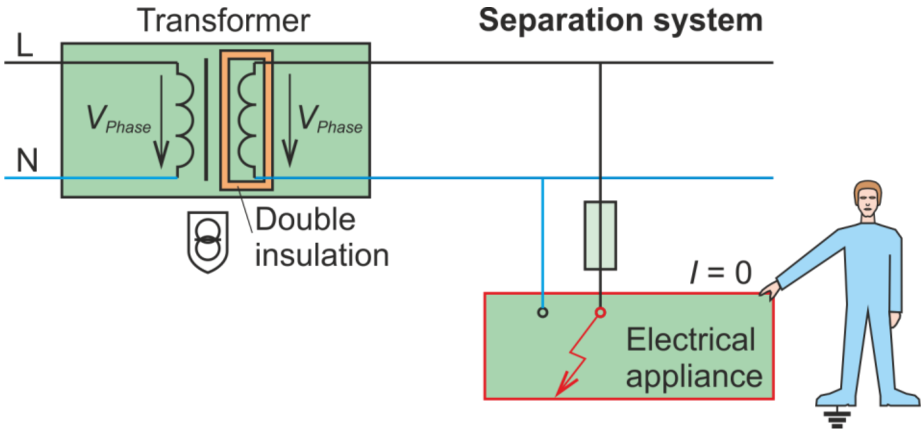


Fig. 7.29. Fault protection in case of a separated system

5 Separation of the electrical equipment

Separation of the electrical equipment means that its chassis can not be touched because of applying one the following measures:

- Active parts are enclosed with insulation which can removed only destruction.
- Active parts are placed behind protective enclosures the protection of which is at least 2X.

This fault protection method is allowed to be applied only in case of special precondition are met. It ensures only basic protection if the presence of unqualified persons is not allowed without supervision.

6 Separation of the environment

Separation of the environment prevents the simultaneous touching of parts of the electrical equipment which can get different potentials in case of a fault of the basic protection. Protective conductor must not be applied. This method can be realized as follows:

- Walls and floor of the room is made of insulating materials.
- Exposed parts of the electrical equipment are placed in appropriate distance from each-other and from foreign conductive parts. The appropriate distance means at least 2.5 m and 1.25 m outside of the range that can be reached with hands.

This method of fault protection can only be applied under continuous professional supervision of the equipment.

7 Fault protection with unearthed local bonding

This method of fault protection can only be applied under continuous professional supervision of the equipment. Every electrical equipment have to be provided with basic protection.

8 Separation of several electrical circuitries

This method of fault protection can only be applied under continuous professional supervision of the equipment.

In both cases a protective conductor is connected to the terminal available on the exposed parts of the electric appliance and the disconnecting device switches the faulty appliance from the mains in case of earth fault.

Main earthing busbar on the level of income, PE busbar in the other distributors and main earthing terminal are applied.

- In the main distributor only one protective conductor (of one circuit) is allowed to be connected to one terminal.
- The conductor has to be led from terminal to terminal without extension.
- Stranded conductors have to be connected with terminal blocks and protective metal terminals of appropriate size.

Protective earth:

- Exposed parts of an electric appliance has to be connected to the protective conductor according to the given conditions depending on the type of earthing of the given system.
- Exposed parts that can be touched simultaneously have to be connected to the same earthing system individually, in groups or collectively.
- Conductors used as protective earth conductors must comply with the standard HD 60361-5-54.
- Every circuit must have appropriate protective conductor connected to the appropriate earthing terminal.

Equipotential bonding

An inevitable measure of the fault protection with automatic disconnection of the supply is the equipotential bonding. Apart from the earthing conductor and the main earthing terminal the following conductive parts have to be involved into the equipotential bonding in every building:

- Public pipes in the building, like gas pipes and water pipes;
- third conductive structural parts accessible during normal use, like conductive parts of the central heating and air conditioning;
- metal parts of the reinforced concrete building elements if they are accessible and are reliably interconnected with each-other;
- all metal mantles of telecommunication cables taking into account the requirements of the owners or operators of the cables.

Conductive parts entering into the building from outside must be involved into the equipotential bonding inside the building closest to their point of entrance. According to some installation standards (KLÉSZ in Hungary) in communal and residential buildings those metal structures, machines must involve into the equipotential bonding to which one or more of the following conditions are valid:

- Their vertical dimension is higher than a complete story height of the building part there.
- Their horizontal dimension is higher than 5 m.

- They are not electrically insulated from the metal ducts leaving or entering the building as a result of their placement or of intentional measures.
- They are not electrically insulated from the above as a result of their placement or of intentional measures.
- Bathtubs of metal or not mobile metal containers with capacity of at least 500 l.

Connection of parts of a building can be omitted in case of which touching third potentials is less possible or can not easily be touched during normal use of the building, like:
- stair railings,
- balcony railings,
- railings of balconies,
- tin-plates of window sills.

Requirements of equipotential bonding conductors and those connected to the main earthing terminal or busbar are:
- Equipotential bonding conductors have to comply with the standard HD 60361-5-54;
- their cross section must not be less than
    - 6 mm^2 in case of copper,
    - 16 mm^2 in case of aluminum,
    - 50 mm^2 in case of iron;
- conductivity of an equipotential bonding conductor connecting two electric exposed parts together must mot be less than the conductivity of the least protective conductor connected to the exposed parts;
- conductivity of an equipotential bonding conductor connecting the exposed part to third conductive parts than the half of the conductivity of the relevant protective conductor, however in case of copper
    - at least 2.5 mm^2 if the conductors are mechanically protected and
    - minimum 4 mm^2 if the conductors are mechanically not protected.

A protective conductor can be a
- protective earth (PE) conductor;
- protective earth neutral (PEN) conductor;
- local equipotential bonding conductor or
- protective bonding conductor:
    - protective equipotential bonding conductor connected to the main earthing terminal or
    - protective equipotential bonding conductor connected to the protective equipotential bonding busbar.

If the protective conductor conducts fault current as well, then its marking is always PE, even if it serves for equipotential bonding at the same time. It is not allowed to use as equipotential bonding conductor the followings:
- Metal water pipes;
- pipes containing flammable gases or liquids;
- structural parts exposed to mechanical loads during their normal operation;
- flexible or rigid metal pipes if they were not intended for this purpose;
- flexible metal parts;
- support wires;
- cable trays and cable ladders.