MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
NATIONAL TECHNICAL UNIVERSITY OF UKRAINE
"IGOR SIKORSKY KYIV POLYTECHNICAL INSTITUTE"

DC AND AC POWER GRIDS WITH ALTERNATIVE ENERGY SOURCES - 2

LECTURE NOTES

Recommended by the Methodical Council of Igor Sikorsky Kyiv Polytechnic Institute as a tutorial for bachelors in the educational program "Electronic Components and Systems" Speciality 171 "Electronics"

Kyiv

Igor Sikorsky Kyiv Polytechnic Institute
2021

DC and AC power grids with alternative energy sources – 2: Lecture notes [Electronic resource]: tutorial for students speciality 171 "Electronics" / Igor Sikorsky Kyiv Polytechnic Institute; compiler: I.V. Verbytskyi – Electronic text data (1 file: 4,00 Mbyte). - Kyiv: Igor Sikorsky Kyiv Polytechnic Institute, 2021. – 88 p.

Stamp assigned Methodical Council of Igor Sikorsky Kiev Polytechnic Institute (Protocol N 8 of June 24, 2021)
at the request of the Academic Council of the Faculty of Electronics (Protocol N 06/2021 of June 22, 2021)

Electronic online educational publication

DC AND AC POWER GRIDS WITH ALTERNATIVE ENERGY SOURCES - 2

LECTURE NOTES

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The lecture notes of the dicipline "DC and AC power grids with alternative energy sources - 2" contain the main technical requirements and measures to coordinate the operation of power grids, reactive power compensation and elimination of power power distortion, describes the possibility of using power electronics to increase energy efficiency. The possibility of using DC power grids to reduce losses during electricity transportation is considered. The advantages and disadvantages after the transition from centralized to distributed power supply systems with intelligent control are analyzed. Also, in the lecture notes the methods of calculation of the devices of power electronics intended for increase of energy efficiency of electric networks are analyzed.

CONTENT

Introduction

The electric form of energy is used to power the vast majority of industrial electrical equipment and household appliances. Electricity transportation is the cheapest from an economic and energy point of view. Therefore, electricity is the main energy source and its consumption will increase over time.

Losses of electricity during its transportation from power plants to consumers in the power system of Ukraine account for 12% of its consumption. In developed countries, this figure is 4-6%. A large amount of losses is associated with the use of obsolete equipment, inconsistencies in the operation of the power system. In turn, these technical problems are caused by the lack of interest of owners of generating capacity and power grids in the modernization of network equipment due to the lack of state compensation programs and a fixed tariff that does not depend on the quality of electricity provided to consumers.

After Ukraine's accession to the European Energy Community, gradual reform of the energy sector began. The main task of the reforms is to create a competitive market where electricity suppliers can enter into contracts directly with consumers. The rules of functioning of the electricity market were approved by the law "On the principles of functioning of the electricity market of Ukraine.

The lecture notes of the credit module " DC and AC power grids with alternative energy sources - 2" contain the main technical measures to be taken to coordinate the operation of power grids, reactive power compensation and distortion power, describes the possibility of using power electronics to increase energy efficiency. The possibility of using DC power transmission to reduce losses during electricity transportation is considered. The advantages and disadvantages after the transition from centralized to distributed power supply systems with intelligent control are analyzed. The normative bases of modernization of the electricity market in accordance with the law "On the principles of functioning of the electricity market of Ukraine" are described. Also in the lecture notes the methods of calculation of the devices of power electronics intended for increase of energy efficiency of electric networks are analyzed.

Lecture 1. Modes of transmission of electrical energy in electric power systems

Basic terms and definitions

Energy efficiency ratio is the ratio of useful energy used to its total volume taken from the source.

Active power is the power expended to get the job done.

Reactive power is the period average of the energy circulating between the generator and the reactive load cells, divided by that period.

Apparent power is a value equal to the product of the effective values of the voltage and current of the network.

Distortion power is present in nonlinear circuits and characterizes the power of the higher harmonics of voltage and current.

For electrical energy on an industrial scale as a primary source often, use mechanical, thermal or light energy form. In this case, the efficiency of energy conversion is estimated by the efficiency η_P, which characterizes the ratio between the amount of energy W_P or the power of the P_P of the primary energy source and, accordingly, the amount of maximum electrical energy W_{Emax} or the maximum power P_{Emax}, that can be developed by the source of electrical energy:

$$\eta_p = W_{E\max} / W_p = P_{E\max} / P_p \,. \qquad (1.1)$$

In the electrical circuit of power supply systems, additional losses occur, which are estimated by the efficiency of electricity delivering (EED) η_E. EED is the ratio of the electrical power of the source P_P and the power of the load P_p:

$$\eta_E = P_p / P_E \,. \qquad (1.2)$$

The total efficiency of the use of primary energy η_Σ is calculated by the formula:

$$\eta_\Sigma = \eta_p \eta_E \,. \qquad (1.3)$$

Efficiency depends on the type of primary energy source and energy conversion technology. The value of the parameter η_P can be considered constant over the entire range of the permissible output power of the source of electrical energy η_P = const. Unlike the efficiency η_P, EED η_E can vary over a wide range; its value depends on the degree of consistency of the parameters of the load and the source of electrical energy and the amount of losses during the conversion of electrical energy parameters.

For the efficient use of energy sources, the maximum value of the efficiency of energy conversion η_P is provided. When transferring electrical energy from an energy source to a load, it may be expedient to both ensure the maximum value of the parameter η_E and the maximum possible output power of the P_E source. The type of primary energy source determines the choice between the criteria for the efficiency of electricity transmission.

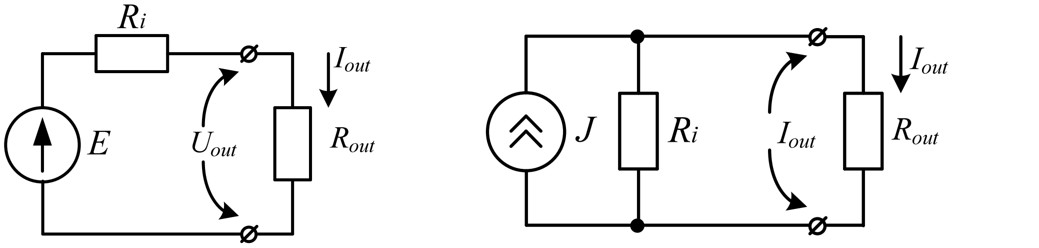
If the source of primary energy is free (solar, wind, geothermal energy), it is advisable to take the maximum electrical power. If the primary energy source is a paid (fossil fuels, nuclear fuel), it is necessary to ensure maximum EED η_E to reduce the cost of energy produced.

Consider the factors that affect the modes of transfer of electrical energy from the source to the load. The main characteristic of any source of electrical energy, which determines the efficiency of energy transfer, is its initial or load characteristic. It describes the dependence of the output voltage U_{OUT} on the output current I_{OUT}. To estimate the change of the output voltage ΔU_{OUT} to change the output current ΔI_{OUT} parameter using the output impedance of the power source R_{OUT}:

$$R_{out} = -\Delta U_{out} / \Delta I_{out}, \tag{1.4}$$

where the minus sign indicates that with increasing current, the output voltage of the source decreases, that is, the losses in the internal resistance of the source R_i increase. Electrical energy transmission modes are dependent on the ratio of the output resistance R_{OUT} source and load resistance R_L. Let's consider the case when the load characteristic of the source is linear. In this case, the output resistance is constant and equal to the internal resistance $R_{out} = R_i$. As you know, energy sources, depending on the principle of their operation, can be represented using an idealized voltage source E or current J, which take into account the conversion of non-electrical types of energy into electrical energy, as well as internal resistance R_i, which takes into account internal energy losses in the primary source.

The models of the system “source of electrical energy - load” is shown in Fig. 1.1.



a) based on a constant voltage source b) based on a constant current source

Fig. 1.1. Models of the system “source of electrical energy - load”

Let us calculate the dependence of EED η_E and the load power of the P_L on the ratio of the resistances R_L and R_i for models based on a voltage and current source. For a voltage source E, the load power of the P_L is calculated:

$$P_L = E^2 R_L / \left(R_i + R_L\right)^2 . \tag{1.5}$$

According to (1.5), the parameter η_E is calculated:

$$\eta_E = \frac{P_L}{P_E} = \frac{E^2 R_L / \left(R_i + R_L\right)^2}{E^2 / (R_L + R_i)} = \frac{R_L}{\left(R_i + R_L\right)} . \tag{1.6}$$

To simplify further calculations, we introduce the variable $k = R_L/R_i$. Given this (1.5) and (1.6) have the form:

$$P_L = \frac{E^2}{\left(R_i + kR_i\right)^2} kR_i = \frac{E^2}{R_i} \frac{k}{\left(1+k\right)^2} . \tag{1.7}$$

$$\eta_E = k / 1 + k . \tag{1.8}$$

Maximum load power $P_{L\max}$ according to (1.7), attainable at $k = 1$, that is, when the load resistance is equal to the source resistance $R_L = R_i$:

$$P_{L\max} = \frac{E^2}{\left(R_i + kR_i\right)^2} kR_i = \frac{E^2}{4R_L}. \tag{1.9}$$

According to this condition, the power dissipated at the load R_L is equal to the power dissipated at the internal resistance of the source R_i, that is, EED $\eta_E = 0.5$. Let us analyze the value of the parameter η_E and the power of the P_L for other values of k using the graphs of their functions $\eta_E(k)$ and $P_L(k)$, which are shown in Fig. 1.2.

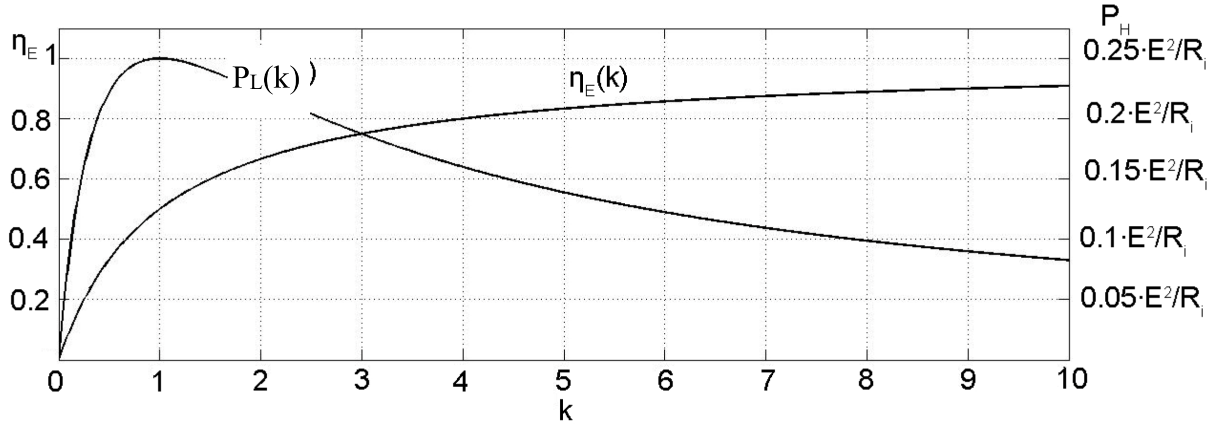


Fig. 1.2. Graphs of power and efficiency of the power supply system based on the voltage source

Analysis of the dependencies shown in Fig. 1.2, shows that at $R_L < R_i$, the use of the power supply system is ineffective, since in this mode both parameters: P_L power and efficiency η_E are less than at the point of maximum power $R_L = R_i$.

At $R_L > R_i$, the power of the P_L is less than the $P_{L\max}$, but the power transmission EED increases. Therefore, to reduce losses in the system, an energy source with a power reserve is often used and the operating mode is provided from the condition $R_L > R_i$. For most systems operating on fossil energy sources $\eta_E > 0.9$, which corresponds to the ratio $R_L > 9\,R_i$. In this case, a voltage source running at close to idle.

When using power systems based on a current source, the P_L load power is calculated:

$$P_L = \frac{J^2 R_i^2}{\left(R_i + R_L\right)^2} R_L = \frac{J^2 R_i^2}{\left(R_i + kR_i\right)^2} kR_i = J^2 R_i \frac{k}{\left(1+k\right)^2}. \tag{1.10}$$

Taking into account (1.10), the parameter η_E is equal to:

$$\eta_E = \frac{P_L}{P_E} = \frac{J^2 R_i^2 R_L / \left(R_i + R_L\right)^2}{J^2 R_i R_L / (R_i + R_L)} = \frac{R_i}{\left(R_i + R_L\right)} = \frac{1}{1+k}. \tag{1.11}$$

The graphs of the functions $P_L(k)$ and $\eta_E(k)$, calculated by (1.10) and (1.11), are shown in Fig. 1.3.

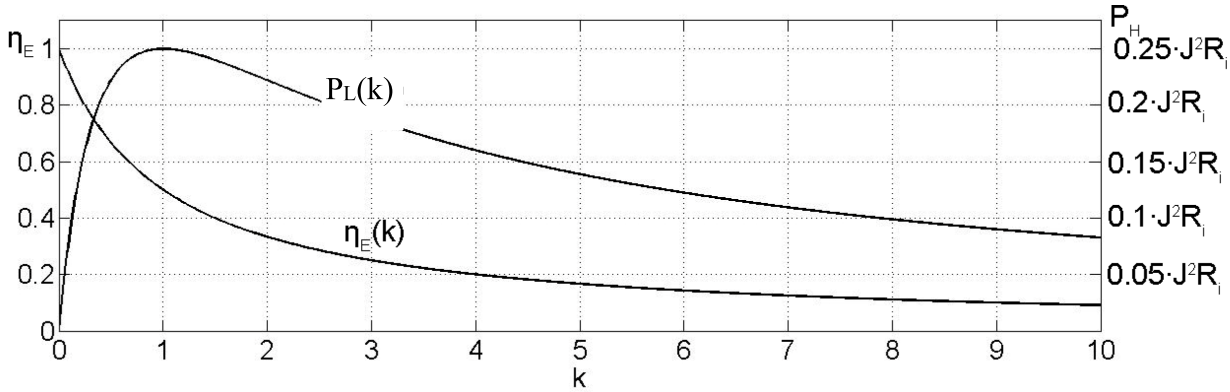


Fig. 1.3. Graphs of dependences of power and efficiency of the power supply system

Analysis of Fig. 1.3, we can conclude that the maximum power from the current source is achieved under the same condition as for the voltage source, $R_L = R_i$. To ensure a high EED η_E, it is advisable to operate the system at $R_L << R_i$.

For energy sources with nonlinear internal resistance, the graphs of output power and EED are built based on graphs of their load characteristics, which can be divided into two types, which is shown in Fig. 1.4.

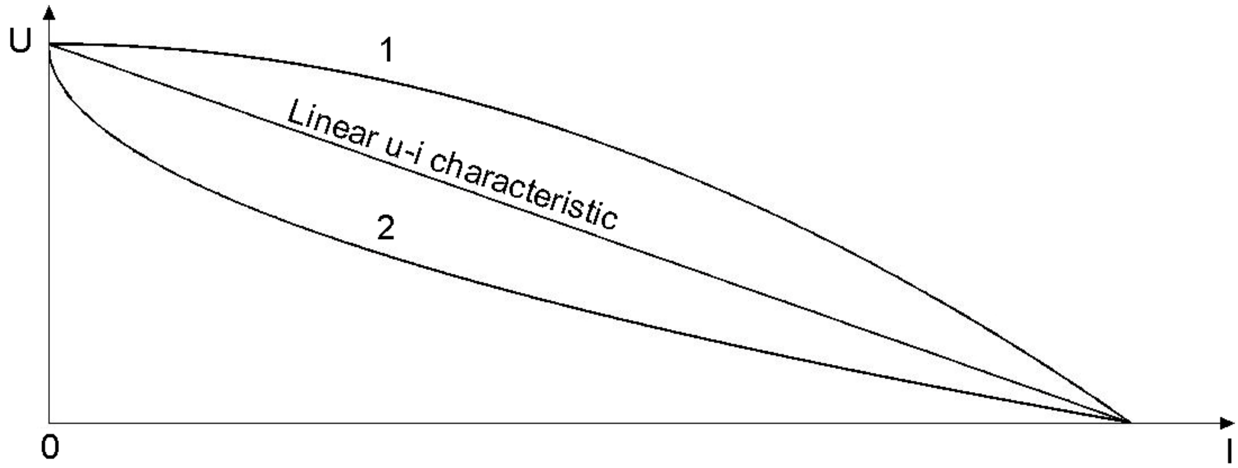


Fig. 1.4. Types of nonlinear current-voltage characteristics

Power supplies with load characteristics of type 1, which are above the linear characteristic, have a higher EED, and their maximum power point is shifted towards higher currents and voltages. Sources of type 2 have a lower EED, their maximum power point is shifted towards lower currents and voltages. To ensure operating modes with a constant EED or output power, it is necessary to maintain a constant ratio of the output impedance of the source and the load. In DC power systems, for this purpose, pulse regulators (PR) of constant voltage are used, which are connected between the power source and the load, as shown in Fig. 1.5.

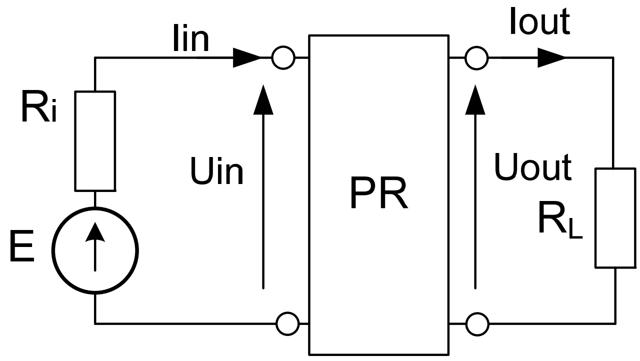


Fig. 1.5. Scheme of matching the parameters of the constant current source and load

In this scheme, the PR acts as a DC voltage transformer. Let the voltage at the input of the converter be n times greater than at the output: $U_{input} = nU_{output}$. If losses in the converter are applied, that is $P_{input} = P_{out}$, the input current of the converter is n times less than the output current: $I_{input} = I_{out}/n$. Then the input impedance of the converter is:

$$R_{in} = U_{in} / I_{in} = n^2 U_{out} / I_{out} = n^2 R_L . \tag{1.12}$$

Analysis (1.12) shows that the use of a converter allows changing the input load impedance at the generator output. When using PR, it is necessary to take into account that the input, output current and voltage of the PR contain an alternating component.

As a rule, the voltage ripple is insignificant, but in some PR, for example, in buck converters, the amplitude of the variable component of the input current is commensurate with its average value, which significantly reduces the EED of energy sources. An increase in the ripple amplitude does not affect the value of the energy that is transferred to the load, since it depends on the average values of the current I_d and voltage U_d. However, with an increase in the ripple amplitude, the effective value of the current I and the voltage U increases. Therefore, the energy losses in the conversion circuit also increase. For example, the effective value of the current I, taking into account the average value of I_d and the amplitude of the ripple $I_{m\sim}$, the shape of which is shown in Fig. 6 a), calculate:

$$I = I_d \sqrt{1 + \frac{1}{3}\left(\frac{I_{m\sim}}{4I_d}\right)^2} . \tag{1.13}$$

From the analysis of (1.13), it can be concluded that the effective value of the current I increases with an increase in the current ripple factor $K_{p(i)} = I_{m\sim} / I_d$.. The current, the shape of which is shown in Fig. 1.6 a), typical for converters at the input of which a choke is installed, for example, for a boost converter. Converters, at the input of which a key element is installed, for example, a step-down or inverted type, have a pulse shape of the input current, which is shown in Fig. 1.6 b). The effective value of the current of the specified form is calculated:

$$I = \frac{I_d}{\sqrt{\gamma}} \sqrt{1 + \frac{1}{3}\left(\frac{I_{m\sim}}{4I_d}\right)^2} . \tag{1.14}$$

Comparing (1.13) and (1.14) we can conclude that the current pulse shape is much more effective value than continuous current.

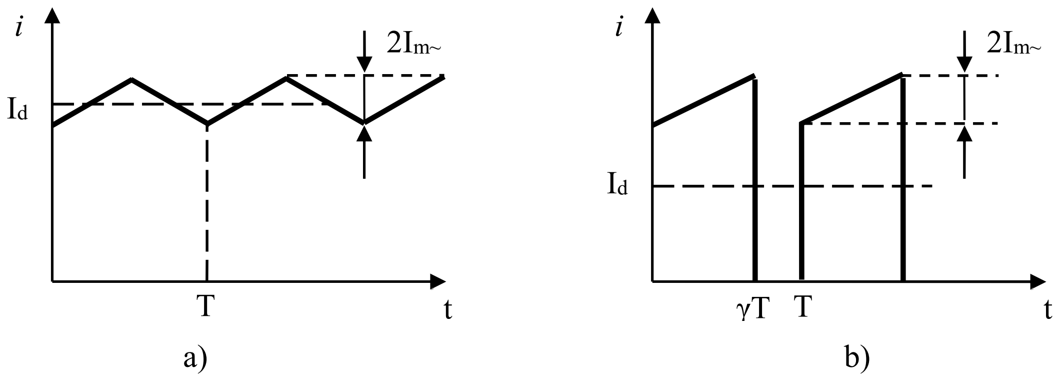


Fig. 1.6. Timing diagrams of the input current PR

An increase in the amplitude of the current ripple and its effective value significantly reduce the EED for the following reasons:

1. The energy source works with maximum EED only near the operating point (*I, U*). With an increase in the ripple of the voltage and current of the energy source, the amplitude of the displacement of its operating point ($I \pm \Delta I$, $U \pm \Delta U$) increases relative to the point with the maximum EED, therefore, the efficiency of the source becomes less.

2. The energy loss of the P_{LOSS} in the circle of the converter is calculated by the formula $P_{LOSS} = I^2 \cdot r$, where r is the resistance of the equivalent losses of the PR. Therefore, under the condition of an increase in ripple and an increase in the effective value of the current, the losses in the converter increase.

Thus, the use of PR as a matching device imposes restrictions on the form of its input current and voltage, which determine the EED of energy sources. To increase the EED, it is necessary that the ripple of the input current and voltage of the PR be minimal. In AC circuits, transformers are used to match the parameters of the source and load, in addition to matching the active components of the source and load resistance, it is also necessary to take into account the reactive components of their resistances, which leads to the complication of the flow of electromagnetic processes in the power supply system. To find out the conditions for the coordinated operation of alternating current sources, let us analyze their operation on a linear reactive load. Let the voltage $e(t) = U_m \sin(\omega t)$ to the load of the applications and a harmonious current flows through it, which is phase-shifted by an angle φ relative to the voltage and $(t) = I_m \sin(\omega t + \varphi)$. The instantaneous value of the power at the load $s(t)$ is calculated:

$$s(t) = u(t)i(t) = U_m I_m \sin(\omega t)\sin(\omega t + \varphi) = UI\cos(\varphi) - UI\cos(2\omega t + \varphi). \quad (1.15)$$

Graphs of instantaneous values of current, voltage and power are shown in fig. 1.7.

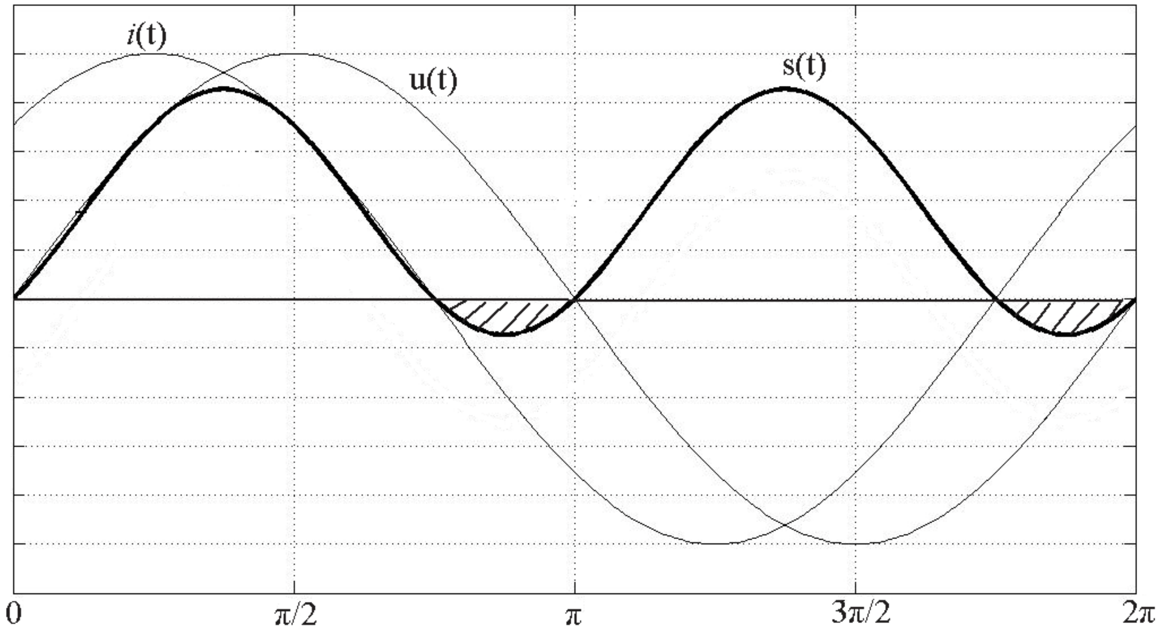


Fig. 1.7. Diagrams of electromagnetic processes in a linear circuit

As can be seen from Fig. 1.7, the apparent power $S(t)$ in certain areas is negative, which corresponds to the transfer of energy from the load back to the source. In this regard, the apparent power S has active P and reactive Q components. The power consumed by the load corresponds to the active power P:

$$P = U \cdot I \cos(\varphi). \qquad (1.16)$$

Reactive power Q, circulating in the circuit without performing useful work:

$$Q = U\, I \sin(\varphi). \qquad (1.17)$$

Total power S has the following relationship with active and reactive power:

$$S = \sqrt{P^2 + Q^2}\ . \qquad (1.18)$$

Under this condition, the power for which the source is calculated corresponds to the total power S and is equal to the product of the effective values of current and voltage at its terminals:

$$S = U \cdot I. \qquad (1.19)$$

As can be seen from (1.16) and (1.19), in the general case, the effective value of the power taken from the source is greater than the power delivered to the load. Therefore, in the presence of the reactive component of the power, the source transfers only part of its energy to the load. Elimination of the reactive component of power is achievable if the reactive components of the resistance of the source and load are matched: $X_i = -X_L$. In this case, there is no phase shift between the current and the load voltage and, according to (1.15):

$$s(t) = UI(1 - \cos(2\omega t)) \geq 0. \qquad (1.20)$$

Many consumers of the network require direct current electricity, for which they use power converters, the input stage of which consists of an uncontrolled rectifier with a capacitive filter. As you know, the rectifier is a non-linear load; its input current has a pulse form with a high content of higher harmonics. Since the active component of the power is transmitted only by the first harmonic of the current, all higher harmonics do not perform useful work and form the distortion power of the system *T*. The relationship between the total power of the system S and its components is as follows:

$$S = \sqrt{P^2 + Q^2 + T^2} \,. \tag{1.21}$$

The sinusoidality of the current is estimated by calculating the distortion factor ν:

$$\nu = I_{(1)} / I \,. \tag{1.22}$$

where $I_{(1)}$ is the effective value of the first harmonic of the current.

To assess the efficiency of energy transfer from the source to the load, the power factor χ is used:

$$\chi = \nu \cdot \cos(\varphi_1), \tag{1.23}$$

where $\varphi 1$ is the phase shift between the voltage and the first harmonic of the current.

According to the standards, the power factor of industrial converters should not be less than 0.95. To increase the power factor at the input of the converters, special devices are included - power factor correctors. Therefore, to match the AC source and the load, it is necessary that the load current have the same phase and shape as the voltage applied to the load. Reducing electrical energy losses is especially important in systems where electricity is transmitted over long distances, and where, as a rule, it is in the form of alternating current. Therefore, it is first advisable to consider the structure and composition of AC power supply systems.

Questions

1. Give the definition of the utilization rate of electrical energy.
2. Describe the features of taking energy from free and paid energy carriers.
3. Specify the maximum power take-off condition for DC systems, which are described by linear and non-linear models.
4. Specify the range in which the load resistance should be compared with the value of the internal source resistance for selecting the maximum power and energy extraction with the maximum efficiency. Consider cases where the power source is both a voltage source and a current source.
5. Describe the influence of the pulsation current and voltage of the switching regulator on the characteristics of the power supply system.
6. Describe the conditions for coordinated operation of the AC power supply system.
7. Characterize power system parameters that affect the value of L on the power factor.
8. Describe the physical meaning of the distortion power.

Lecture 2. Design and parameters of AC power lines

Basic terms and definitions

Power line is an electrical installation designed to transfer electrical energy between two points of the power system with possible intermediate withdrawal, which consists of wires, insulating elements and supporting structures.

An overhead line is a power line, the wires of which are supported above the ground by means of supports, insulators and fittings.

Cable line is a power line based on one or more cables, placed in the ground or in cable structures (collectors, tunnels, channels, blocks, etc.).

A cable is a finished factory product consisting of cores insulated from each other, located in a sealed sheath and armor, which protect the cores from moisture and mechanical damage.

Corona discharge is a form of gas discharge that occurs in highly inhomogeneous fields.

Power transmission line (PTL) is the central element of the transmission and distribution system of electricity. Most often, overhead and cable power lines are used. The choice of the type of power transmission line, its design is determined by the purpose of the line, the place of laying, the rated voltage, the power that is transmitted by the line, the distance to the consumer, the area of the territory on which the power transmission line is laid, climatic conditions, electrical safety requirements, etc.

The classification of power transmission lines is shown in table 2.1.

Table 2.1. Classification of power transmission lines

Sign	Line type	Varieties
Current type	Constant current	-
	Three-phase alternating current	-
	Multiphase alternating current	Six-phase
		Two-twenty-phase
Rated voltage	Low voltage (up to 1 kV)	-
	High voltage	3-35 kV
		110-220 kV
		330-750 kV
		1000 kV and above
Design	Overhead	-
	Cable	-
Number of chains	Single chain	-
	Double-chain	-
	Multi-chain	-
Topological characteristics	Radial	-
	Trunk	-
	Offshoot	-
Functional purpose	Distributive	-
	Nourishing	-
	Interconnection	-

Overhead lines

Overhead lines (OHL) are operated in various climatic conditions that provides protection from atmospheric phenomena.

In terms of the design of the supports, the most common are one and two-circuit OHL. One circuit of a high-voltage line unites three wires (sets of wires) of a three-phase line, in a low-voltage line - from three to five wires. The structural elements of the overhead line are shown in Fig. 2.1, where the following designations are given: 1-phase wires, 2-protective cables, 3-support, 4-string of insulators, 5-reinforcement elements, 6-foundation.

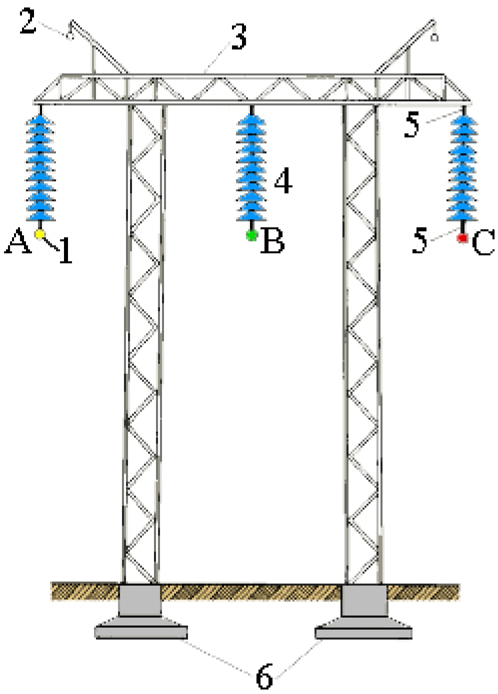


Fig. 2.1. Structural elements of OHL

The supports are the supporting structure of the overhead line, on which the phase wires are attached with the help of insulators; cables are used to protect the phases from thunder strikes.

There are various types and designs of supports. Depending on their functional purpose, they are divided into intermediate and anchor ones. Intermediate supports are used to support wires in straight sections of the line. Their fate is 80-90%.

Anchor supports are installed in places where the wires are rigidly attached. They are divided into final, angular, intermediate and special.

On overhead lines, mostly bare wires are used. By design, the wires can be single- or stranded. Single-core, mainly steel wires are used in low-voltage networks. To increase flexibility and strength, stranded wires of one metal (aluminum or steel) or combined (aluminum + steel) are also used. The addition of steel increases the mechanical strength.

In lines with a voltage of (220/380) V, the wires are composed of a non-insulated carrier wire, which is zero, three insulated phase wires and one insulated wire of any phase for street lighting. Phase insulated wires wound around zero, fig. 2.2.

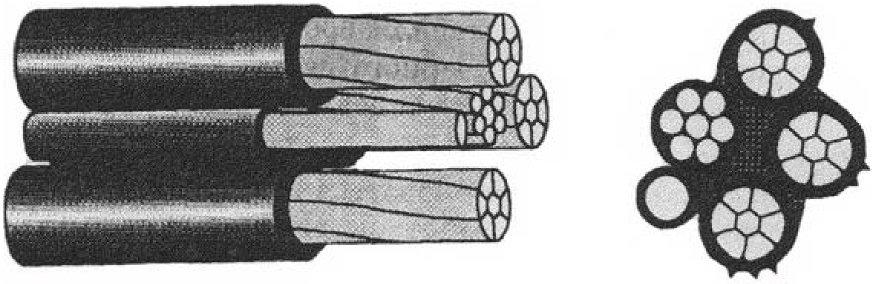


Fig. 2.2. Distribution of zero and phase darts

The supporting wire is steel-aluminum, phase - aluminum. The advantages of OHL with insulated wires compared to non-insulated ones include the absence of insulators on the supports.

Cable lines (CL)

CL is laid in places where it is impossible or impractical to use the OHL. CL is mainly used in industrial enterprises, in cities, if energy is transported through large bodies of water. Advantages of CL in comparison with OHL:

- no impact of environment;
- inaccessibility for outsiders;
- less damage;
- compactness.

Despite the advantages, the use of cable lines is limited due to their high cost, which is several times higher than in OHLs designed for the same voltage. The composition of the cable includes: cable, connecting and end couplings, cable structures, fasteners, etc. Power cables are made of 1-4 copper or aluminum cores with an area of 1.5-2000 mm^2. Lives up to 16 mm^2 - single-wire, with a larger area - multi-wire. Cables with voltage up to 1 kV - four-core, 6-35 kV - three-core, 110 kV and above - single-core.

Schemes of replacement of transmission lines

The phase parameters of the transmission line are evenly distributed along its length, i.e. the transmission line is a chain with distributed parameters. To calculate the currents and voltages of transmission lines, it is possible to use triangular (T) and rectangular (R) -shaped similar schemes for replacing transmission lines with concentrated parameters, Fig. 2.3.

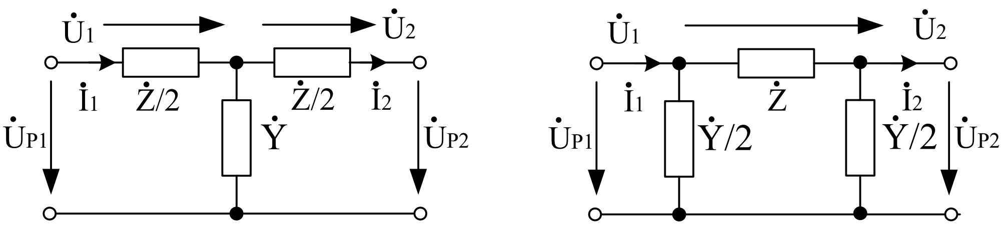


Fig. 2.3. T and R-shaped substitution schemes with concentrated parameters

The assumption about the concentration of distributed parameters along the power transmission line is valid for overhead lines up to 350 km long, for cable lines up to 50-60 km. In practice, the R-shaped equivalent circuit is more often used, since it has fewer nodes. Longitudinal supports Z = R + jX and transverse conductivities Y = G + jB of equivalent circuits are complex quantities. The value of the active component R of the longitudinal resistance Z depends on the length of the line and the cross-sectional area of the transmission line wires. The reactive component X is the inductive reactance of the transmission line. The inductive resistance of the transmission line X0 per 1 km of the line is calculated using the empirical formula:

$$X_0 = \omega L_0 = \omega\left(0.46\,\mathbf{lg}\frac{D_{av}}{r_d} + 0.05\mu\right)\cdot 10^{-3}, \tag{2.1}$$

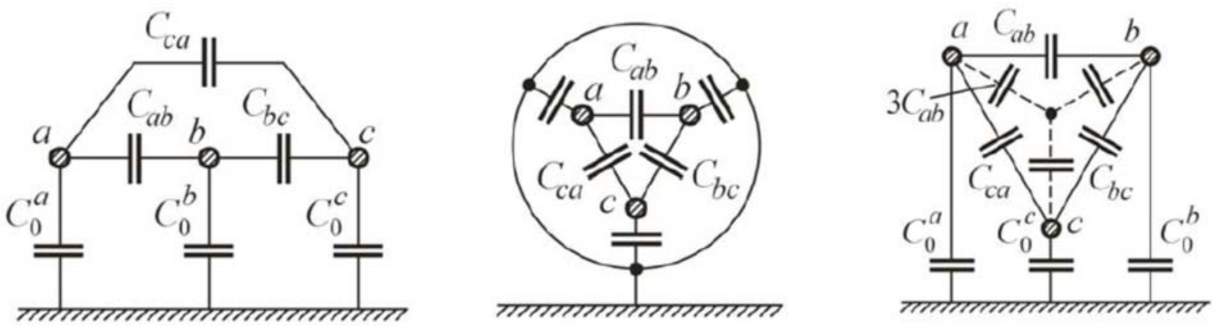
where D_{av} is the average distance between the wires of the line, r_d is the diameter of the wire, μ is the magnetic permeability of the wire material.

For wires made of non-ferrous metals ($\mu = 1$) for network frequencies of 50, 60 Hz, (2.1) has the following form:

$$X_{0\_50} = 0.144\,\mathbf{lg}\frac{D_{av}}{r_d} + 0.016. \tag{2.2}$$

$$X_{0\_60} = 0.173\,\mathbf{lg}\frac{D_{av}}{r_d} + 0.019. \tag{2.3}$$

Capacitive conductance is due to the capacitance between phases, phase conductors and earth. In fig. 2.4 a) and 2.4 b) show the capacitive conductivity of overhead lines and cable lines, in Fig. 2.4 c) - the equivalent circuit of the overhead line during the transition from the triangle of capacities to the star.



a) air; b) cable; c) equivalent circuit of the transmission line

Fig. 2.4. Capacitive conductivities of lines

In practice, the capacity of a three-phase OHL with one wire in phase per unit length is calculated by:

$$C_0 = \frac{0.024}{\mathbf{lg}\dfrac{D_{av}}{r_d}}\cdot 10^{-6}. \tag{2.4}$$

The capacitance of the cable is much larger than that of the line, which is due to the close placement of the phase wires and grounding. Capacitive conductivity is calculated by:

$$B_0 = \omega C_0 . \qquad (2.5)$$

For a network frequency of 50 and 60 Hz, the capacitive conductivity per 1 km of line length is as follows:

$$B_{0\_50} = \frac{7.58}{\lg \frac{D_{av}}{r_d}} \cdot 10^{-6} \text{ Sm/km.} \qquad (2.6)$$

$$B_{0\_60} = \frac{9.04}{\lg \frac{D_{av}}{r_d}} \cdot 10^{-6} \text{ Sm/km.} \qquad (2.7)$$

Under the action of the voltage applied to the line through the capacitance of the lines flow charging currents. The estimated value of the charging current per 1 km of line length is:

$$I_{C0} = U_P \cdot B_0 \text{ kA/km,} \qquad (2.8)$$

and the charging power of the transmission line corresponding to this current:

$$Q_{C0} = 3U_P \cdot I_{C0} = 3U_P^2 \cdot B_0 \text{ Mkvar/km,} \qquad (2.9)$$

depend on the voltage at each point of the line.

The values of charging power for the entire transmission line are calculated from the values of voltages at the beginning and end of the line U_1 and U_2, respectively:

$$Q_C = \frac{1}{2}(U_1^2 + U_2^2) \cdot B_0 \cdot l = \frac{1}{2}(U_1^2 + U_2^2) \cdot B , \qquad (2.10)$$

where l is the length of the line, or approximately the nominal value of the line voltage U_{nom}:

$$Q_C = U_{nom}^2 \cdot B . \qquad (2.11)$$

The average value of charging power per 100 km for the 110 kV OHL is about 3.5 Mvar.

The active conductivity of the transmission line is due to the loss of active power ΔR due to imperfect insulation and ionization of the air around the conductor due to corona discharge, for CL - dielectric losses in the insulation material. The specific active conductivity is calculated by:

$$G_0 = \frac{\Delta P_P}{U_{nom}^2} . \qquad (2.12)$$

The loss of active power from the corona discharge depends on the nominal line voltage, wire radius, weather conditions, and the condition of the wire surface. The greater the operating voltage and the smaller the diameter of the wires, the greater the field strength and, accordingly, the corona discharge. To reduce discharge losses, a split phase wire is used, in which several phase wires are placed in a certain way in space. Corona losses must be taken into account, starting with a voltage of 220 kV.

The lowest value of the electric field strength E_L, at which there is a corona discharge, is calculated by

$$E_L = 24{,}5m\delta\left[1+0{,}63/(r_0\delta)^{0{,}4}\right]\ 10^{-5}\ \text{V/m}, \qquad (2.13)$$

where δ is the relative density of air, $\delta = 1{,}04$, r is the radius of the wire, cm, m is the coefficient of wire roughness, $m = 0.82$.

The crown on the surface of the wires and line elements is a source of electromagnetic and acoustic interference, leading to additional energy loss. In the table. 2 shows the targeted values of losses on the crown in different weather conditions.

Table 2.2. Corona losses

voltage, kV	Make and number of wires in phase	Average specific value of corona losses for different weather, kW / km				Average annual specific corona losses, kW / km
		good	dry snow	Rain	пafrost	
1150	8xAC-300/48	12,6	39,0	119,0	294,0	32,0
	8xAC-330/43	9,8	29,5	97,5	262,0	27,0
750	4xAC-600/72	4,6	17,5	65,0	130,0	15,0
	5xAC-240/56	3,9	15,5	55,0	115,0	13,0
500	3xAC-330/43	2,8	11,0	36,0	96,0	9,0
	8xAC-500/64	1,8	6,5	22,0	56,0	5,5
330	2xAC-300/39	1,0	4,5	15,0	44,0	3,8
	2xAC-400/51	0,8	3,3	11,0	33,5	2,9

From the table. 2.2 it can be concluded that the losses on the corona depend on the line voltage, phase wire configuration and weather conditions.

In CL the tangent of the dielectric loss angle characterizes active losses. Active cable conductivity per unit length:

$$G_0 = \omega C_0 tg\delta = B_0 tg\delta, \qquad (2.14)$$

and the corresponding surge current:

$$I_{loss} = U_P \cdot B \cdot tg\delta = U_P \cdot G. \qquad (2.15)$$

Due to this, the dielectric losses in the insulation material:

$$\Delta P_{loss} = 3I_{loss}^2 \frac{1}{\omega C \cdot tg\delta} = U^2 \cdot G. \qquad (2.16)$$

Dielectric losses in the transmission line are taken into account, starting from the value of the nominal voltage of 220 kV.

Schemes of line substitution are made on the basis of the considered elements of line substitution, fig. 2.5.

When calculating symmetric modes, the parameters of the substitution scheme are given for one phase. In OHL with voltage up to 220 kV, power losses per corona and in OHL with voltage up to 35 kV dielectric losses are insignificant. Therefore, for the specified voltage range, the active conductivities are not taken into account. The substitution schemes of direct current transmission lines are considered as a special case of alternating current lines under the condition X = 0 and B = 0.

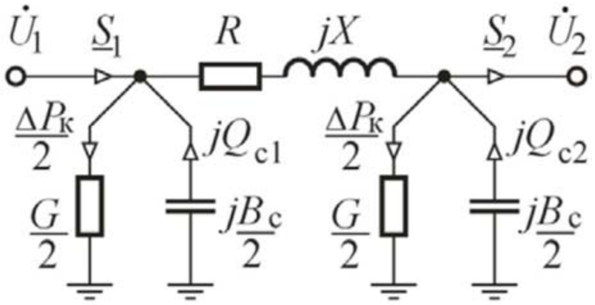


Fig. 2.5. Scheme of replacement of an electric line

When solving a number of tasks of operation, development and design of electrical networks, it is necessary to assess the operating conditions of consumers and equipment of the electrical network. The calculations make it possible to estimate the mode of electricity transmission. In addition, the obtained data make it possible to anticipate measures to ensure the required quality of electricity and to determine the conditions for a rational mode of generation, transmission and distribution of electricity. Below are the methods of calculating simple electrical networks.

Consider the scheme of replacement of the electrical network, Fig. 2.6.

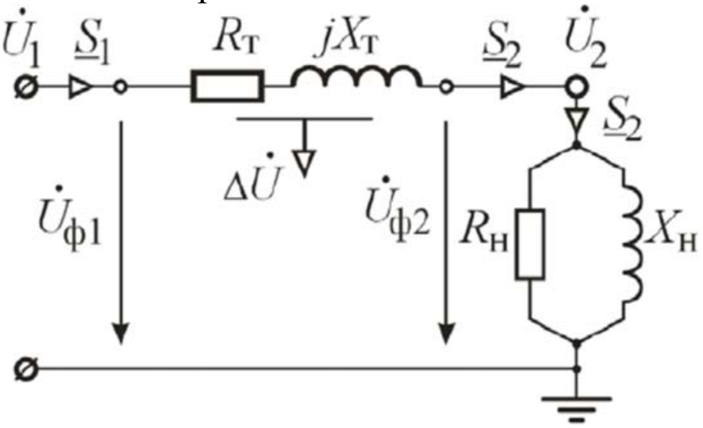


Fig. 2.6. Scheme of phase replacement of the network section

The network section feeds a symmetrical three-phase load, which is set at the end of the section by current I or three-phase power S_2, which is consumed by the load with active resistance R_L and reactive resistance X_L. With a symmetrical load and the same phase resistance, their currents have the same value and the same phase shift relative to the phase voltages at the end of the section.

$$i_A = I_m \mathbf{sin}(\omega t - \varphi); \tag{2.17}$$

$$i_B = I_m \mathbf{sin}(\omega t - \frac{2\pi}{3} - \varphi); \tag{2.18}$$

$$i_C = I_m \mathbf{sin}(\omega t + \frac{2\pi}{3} - \varphi); \tag{2.19}$$

$$u_A = U_m \mathbf{sin}(\omega t - \delta_2); \tag{2.20}$$

$$u_B = U_m \mathbf{sin}(\omega t - \frac{2\pi}{3} - \delta_2); \tag{2.21}$$

$$u_C = U_m \mathbf{sin}(\omega t + \frac{2\pi}{3} - \delta_2)\,. \qquad (2.22)$$

Given the calculation of symmetrical modes of three-phase networks, it is sufficient to determine the currents and voltages of only one phase. Let us represent the voltage at the end of the section U_{P2} and the current of the I_P phase in a complex form:

$$\dot{U}_{P2} = U_{P2\_a} - jU_{P2\_p} = U_{P2}e^{-j\delta 2},\ \dot{I}_P = I_{P\_a} - jI_{P\_r} = I_P e^{-j\varphi}\,. \qquad (2.23)$$

Let the values of U_{P2}, I_P and angle φ be known. It is necessary to find the voltage and phase at the beginning of the line U_{P1} and δ_2, respectively, and the phase shift between the voltages U_{P1} and U_{P2}. The difference in phase voltages at the beginning and end of the line is calculated through the equivalent resistance of the line:

$$\begin{aligned}\dot{U}_{\Phi 1} - \dot{U}_{\Phi 2} = \Delta\dot{U} = \dot{I}_{\Phi}\cdot\dot{Z} = (I_{\Phi\_a} - jI_{\Phi\_p})\cdot(R_T - jX_T) = \\ = I_{\Phi\_a}R_T + I_{\Phi\_p}X_T + j(I_{\Phi\_a}X_T - I_{\Phi\_p}R_T).\end{aligned} \qquad (2.24)$$

From (2.23) calculate the value of the voltage U_{P1}. To calculate the phase shift between voltages, the voltage phase U_{P2} is taken equal to zero. Then the phase δ_1 is equal to:

$$\delta_1 = arctg\left(\frac{I_{P\_a}X_T - I_{P\_r}R_T - U_{P2\_r}}{I_{P\_a}R_T + I_{P\_r}X_T + U_{P2\_a}}\right). \qquad (2.25)$$

Another type of problem is the calculation of the total power S_2 and the voltage U_2 at the end of the section by known values of S_1 and U_1 at the beginning of the section. This problem is solved to calculate the energy transfer losses from the generator to the load. The I_F current at the beginning of the section is equal to:

$$\dot{I}_P = \frac{\overset{*}{S}_1}{3U_{P1}} = I_{P\_a} - jI_{P\_r}\,. \qquad (2.26)$$

Given the flow of current through the section of the circuit with resistance $Z = R + jX$ losses of active and reactive power are:

$$\Delta S = 3I_P^2 Z = 3(I_{P\_a}^2 + I_{P\_r}^2)(R + jX), \qquad (2.27)$$

or provided that the full power value is used:

$$\Delta S = \frac{S_1^2}{3U_{P1}^2}Z = \frac{P_1^2 + Q_1^2}{3U_{P1}^2}(R + jX), \qquad (2.28)$$

where to calculate the loss of active and reactive power:

$$\Delta P = 3(I_{P\_a}^2 + I_{P\_r}^2)R = (P_1^2 + Q_1^2)R / 3U_{P1}^2, \qquad (2.29)$$

$$\Delta Q = 3(I_{P\_a}^2 + I_{P\_r}^2)X = (P_1^2 + Q_1^2)X / 3U_{P1}^2\,. \qquad (2.30)$$

The power flow at the end of the section is less by the amount of losses:

$$S_2 = S_1 - \Delta S = P_1 - \Delta P + j(Q_1 - \Delta Q)\,. \qquad (2.31)$$

Similarly, the losses in the line are calculated if the total power S_2 and the voltage U_2 at the end of the line are known.

The most typical problem is the calculation under the condition of known power S_2 at the end of the section and voltage U_1 at the beginning of the section. Then the calculation is performed by the method of successive approximations.

At the beginning of the iteration, for practical reasons, set the approximate voltage value at the end of the line $U_{P2}^{(0)}$ and calculate the current of the line $I_P^{(0)}$:

$$I_P^{(0)} = \overset{*}{S}_2 / \dot{U}_{P2}^{(0)} = I_{P\_a}^{(0)} - jI_{P\_r}^{(0)}. \tag{2.32}$$

According to the values of current and line resistance, the power losses $\Delta S^{(1)}$ are found by (2.27). According to the value of losses using the formula $S_1^{(1)} = S2 + \Delta S^{(1)}$ find the first approximation of total power at the beginning of the line. According to (2.25) specify the current of the line $I_P^{(1)}$, and according to the formula $U_{P2}^{(1)} = U_{P1}^{(1)} - I_P^{(1)}Z$ - voltage at the end of the line. Then perform the following iterations to achieve the required accuracy of calculations.

If the full power at the beginning of the line is known, and it is necessary to calculate the voltage at the end of the line, the calculation begins with the node where the power is known, ie from the beginning of the line. Let us perform a similar calculation for the line shown in Fig. 2.7.

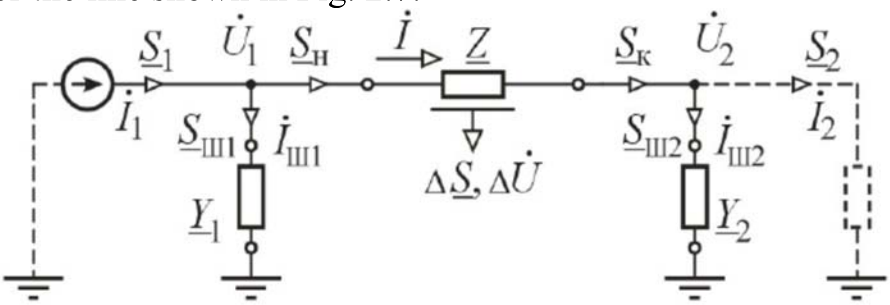


Fig. 2.7. R-shaped line replacement scheme

In contrast to the previous analysis, the line has transverse elements (shunts), which are represented by complex conductivities:

$$Y_1 = Y_2 = 0.5Y = 0.5(G + jB) = G_1 + jB_1 = G_2 + jB_2. \tag{2.33}$$

Conductions have an active-capacitive nature, for the case of active-inductive conductivity before the reactive power component, it is necessary to change the sign.

If the values of voltage U_1 and power S_1 at the beginning of the line are known, the steady state of the line is calculated according to the following method.

First, the source current is calculated:

$$\dot{I}_1 = \overset{*}{S}_1 / (3U_{P1}) = I_{P\_a} - jI_{P\_r}, \tag{2.34}$$

as well as the current and power of the shunt at the beginning of the line:

$$\dot{I}_{Ш1} = U_{P1}Y_1 = U_{P1}(G_1 + jB_1). \tag{2.35}$$

$$\dot{S}_{Ш1} = 3U_{P1}\overset{*}{I}_1 = 3U_{P1}^2\overset{*}{Y}_1 = 3U_{P1}^2(G_1 - jB_1). \tag{2.36}$$

Due to this, the power at the beginning of the line is equal to:

$$\dot{S}_S = \dot{S}_1 - \dot{S}_{Ш1}. \tag{2.37}$$

Similarly, the current at the beginning of the line is calculated:

$$\dot{I}_S = \dot{I}_1 - \dot{I}_{Ш1}. \tag{2.38}$$

According to the current at the beginning of the line find the voltage drop across the transverse elements of the line and the power loss on these elements, (2.24) and (2.27). Due to this, the voltage at the end of the line $U_2 = U_1 - \Delta U$. Power at the end of the line $S_E = S_P - \Delta S$.

The current at the end of the line is calculated from these values:

$$\dot{I}_E = S_E / (3U_2). \tag{2.39}$$

Next, calculate the current and power on the shunt at the end of the line.

$$\dot{I}_{Ш2} = U_{P2} Y_2 = U_{P2}(G_2 + jB_2). \tag{2.40}$$

$$\dot{S}_{Ш2} = 3U_{P2} \overset{*}{I}_2 = 3U_{P2}^2 \overset{*}{Y}_2 = 3U_{P2}^2 (G_2 - jB_2). \tag{2.41}$$

Due to this, the power and load current are equal to:

$$S_2 = S_E - S_{Ш2}. \tag{2.42}$$

$$I_2 = I_E - I_{Ш2}. \tag{2.43}$$

Calculation of the steady-state mode of the electric line fig. 7 is carried out similarly to the calculation of the line of Fig. 6 taking into account (2.34) - (2.43).

In practice, the mode of operation of the transmission line is also calculated under the condition of disconnected load. For this purpose it is expedient to use the scheme of substitution which is shown in fig. 2.7. Under the condition $S_2 = 0$. Also under the condition of idling calculation do not take into account the loss on the corona, i.e. $G_1 = 0$, $G_2 = 0$. In this case, the shunt at the end of the line generates reactive power:

$$\dot{S}_{Ш2} = 3U_{P2}^2 \overset{*}{Y}_2 = 3U_{P2}^2 jB_2. \tag{2.44}$$

In this mode, the power losses caused by the circulation of power from the shunt to the source are equal to:

$$\Delta S = \left(S_{Ш2} / U_2\right)^2 (R + jX). \tag{2.45}$$

Power flow at the beginning of the line:

$$S_S = \Delta S + S_{Ш2}. \tag{2.46}$$

These ratios are valid for relatively short transmission lines (up to 300 km). To describe electromagnetic processes in longer transmission lines, it is necessary to consider them as long lines.

Questions

1. Give the characteristics of the classification of power lines.
2. List the structural elements of the overhead power line.
3. Give examples of where it is advisable to use cable power lines.
4. List the schemes, types of schemes for the replacement of power lines.
5. Compare the individual elements of the substitution circuits with the corresponding parameters of overhead and cable AC power lines.
6. Describe the phenomenon of corona discharge and give the parameters on which the losses on the corona depend the most.
7. List the main sources of losses in the overhead power line.
8. List the main sources of losses in the AC power line.

Lecture № 3. Quality standards of electric energy parameters. GOST 13109-97

Basic terms and definitions
(for GOST 13109-97)

Conductive electromagnetic interference in the power supply system is an electromagnetic interference that is propagated by elements of the electrical network.

The level of electromagnetic compatibility in the power supply system is a regulated level of conductive interference, which is used as a standard for coordination between the permissible level of interference generated by technical means of energy supply organization and consumers and the level of interference perceived by technical means without disrupting their normal functioning.

The envelope of the RMS voltage values is a stepped time function formed by the RMS voltage values, discretely determined for each half of the fundamental frequency voltage period.

Flicker is a person's subjective perception of fluctuations in the luminous flux of artificial light sources caused by voltage fluctuations in the electrical network that supplies these light sources.

Flicker dose is the degree to which a person perceives the action of a flicker over a set period of time.

Voltage change frequency is the number of single voltage changes per unit time.

Voltage change duration is the time interval from the beginning of a single voltage change to its final value.

Voltage failure is a sudden decrease in voltage at a point in the electrical network to a value lower than 0.9 · UHOM, followed by the restoration of voltage to the initial or close to it level after a period of time from ten milliseconds to several tens of seconds.

Voltage failure duration is the time interval between the initial moment of voltage failure and the moment of voltage recovery to the initial or close to it level.

Frequency of voltage dips is the number of voltage dips of a certain depth and duration for a certain period of time relative to the total number of failures for the same period of time.

Voltage pulse is a sharp change in voltage at a point in the electrical network, which is the restoration of voltage to the initial or close to it level for a period up to several milliseconds.

Pulse amplitude is the maximum instantaneous value of the voltage pulse.

Pulse duration is the time interval between the initial moment of the voltage pulse and the moment of restoration of the instantaneous value of the voltage to the initial or close to it level.

Temporary overvoltage is an increase in voltage at a point in the mains higher than 1.1 Unom with a duration of more than 10 ms, which occurs in power supply systems during switching or short circuits.

Coefficient of temporary overvoltage is a value equal to the ratio of the maximum value of the envelope of the amplitude values of the voltage during the existence of the temporary overvoltage to the amplitude of the nominal voltage of the network.

Duration of temporary overvoltage is the time interval between the initial moment of occurrence of temporary overvoltage and the moment of its disappearance.

Over the past few decades, the number and range of electronic and electrical equipment powered by the grid (electric motors, switching voltage converters, electric arc furnaces, and household appliances) has been growing rapidly. Therefore, the share of electricity they consume is also growing. On the one hand, the specified equipment for the network is a nonlinear load, so its current consumption contains higher current harmonics. On the other hand, the parameters of electricity required to power these devices have a small tolerance. In view of this, for the regulation of electricity parameters, each country develops electricity quality standards: in Ukraine there is an international standard GOST 13109-97, in Russia - GOST 54149-2010, in the EU - EN 50160, EN 61000-2-2, EN 61000-2-12, EN 61000-4-7, EN 61000-4-30.

The presence of higher current harmonics has a negative effect on:

1. Electric network:

- distortion of the mains voltage form;
- additional voltage drop in the distribution network;
- a significant increase in the current of the neutral wire due to the presence of current harmonics, multiples of three;
- resonant phenomena at higher harmonic frequencies;
- heating of transformers, network cables;

2. Electric generator:

- reduction of power transmission power factor;

3. Consumer:

- radiation of electromagnetic interference;
- the appearance of acoustic noise in electronic equipment;
- the appearance of vibration in electrical machines.

Voltage distortion rates

The following indicators characterize the influence of higher harmonics on the parameters of the mains voltage:

Non-sinusoidal coefficient:

$$K_H = U_{(1)} / U ,$$

where U, $U_{(1)}$ are the effective values of voltage (current) and its first harmonic.

Sinusoid distortion factor (harmonic coefficient):

$$K_Г = \sqrt{U^2 - U_{(1)}^2} / U .$$

Amplitude factor:

$$K_A = U_{\max} / U,$$

where U_{max} is the voltage amplitude.

Influence of higher harmonics on the power supply system

As sources of higher harmonics consider pulse voltage converters. In most pulse voltage converters, the input link is an uncontrolled rectifier, at the output of which a capacitive filter is installed. Therefore, the input current of the pulse converter has a pulse shape, Fig. 3.1.

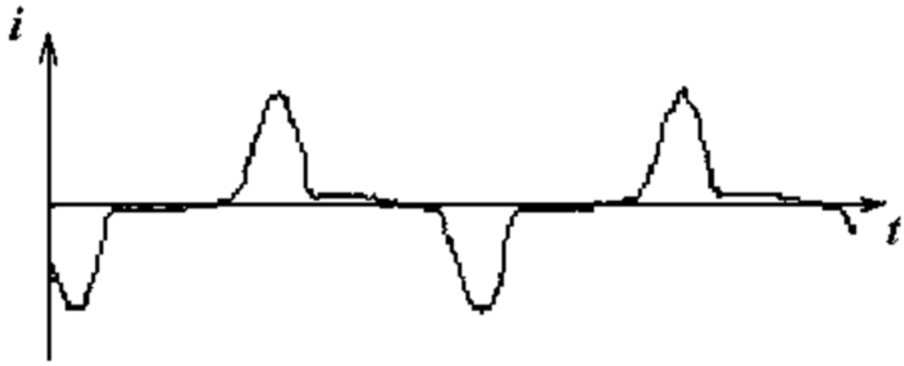


Fig. 3.1. The form of the input current of the pulse converter with the input capacitive filter

The current of this form has a high content of higher harmonics. As a result, the current value of the network current I increases in comparison with the current value of the first harmonic $I_{(1)}$. Higher harmonics cause heating of the mains and additional losses. The increased value of the amplitude coefficient C_A indicates its large amplitude. The higher the amplitude value and the shorter the current, the greater its distortion factor. To power this type of load, the energy source must have a low output resistance and power reserve, which leads to increased costs for the purchase and operation of equipment.

The influence of the source of higher harmonics on the voltage quality parameters is explained in Fig. 3.2.

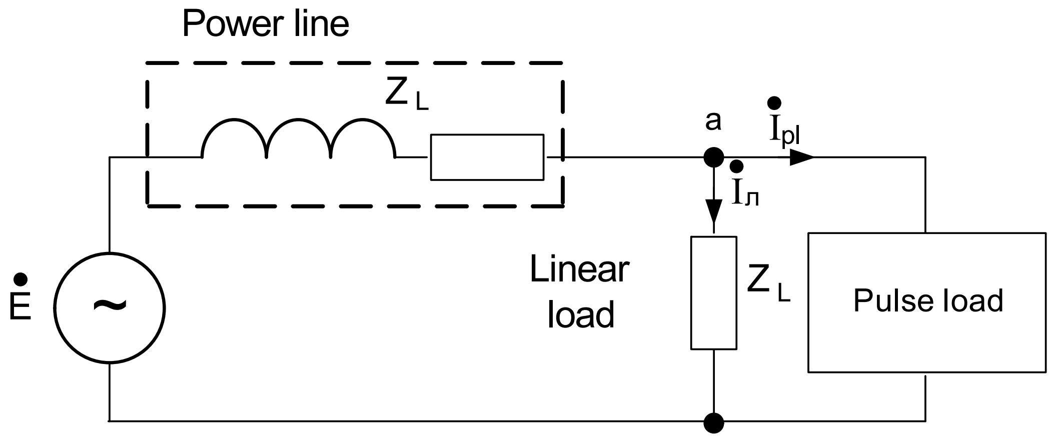


Fig. 3.2. Model of AC power supply system with nonlinear load

A linear consumer with resistance Z, consumes the current I_L and does not distort the voltage, but only reduces its effective value at the point of connection of consumers to the value ΔU, compared with the voltage of the power supply E:

$$\Delta \dot{U} = \dot{I}_{lin} X_L . \tag{3.1}$$

Higher harmonics of the nonlinear consumer current distort the voltage shape at the connection point. The degree of distortion depends on the harmonic number *n* and its amplitude *I*imp:

$$\Delta \dot{U}_n = \dot{I}_{imp(n)} (jn\omega L + R_L) , \tag{3.2}$$

where L, R_L - power line parameters, ω - network frequency.

From the analysis of (3.2) we can conclude that the voltage distortion at the point of connection of consumers increases in proportion to the harmonic number *n*, so to ensure the required quality of voltage parameters it is necessary to limit the amplitude of higher harmonics.

Harmonics multiples of three $n = 3\ (2k + 1)$, in addition to this effect, create an additional load on the neutral wire of the power line. This is due to the fact that the harmonics of multiples of three of each phase are shifted by an angle of multiples of 360 ° and therefore are not compensated in the neutral wire. As a result, the current value of the neutral wire I_0 may exceed the phase current:

$$I_0 = 3\sqrt{I_3^2 + I_9^2 + I_{15}^2 + ..} . \tag{3.3}$$

Therefore, in networks with a large proportion of nonlinear consumers, the cross-sectional area of the neutral wire must be the same or exceed the cross-sectional area of the phase wires.

Higher harmonics can also lead to resonant phenomena. In this case, the amplitude of the harmonic of the current to which the resonance occurs may exceed the amplitude of the first harmonic, which adversely affects the performance of network equipment and consumers.

Particularly negative higher harmonics affect the following equipment:

- transformers, inductors. In these devices, higher harmonics create additional acoustic noise and increase losses due to the skin effect, the occurrence of eddy currents, reversal of the core at a higher frequency;

- electric machines. In addition to these phenomena in transformers and inductors, in electric machines there are vibrations due to the creation of higher harmonics of additional torque on the motor shaft, which reduces its service life and can lead to accidents;

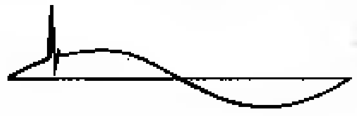
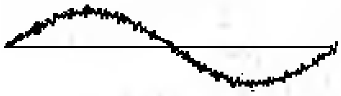
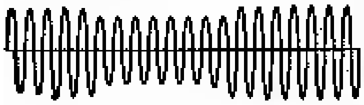
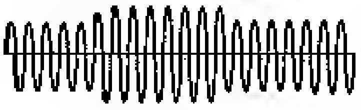
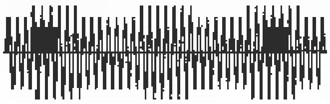
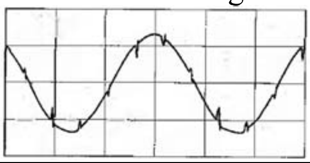
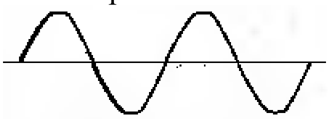
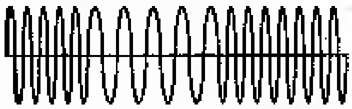
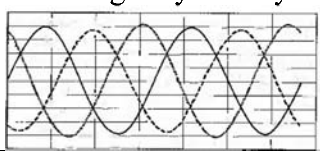
- capacitors. The tangent of the capacitor loss angle is proportional to the current frequency, so higher harmonics cause additional capacitor losses and heating.

Another negative phenomenon created by higher current harmonics is the increase of electromagnetic interference along the power line.

Types of interference in the power supply system

When designing power supply systems, it is necessary to ensure the parameters of electricity quality, which provide the nominal mode of operation of consumers connected to it. To do this, regulate the possible types of voltage distortions that may occur in the system, and their allowable values. In most power quality standards, the types of voltage distortions are the same. In the table. 3.1 shows their classification, brief description and cause.

Table 3.1. Types and causes of voltage distortion

Type of distortion	Description	Causes
Voltage pulse 	Short voltage pulses with steep leading edge and with exponential or oscillating drop	Switching consumers on or off, lightning discharges
Radio interference 	Radio interference with a frequency of 10 kHz - 1 GHz	Operation of switching power supplies, electric motors, radio waves from the air
Voltage failures 	Reduction of the current voltage value	Switching on of powerful consumers, switching in power supply networks, short circuit
Overstrain 	Increasing the current value of voltage	Shutdown of powerful consumers, switching in power supply networks
Voltage fluctuations 	Periodic change of the current voltage value	Pulsating change of consumer power
Perforations of voltage 	Periodic voltage dips of short duration	Switching of diodes or thyristors in three-phase rectifiers and converters
Shape distortion 	Deviation of the voltage form from the ideal sinusoidal due to the presence of higher current harmonics	Operation of pulse voltage converters and other nonlinear consumers
Frequency deviation 	Deviation of frequency from nominal value	Unsatisfactory setting of power generation equipment
Voltage asymmetry 	The difference between the current values of the phase voltage	Phase load unbalance

In Ukraine, GOST 13109-97 regulate the quality parameters of the mains voltage.

GOST 13109-97
Content

1. Scope.

2. Regulatory references.
3. Definitions, designations and abbreviations.
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7. Requirements for error of NPP measurements.
8. Requirements for averaging intervals of NPP measurement results.
Appendix A. Properties of electric energy, indicators and the most probable culprits of deterioration of energy quality.
Appendix B. Methods of calculation and methods for determining energy quality indicators and auxiliary parameters.
Appendix C. Analytical methods for assessing the compliance of voltage fluctuations with a shape other than the meander, the established norms.
Appendix D. Characteristics of voltage dips in electrical networks with a voltage of 6-10 kV.
Appendix E. Values of lightning and switching pulse voltages, as well as coefficients of temporary overvoltage at the points of general connection.
Appendix F. Energy quality control and basic requirements for digital measuring instruments.

The main parameters of electricity:

- voltage deviation δU_y;;
- voltage fluctuations δU_t;
- dose of flicker P_t;;
- distortion coefficient of the sinusoidal voltage curve K_U;
- coefficient of the n-th voltage harmonic $K_{U(n)}$;
- voltage asymmetry coefficient in the reverse sequence K_{2U};
- coefficient of voltage asymmetry in the zero sequence K_{0U};
- frequency deviation Δf;
- duration of voltage failure Δt_f;
- pulse voltage U_{imp};
- temporary overvoltage factor K_{overU}.

Voltage deviation

An indicator of steady-state deviation, for which the following norms are set, characterizes voltage deviation: normally permissible and maximum permissible values of steady-state deviation at the level of 5% and 10% of the rated voltage.

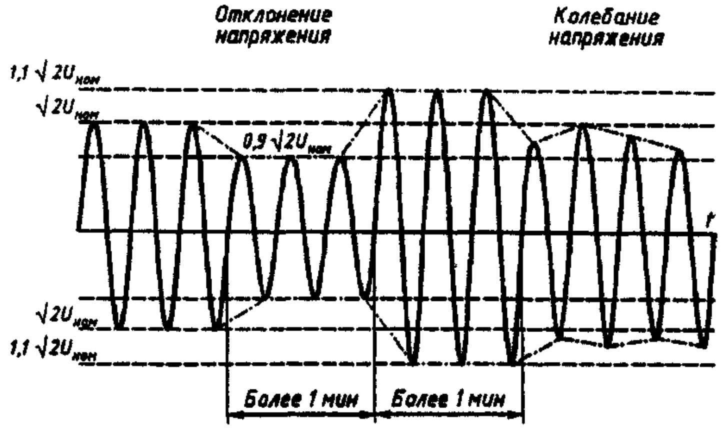


Fig. 3.3. Voltage deviations and fluctuations

Voltage fluctuations

The following indicators characterize voltage fluctuations:

- amplitude of voltage fluctuations;
- dose of flicker.

The maximum allowable values of voltage fluctuations δUt, the envelope of which has the shape of a meander (Fig. 3.4), depending on the frequency of voltage fluctuations $F\delta_{Ut}$ or period $\Delta t_{i,\,i+1}$ is determined by curve 1, and for consumers using incandescent lamps - along curve 2.

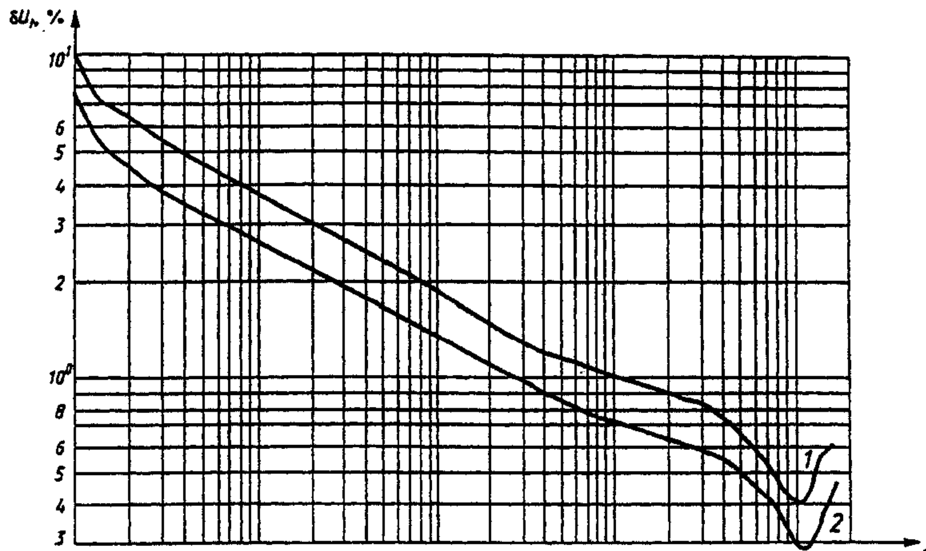


Fig. 3.4. Limit allowable voltage fluctuations depending on the frequency or period of voltage fluctuations, the envelope of which has the shape of a meander

The maximum allowable value of the sum of voltage deviations and fluctuations is 10%.

Voltage asymmetry

The following indicators characterize voltage asymmetry:

- the coefficient of voltage asymmetry in the reverse sequence;
- the coefficient of voltage asymmetry in the zero sequence.

Normally and maximum allowable values of the asymmetry coefficient are 2.0 and 4.0%, respectively.

Frequency deviation

Normally and maximum allowable values of frequency deviation are ± 0.2 and ± 0.4 Hz, respectively.

Non-sinusoidal voltage

The following indicators characterize non-sinusoidal voltage:

- voltage distortion coefficient;
- n-th harmonic coefficient.

Normally and maximum allowable values of the distortion coefficient of the voltage shape are given in table. 3.2.

Table 3.2. The value of the distortion coefficient of the voltage shape,%

Normally permissible value by Unom, kV				Maximum permissible value by Unom, kV			
0,38	6-20	35	110-330	0,38	6-20	35	110-330
8,0	5,0	4,0	2,0	12,0	8,0	6,0	3,0

Normally permissible values of the coefficient of the n-th harmonic are given in table. 3.3.

Table 3.3. The value of the coefficient of the n-th harmonic,%

Odd harmonics, not multiples of 3, by U_{nom}, kV					Odd harmonics, multiples of 3**, by Unom, kV					Paired harmonics by Unom, kV				
*n**	0,38	6-20	35	110-330	*n**	0,38	6-20	35	110-330	*n**	0,38	6-20	35	110-330
5	6,0	4,0	3,0	1,5	3	5,0	3,0	3,0	1,5	2	2,0	1,5	1,0	0,5
7	5,0	3,0	2,5	1,0	9	1,5	1,0	1,0	0,4	4	1,0	0,7	0,5	0,3
11	3,5	2,0	2,0	1,0	15	0,3	0,3	0,3	0,2	6	0,5	0,3	0,3	0,2
13	3,0	2,0	1,5	0,7	21	0,2	0,2	0,2	0,2	8	0,5	0,3	0,3	0,2
17	2,0	1,5	1,0	0,5	>21	0,2	0,2	0,2	0,2	10	0,5	0,3	0,3	0,2
19	1,5	1,0	1,0	0,4						12	0,2	0,2	0,2	0,2
23	1,5	1,0	1,0	0,4						>12	0,2	0,2	0,2	0,2
25	1,5	1,0	1,0	0,4										
>25	$0{,}2+Z^{***}\ x25/n$													

* n - voltage harmonic number.

** Normally valid values specified for n = 3 and 9 for single-phase circuits. In three-phase three conductors, the allowable value of the harmonic amplitude is twice less.

***Z=1,3 at U_{norm} = 0,38 кV, Z=0,8 at U_{norm} = 6-20 кV, Z=0,6 at U_{norm} = 35кV, Z=0,2 at U_{norm} = 110-330 кV.

The maximum allowable value of the n-th harmonic is 1.5 times higher than the normal allowable.

Voltage failure

Voltage failure is a sudden decrease in voltage to a level lower than 0.9 U_{nom}, after which the voltage returns to its permissible level in a time from 10 ms to up to several tens of seconds.

Voltage failure is characterized by a duration, the maximum allowable value of which for networks up to 20 kV is a time interval of 30 s.

Voltage pulse

Voltage pulse - a sharp change in voltage, after which the voltage returns to its permissible level in less than a few milliseconds.

An indicator of the pulse voltage characterizes the voltage pulse.

Temporary overvoltage

An indicator of the coefficient of temporary overvoltage characterizes temporary overvoltage. The values of the coefficient are given in table 3.4.

Table 3.4. The value of the overvoltage factor

Duration of temporary overvoltage $\Delta t_{\text{пер}U}$, sec	Up to 1	Up to 20	Up to 60
Coefficient of temporary overvoltage $K_{\text{пер}U}$	1,47	1,31	1,15

Due to the regulation of electricity quality parameters, it is necessary to regulate the parameters of electricity transmission by the power line, first of all - to regulate the reactive power of the line.

Questions

1. List the factors of negative influence of higher harmonics on the generators of power supply systems.
2. List the factors of negative influence of higher harmonics on the equipment of electric networks.
3. Name the indicators of distortion of mains voltage.
4. Describe the influence of sources of higher harmonics of current on the parameters of the mains voltage.
5. List the types of interference in the AC power supply system.
6. List the parameters of electricity quality, which are regulated by GOST 13109-97.
7. List the factors of negative influence of higher harmonics, multiples of three, on the power supply system.
8. Define the term "conductive electromagnetic interference".

Lecture № 4. Reactive power compensators

Basic terms and definitions

A reactor is a choke with a constant inductive resistance connected in series with an electrical circuit.

A capacitor bank is electrical equipment composed of capacitors and ancillary equipment designed to compensate for reactive power.

STATCOM (Static compensator) is a voltage converter on controlled valves or switches, designed to regulate reactive power and connected in parallel to the line.

One of the important tasks of operation of alternating current electrical networks is to increase their throughput, which uses reactive power compensators, which eliminate the phenomenon of energy exchange between the reactive elements of the transmission line, load and generators. They are connected at the beginning and end of the line, which eliminates the circulation of energy along the line and allows you to increase the amount of energy that is transported to the consumer.

The term reactive power source (RPS) refers to devices that purposefully affect the balance of reactive power in the power system. This effect is carried out by increasing or decreasing the generated or consumed reactive power. The main parameter of RPS regulation is the voltage at the point of its connection or the reactive power of the load. To increase the sensitivity of the RPS controller, channels are introduced that respond to the rate of change of voltage or reactive power. The structure of the RPS controls and the law of its regulation are determined by the purpose of the device.

In general, RPS is a multifunctional device. It is used to solve the following problems:

- reduction of power losses;
- voltage regulation at the point of load connection;
- increasing the capacity of the power line;
- increasing the stock of static stability of power transmission and power plant generators;
- improving the dynamic stability of power transmission;
- limitation of overvoltage;
- load balancing.

In the power supply systems of industrial enterprises, RPS is used to compensate for reactive power consumed by consumers and load balancing. In addition, in power supply systems with nonlinear load, higher current harmonics occur, so in this case, RPS perform the function of filter-compensating devices.

Reactive power compensation is provided by RPS, which are connected in parallel to the substation and load busbars (cross-connection RPS) or in series - in the phase break (longitudinal RPS). In practice, cross-connection RPS are more commonly used. In addition to reactive power compensation at the beginning and end of the line, they are often connected along the line, which allows it to be divided into a number of short sections, the voltage at the end of which is maintained at a constant level. Then the bandwidth of the transmission line will depend not on the wavelength of the entire line λ, but on the length of its individual sections, the number of which is *m*:

$$P = U^2 / (Z_C sin(\lambda / m)). \qquad (4.1)$$

For example, if a line of length l = 1000 km has a bandwidth of $P = P_{HT}/\mathrm{Sin}(60°) = 1{,}16\ P_{HT}$, where P_{HT} is the natural power of the line. Under the condition of voltage stabilization at two intermediate points, as shown in Fig. 4.1, the wavelength of the section, 333 km long, is λ = 20 °, which increases the bandwidth of the line to the value of $P = P_{HT}/\mathrm{Sin}(20°) = 2{,}39\ P_{HT}$.

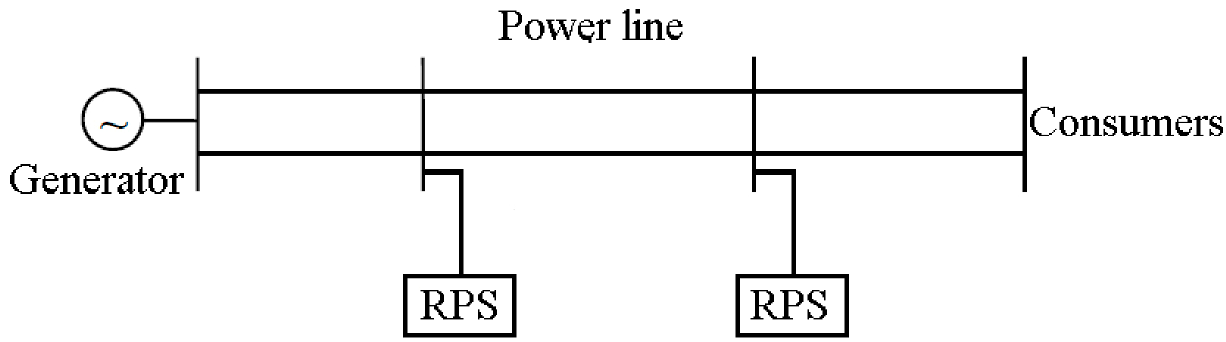


Fig. 4.1. Wiring diagram of RPS along the power line

Therefore, in this example, the use of RPS allows you to increase the bandwidth of the line twice. Consider devices that can be used as RPS.

Types of RPS

RPS can be divided into two groups. The first group includes synchronous motors that can smoothly change the amount of reactive power consumed or transmitted to the network. The second group includes static reactive power compensators: capacitor banks, reactors, devices based on converters.

Synchronous compensators (SC)

The adjustable parameter of the synchronous generator is the voltage at its terminals, which can vary in the range of $0{,}95U_{nom} \le U_г \le 1{,}05U_{nom}$. The generator voltage is maintained at a given level if the reactive power generation is within $Q_{min} \le Q_г \le Q_{max}$. The maximum reactive power Q_{max} is generated in the overexcitation mode and is its nominal power. In the mode of understimulation, the SC is a consumer of reactive power, the minimum value of which Q_{min} is determined by the limit of stability of the generator. The substitution scheme of the SC is shown in Fig. 4.2.

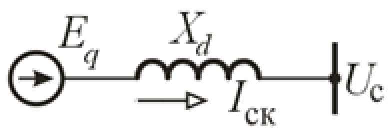


Fig. 4.2. The substitution scheme of the SC

Power on the terminals of the SC is calculated by the formula:

$$Q = (E_q - U_\Phi)U_\Phi / X_d\,. \qquad (4.2)$$

The voltage values of the generator E_q are regulated by the excitation current. The main advantage of the SC is the possibility of smooth regulation of reactive power.

Capacitor batteries

Capacitor batteries (CB) are a simple and reliable static RPS. The reactive power of CB Q_{CB} quadratically depends on the voltage:

$$Q_{CB} = 3\omega C_{CB} U_{ph}^2\,. \qquad (4.3)$$

CB compensates for part of the load requirement in reactive power, which reduces its consumption from the network to the value:

$$Q^{/} = Q - Q_{CB}\,. \qquad (4.4)$$

The active power of the P_{CB} consumed by the SK is proportional to the value of the reactive power:

$$P_{CB} = Q_{CB} \cdot tg\delta\,, \qquad (4.5)$$

and depends on the insulation quality of the capacitors, which is characterized by the tangent of the dielectric loss angle tgδ. The value of the parameter tgδ is 3 - 6 W/kvar, so the consumption of active power CB is insignificant, which determines their high efficiency. To compensate for reactive power, special cosine capacitors designed to operate at a frequency of 50 Hz are used. Their capacity is in the range of 10-100 quar. The scale of rated voltages - 230 V - 10.5 kV. Such capacitors can withstand current overload up to 30% of the nominal and voltage up to 10% of the nominal value.

CB have a negative control effect, so as the mains voltage decreases, the generated reactive power of the CB also decreases, which is their main drawback. This means that the power of the CB is reduced, while according to the requirements of the mode, the power must be increased. The disadvantage is eliminated by using capacitor units (CU), which consists of several sections, each of which contains a voltage and/or power regulator, which is connected to the network independently of the other sections, thus increasing the capacity of the battery as a whole. This allows you to increase the total power of the CB while reducing the voltage. In fig. 4.3 shows a stepwise increase in the generated power with a decrease in the voltage of the CB from three sections.

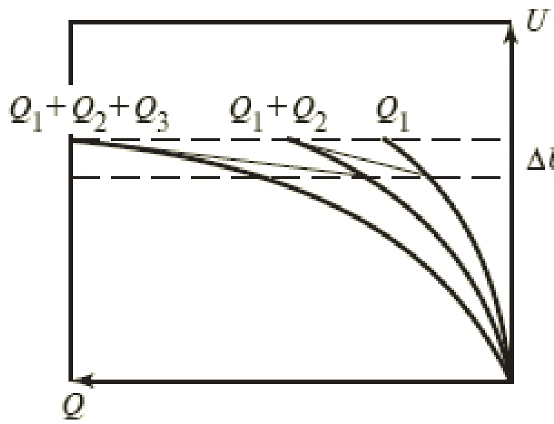
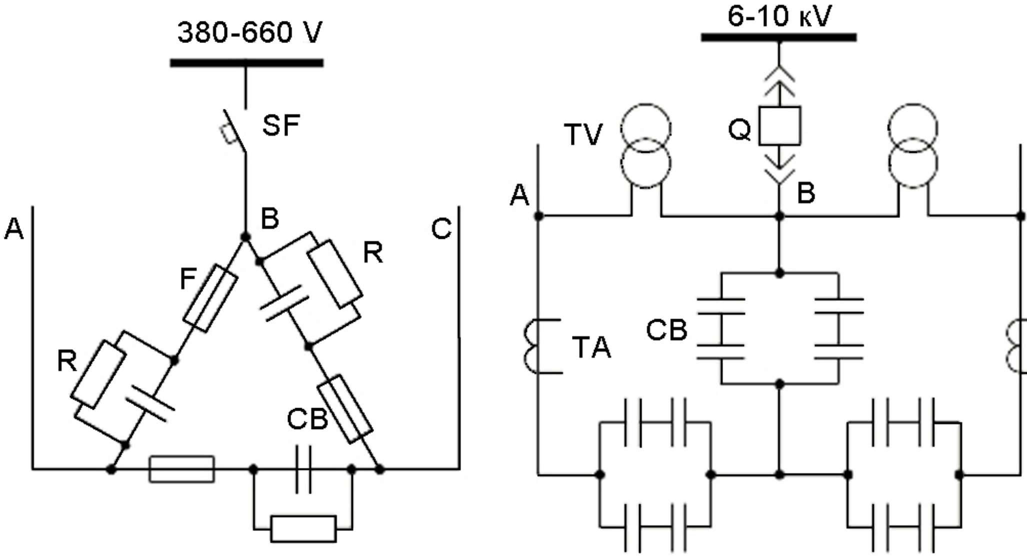


Fig. 4.3. Stepwise increase of the generated power of CB from three sections

Low-voltage CU is assembled from three-phase capacitors connected in parallel. To protect the CU from short circuits in each phase add a fuse, Fig. 4.4, a). In high-voltage switchgear use single-phase capacitors connected in series and in parallel, Fig. 4.4, b).



a) the scheme of switching on the fuses in the CU; b) the scheme of series-parallel switching capacitors

Fig. 4.4. Design of capacitor installations

Step adjustment of the CU requires the introduction of a dead zone ΔU. Within this zone, if the voltage is reduced, the connection of the next section is not allowed. The width of the insensitivity zone must be greater than the voltage gain caused by the connection of the next section of the CB. Otherwise, the CB voltage will exceed the limit value immediately after the next section is switched on.

Switching on and off the CU is accompanied by transients, which reduces the service life of capacitors and switching equipment. Therefore, CU is not recommended to switch more than 2-4 times a day. To limit the starting currents, the capacitors must be discharged with *R*-resistors or TV voltage transformers before switching on.

By their properties, capacitors are sensitive to higher current harmonics, which cause an increase in power losses ΔP and additional heating of capacitors:

$$\Delta P = \sum_{1}^{n} U_n^2 \cdot n \cdot \omega C \cdot tg\delta . \qquad (4.6)$$

The use of CU for systems with high-speed reactive power control is almost impossible due to the occurrence of transients during switching. To switch sections of the CU use symistors or counter-parallel included thyristors. To reduce transients, the battery section is connected to the mains at times when the voltage on it and the mains voltage are close. The section is disconnected when the battery current passes through zero.

In fig. 4.5 shows a diagram of a static thyristor compensator (STC) in single-phase design, which consists of three sections CB.

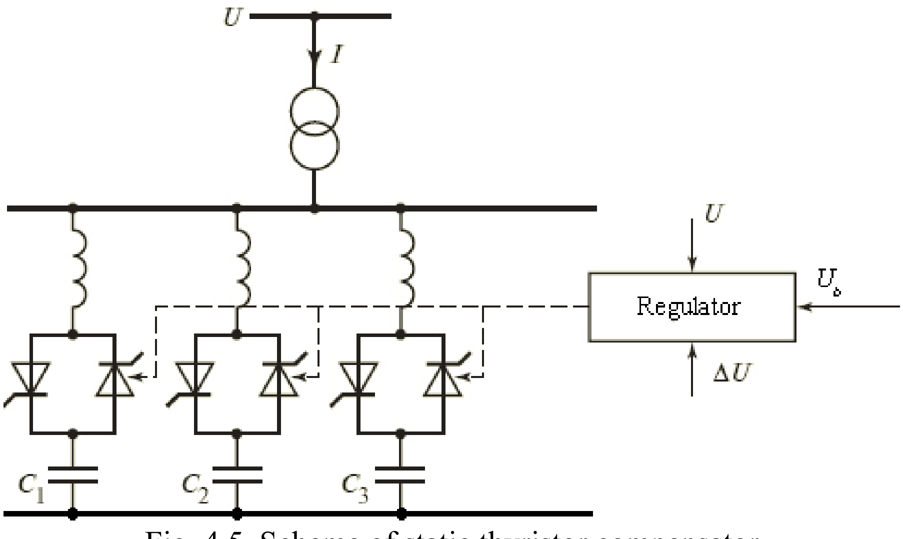
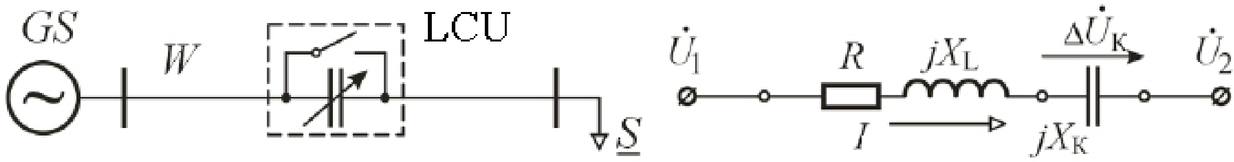


Fig. 4.5. Scheme of static thyristor compensator

To reduce the inductive resistance of high-voltage lines, series-connected capacitors are also used - longitudinal compensation units (LCU). LCU is included in the phase break, Fig. 4.6.



a) switching scheme; b) substitution scheme
Fig. 4.6. Installation of longitudinal capacitive compensation

The bandwidth of the line increases due to the decrease of the wave resistance Z_C of the line and the decrease of the wavelength parameter λ. Usually LCU is installed in the middle of the line. To ensure the protection of the line from short circuits, the resistance of the LCU X_{LCU} must satisfy the following condition:

$$X_{LCU} < X_L, \tag{4.7}$$

where X_L is the inductive resistance of the line.

Installing LCU capacitors in the middle of the transmission line increases the voltage in the middle of the line. Therefore, if necessary, shunt reactors are additionally connected at the place of installation of the LCU.

Reactors

Reactors are used to regulate voltage and compensate the charging capacity in networks of 220 kV and above. Reactors have a positive control effect, ie increase the consumption of reactive power with increasing voltage, which contributes to its limitation. The installed capacity of the reactors can range from 10 Mvar in distribution networks to 150 Mvar in 750 kV networks. The core of the reactor can be with or without a gap, single- or three-phase design. The reactors operate in a linear mode, so do not create higher current harmonics. Reactor losses are 0.2-0.4% of rated capacity.

Saturated reactors are also used to regulate reactive power. Their operating point is at the boundary of the saturation region and they perform the function of a parametric device for regulating reactive power. With increasing voltage, the reactor enters the saturation zone, the current through it increases, which increases the consumption of reactive power and voltage stabilization at the point of connection of the reactor.

In contrast to CB, reactor-based thyristor STCs can be used to smoothly regulate reactive power consumption. Power regulation is provided by adjusting the opening angle of thyristors α. If $\alpha = \pi / 2$ only reactive power is consumed from the network, the current through the reactor has a sinusoidal shape, if $\alpha > \pi / 2$ the reactive power consumed decreases, the current loses its sinusoidal shape, fig. 4.7.

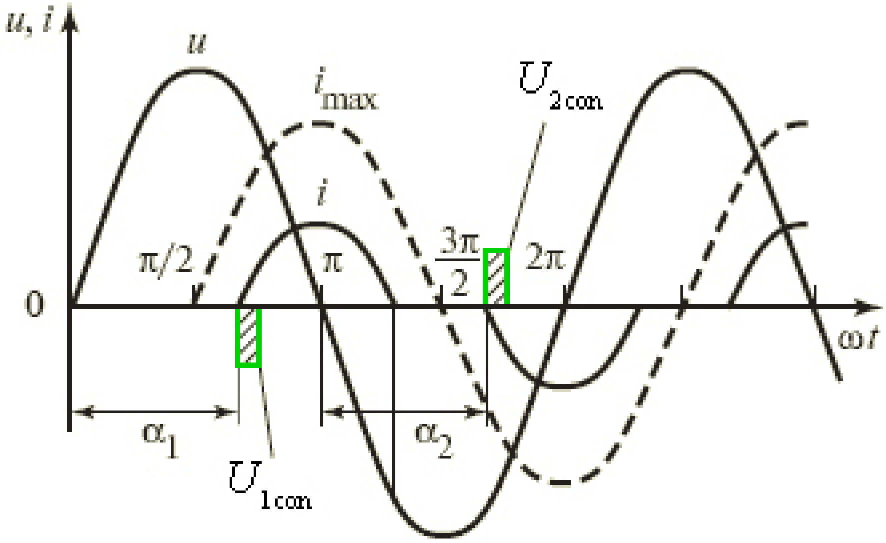


Fig. 4.7. Time diagrams of STK operation based on the reactor

The first harmonic of the reactor current at $\alpha > \pi/2$ relative to the total current $I_L = U/X_L$:

$$I_{(1)} / I_L = \frac{1}{\pi}\left(2(\pi - \alpha) + \sin 2\alpha\right). \quad (4.8)$$

The static characteristic of the reactor depending on the value of the first harmonic $I_{(1)}$ is shown in Fig. 8.

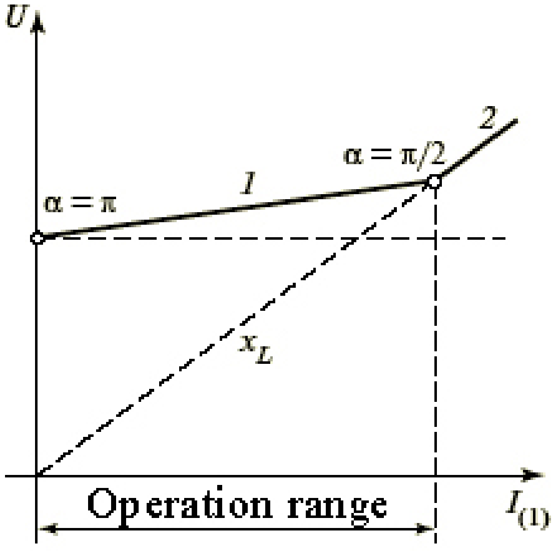


Fig. 4.8. Static characteristics of the STC reactor

Combined RPS

Combined RPSs, called STATCOM, are used in cases where it is necessary to ensure smooth regulation of reactive power in both power consumption and generation mode. Such RPSs are STC based reactors and CB. STATCOM also performs a number of additional functions:

- line voltage stabilization;
- regulation of reactive power flows;
- increasing the capacity of power lines with dynamic and static stability of the system;
- limitation of switching voltages;
- compensation of asymmetric operating modes of the system.

The input data for the calculation to STATKOM are:

- power control range (reactive power generation-consumption);
- type of control (symmetrical or phase-by-phase);
- range of network voltage change;
- speed;
- restrictions on higher current harmonics.

The structure of STATKOM is shown in fig. 4.9.

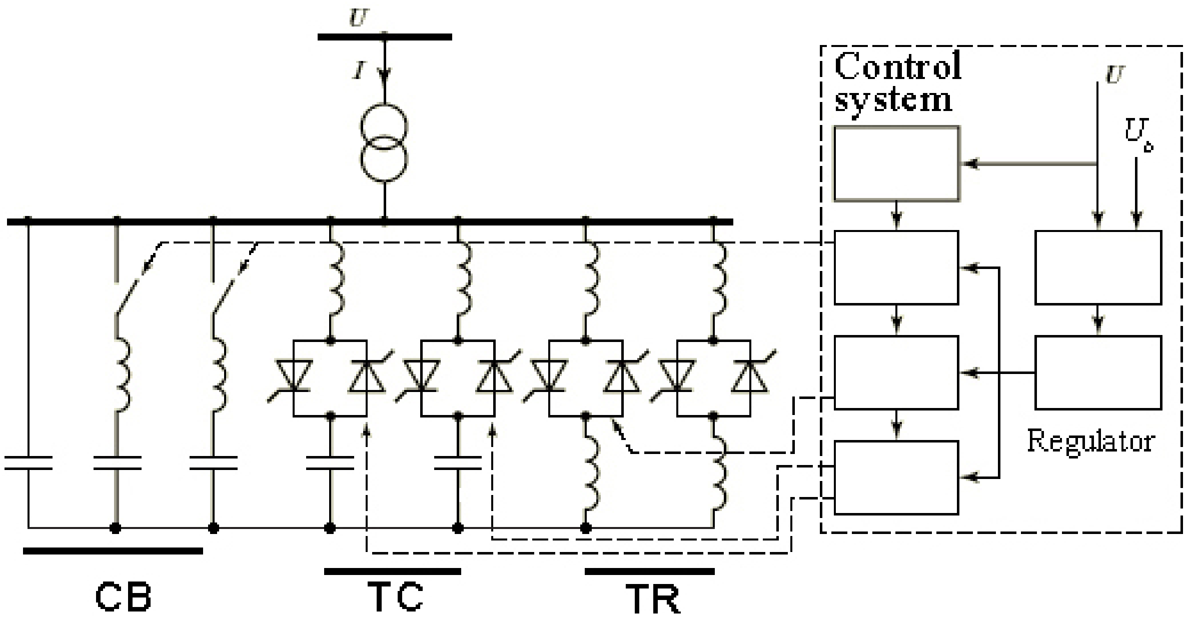


Fig. 4.9. The structure of the compensator STATKOM

As can be seen from Fig. 4.9, the STATKOM compensator generally comprises a multi-section capacitor battery CB, a thyristor-capacitor section TC and a thyristor-reactor section TR.

The operating range of the reactive power control, the set power of the unregulated or step-regulated CB, the power of the thyristor-regulated reactors are selected according to the purpose of the compensator. The following power ratios of CB Q_{CB} and Q_P reactors are possible:

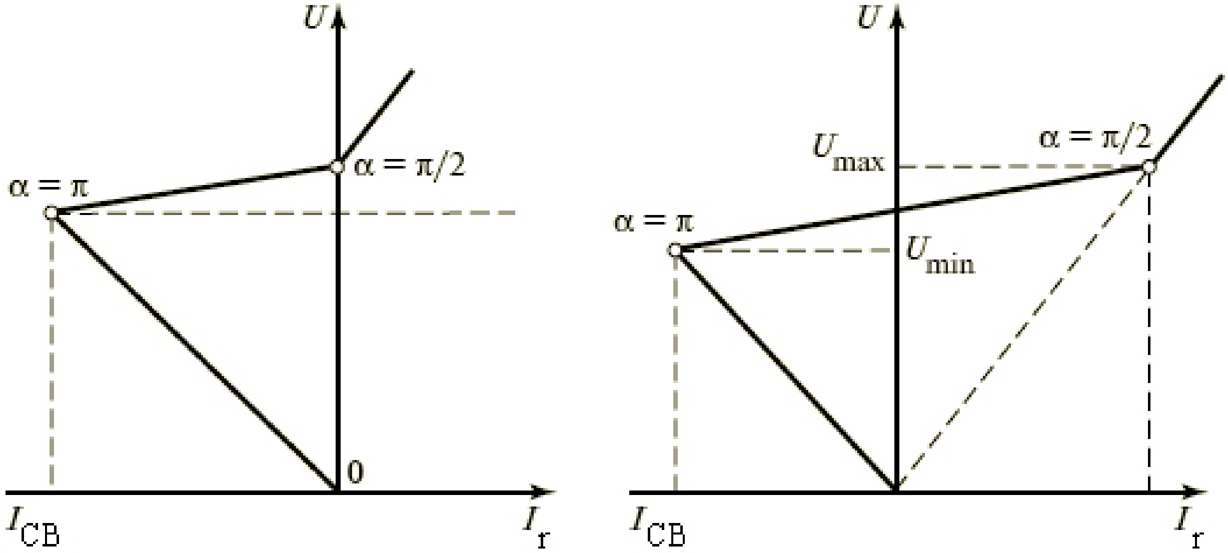
1. $Q_{CB} = Q_P$. Due to the fact that the reactor power is regulated within $Q = 0 .. Q_P$, and the CB power is constant $Q = - Q_P$. The total power can vary smoothly in the

range $Q = - Q_P$ .. 0. That is, such a compensator can generate power from 0 to Q_P quar. Static characteristic STC shown in fig. 4.10 a).

2. $2Q_{CB} = Q_P$. In this case, the power of the STC is regulated in the range $Q = - 0.5Q_P - + 0.5Q_P$. That is, the compensator can generate or consume reactive power. Static characteristic of the STC STC shown in fig. 4.10 b).

In practice, the STATCOM compensator contains a multi-section capacitor battery CB (STC-1) and a thyristor-reactor section TR or a thyristor-capacitor TC and a thyristor-reactor section TR (STK-2), fig. 4.9.

If in STC-1 the reactive power of TR is equal to the power of CB $Q_{CB} = Q_P$, the transition to inductive mode is provided by switching off CB, which reduces the speed of the compensator. Increasing the capacity of the TR section will increase the speed of the installation, but at the same time increase its price.



a) b)

Fig. 4.10. Static characteristics of STATKOM

In STC-2, the power of the TR is determined from the power of one section of the TC, the required power of the inductive mode. Decreasing the TR power reduces the amplitude of the higher current harmonics. In the table. 4.1 shows the characteristics of the modifications of the STC. Due to significant voltage overloads of thyristor valves in TC, the cost of STC-2 is usually higher than STC-1.

Table 4.1. Parameters of STC

Parameter	STC-1	STC-2
Current harmonics	Increased content of current harmonics. Additional filters must be installed	Low harmonic content. There is usually no need to install filters
Capacitor Switching	Slow	Fast
Voltage on thyristors: nominal, emergency	 U U	 2U 4U

From the analysis of data table 1 it can be concluded that the thyristors of the compensator STC-1 have the lowest voltage loads, but this type of compensator has worse characteristics than STC-2.

The main advantage of thyristor STATKOM is:

- generating a given amount of reactive power regardless of the mains voltage;
- low inertia of work (tenths of a second).

STATCOM type compensators can also

be built on fully controlled thyristors or transistors, which reduces the power of higher harmonics with PWM. The schematic diagram of the compensator is shown in Fig. 4.11.

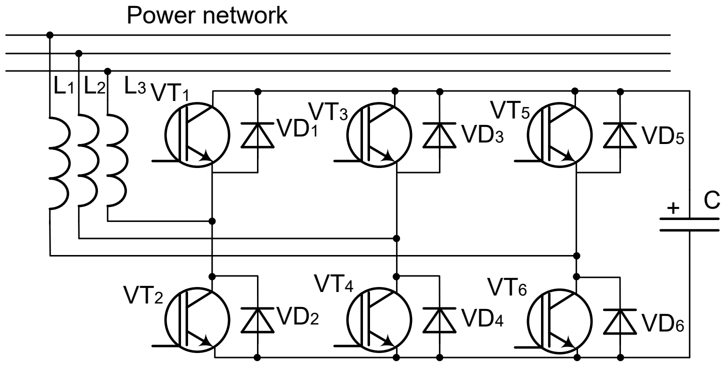


Fig. 4.11. Scheme of the compensator STATKOM

Inductors L_1 - L_3 act as filters in the AC circuit and form the desired shape of the input current. Capacitor C acts as a source of direct voltage. The principle of voltage formation of the converter with PWM is shown in fig. 4.12.

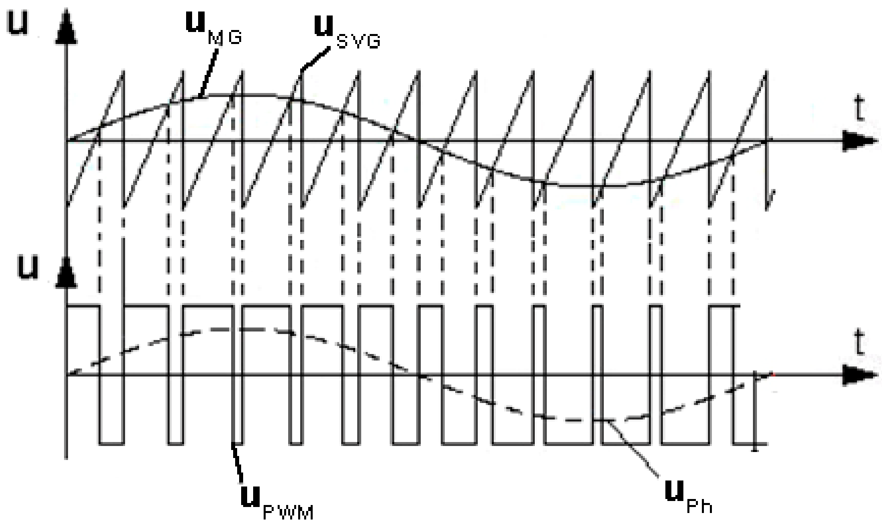


Fig. 4.12. The principle of voltage generation of the converter with PWM

The voltage of one of the phases of the converter u_p is formed by modulating the sinusoidal law u_{PWM}. It is formed based on a comparison of the sinusoidal voltage of the master generator u_{MG} and the voltage of the sawtooth voltage generator u_{SVG}.

The level of reactive power that generates the compensator depends on the phase shift between the mains voltage U and the voltage that generates the converter U_C:

$$Q = \frac{U(U_C cos(\varphi) - U)}{X_L}, \tag{4.9}$$

where X_L is the resistance of the AC choke on the AC side, φ is the phase shift between the voltage of the converter and the network.

From the analysis of (4.9) we can conclude that the reactive power of the compensator can be both capacitive and inductive. Compensators with voltage converters simultaneously with the compensation of the reactive power component are used to compensate for higher harmonics of current consumers.

Questions

1. List the problems for which reactive power sources are used.
2. Name the main types of reactive power sources.
3. Indicate the main disadvantage of capacitor banks as a source of reactive power.
4. Name the main purpose of thyristor switches in capacitor banks and reactor units.
5. Name the possible operating range of reactive power control in reactive power compensators type STATKOM.
6. List the components of static compensators STK-1 and STK-2.
7. Specify the principle of reactive power control in reactor units.
8. Give the advantages of building a static reactive power compensator using a voltage converter on fully controlled switches with PWM.

Lecture № 5. Passive and active filters of higher harmonics

Effect transducers power quality parameters on network

Most converters of electric energy parameters contain a DC link, so a rectifier with a filter, which is a nonlinear load, is installed at their input. Without special measures, odd harmonics are present in the input current spectrum of such converters, the amplitude of which is commensurate with the amplitude of the first harmonic. The spectral composition of the current depends on the type of filter at the output of the rectifier. For low-power single-phase converters (P <100 W) capacitive filters ($CU^2 >> LI^2$) have much higher energy efficiency, which causes their frequent use.

As is known, the input current of a rectifier with a capacitive load has a pulse shape. The current spectrum contains odd harmonics, the amplitude of which decreases slowly depending on the harmonic number. For example, the amplitude of the third harmonic is 70 - 90% of the first, the fifth – 60 - 80%. If a capacitive filter is used, the power factor of the converter is at the level of χ = 0.3..0.4, which indicates a negative impact on the network and irrational use of network energy by most low-power converters.

Inductive, inductive-capacitive filters should be used for three-phase converters of medium and high power. If the inductive resistance of the filter is much greater than the load resistance $\omega L >> R$, the input current of the converter has a rectangular shape. The amplitude of the higher harmonics of the rectangular current is calculated by the $I_{(n)} = I_{(1)}/n$, where $I_{(1)}$, is the amplitude of the first harmonic, n is the number of the harmonic. The power factor of such converters is χ = 0.7. From comparing the power factor of converters with capacitive and inductive filter, we can conclude that the use of converters with inductive filter has less negative impact on the network. To reduce the negative impact on the network, it is advisable to use three-phase rectifiers, which have a much higher power factor. For example, if you use a three-phase bridge circuit with an inductive filter, the power factor is $\chi \approx 0.95$.

Additional sources of higher current harmonics can be transformers, if they operate with an inflated value of magnetic induction, which leads to its saturation at the end of each half-cycle of the mains voltage and the corresponding increase in input current, Fig. 5.1. Other sources of excitation of higher harmonics of current are AC motors, electronic ballasts of fluorescent lamps, steelmaking furnaces, etc.

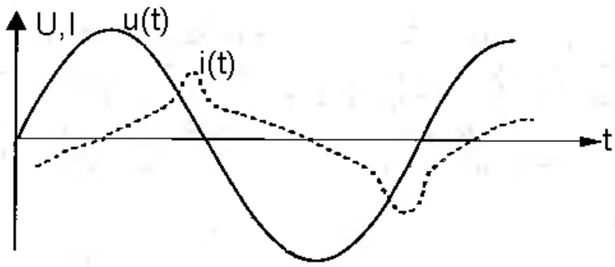


Fig. 5.1. The shape of the current at saturation of the transformer

If electricity consumers have a low power factor, higher harmonic filters are installed to increase it.

Passive filters

The simplest way to suppress higher harmonics is to use passive LC filters (PF), the resonant frequency of which is tuned to a specific harmonic. They can be installed separately in each phase relative to the neutral wire or between the phases of the network, Fig. 5.2.

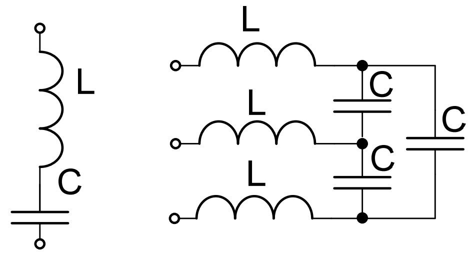


Fig. 5.2. Passive filters of higher harmonics

To improve the harmonic composition, it is necessary to suppress the first few higher harmonics, for which multi-section filters are used, each link of which is tuned to the corresponding harmonic. The following recommendations should be considered when designing multi-section passive filters:

1. Settings. The filter sections must be tuned to resonant frequencies that are lower than the frequencies of the corresponding harmonics. In this case, during the operation of the filter capacitors, which is associated with a decrease in their capacity, the resonant frequency will increase.
2. Protection. To protect against large starting currents that may flow through the filter capacitor, fuses are connected in series with them.
3. Shutdown. In near-idle modes, it is advisable to disconnect some of the filter capacitors to eliminate the increase in supply voltage associated with the increased capacitive response of the filter.
4. Tolerances on the reactive elements of the filter must ensure the impossibility of resonant phenomena at higher harmonics.
5. The maximum allowable voltage and current on the capacitors and chokes of the filter is chosen taking into account the higher harmonics of voltage and current.
6. Accommodation. It is advisable to install higher harmonic filters directly near the nonlinear load.
7. Aging. Over time and under the influence of adverse conditions (high temperature and humidity), the parameters of the filter elements can change significantly, so it is necessary to periodically measure and adjust them.

Active filters of higher harmonics

Promising devices for suppressing higher harmonics are active filters (AF). The principle of their work is to form a voltage (current) in antiphase with higher harmonics, which occur in a nonlinear load, Fig. 5.3.

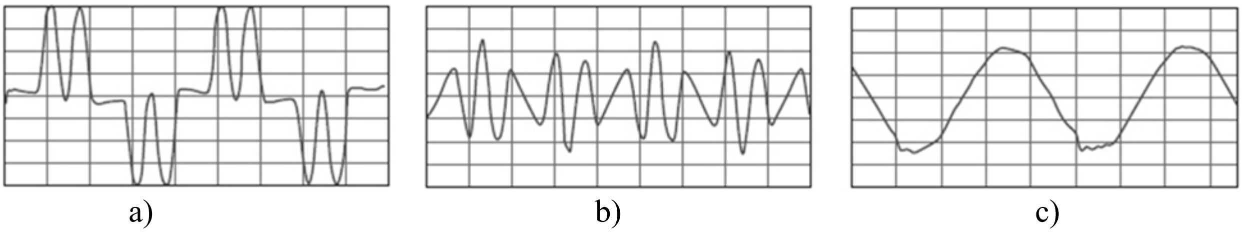


Fig. 3. Diagrams of the active filter

In fig. 5.3 shows timing diagrams: a) nonlinear load (three-phase rectifier) i_L; b) the current AF i_{AF} and c) the generator current $i_G = i_L + i_{AF}$. As can be seen from Fig. 3, AFs suppress all harmonics at the same time, so in contrast to multi-section PFs have smaller dimensions. In addition, AF can be used as reactive power compensators, voltage regulators. The basic principles of AF were developed in the 70s of the twentieth century. However, the use of AF began in practice in the late 90's, due to the improvement of technology for the production of powerful semiconductor key and valve elements (reduction of losses in the keys in static and dynamic modes). AF can be connected in parallel or in series with the load. In the first case, they are considered as a controlled current source, in the second - as a controlled voltage source, Fig. 5.4.

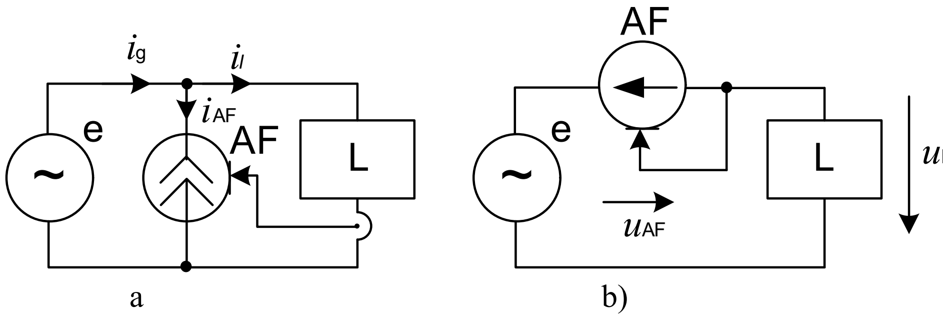


Fig. 5.4. Functional connection diagrams of a) shunt AF and b) serial AF

Shunt AF is used to reduce the level of higher harmonics of current caused by nonlinear consumers. Serial AF - in addition to the main function, can be used to adjust the amplitude of the fundamental harmonic, as well as to eliminate voltage asymmetry.

Voltage inverters with PWM are usually used in AF circuits. The PWM frequency is chosen based on Kotelnikov's theorem taking into account the number of the highest harmonic $n_{\max}$, the value of which is taken into account during the correction of the generator voltage:

$$f_{PWM} = 2n_{\mathbf{max}} \cdot f_M \,, \qquad (5.1)$$

where f_M is the mains voltage frequency.

Schemes of connection of AF to a network based on inverters are shown in fig. 5.5 and 5.6.

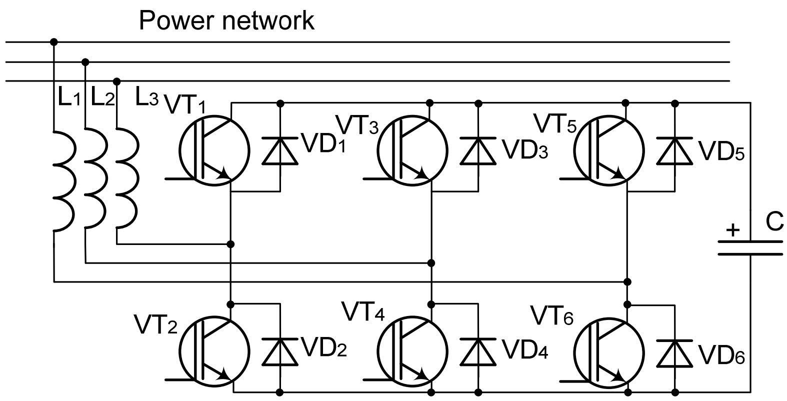


Fig. 5.5. Connection scheme of the parallel AF to power network

AF control methods

Theory of instantaneous power

The quality of AF depends on the method of forming the setting action on the power part of the filter. AF control methods can be divided into two groups: time and frequency.

Hardware implementation of time methods is simpler than frequency, because it does not require a large amount of real-time calculations. For most control methods in the time domain, the transformation of a three-phase system of vectors A-B-C (currents and load voltages) into a linearly independent system α-β-0, which is stationary in space, is used. The current and voltage vectors rotate in this system with the mains frequency and can be calculated according to their projections at any time. The transformation from one coordinate system to another is called the Clark transformation:

$$\begin{bmatrix} f_0 \\ f_\alpha \\ f_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} f_A \\ f_B \\ f_C \end{bmatrix}, \quad \begin{bmatrix} f_A \\ f_B \\ f_C \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} f_0 \\ f_\alpha \\ f_\beta \end{bmatrix}, \quad (5.2)$$

where f_0, f_α, f_β is a system of three-phase vectors in the coordinate system α-β-0, f_A, f_B, f_C - system of three-phase vectors in the coordinate system A-B-C.

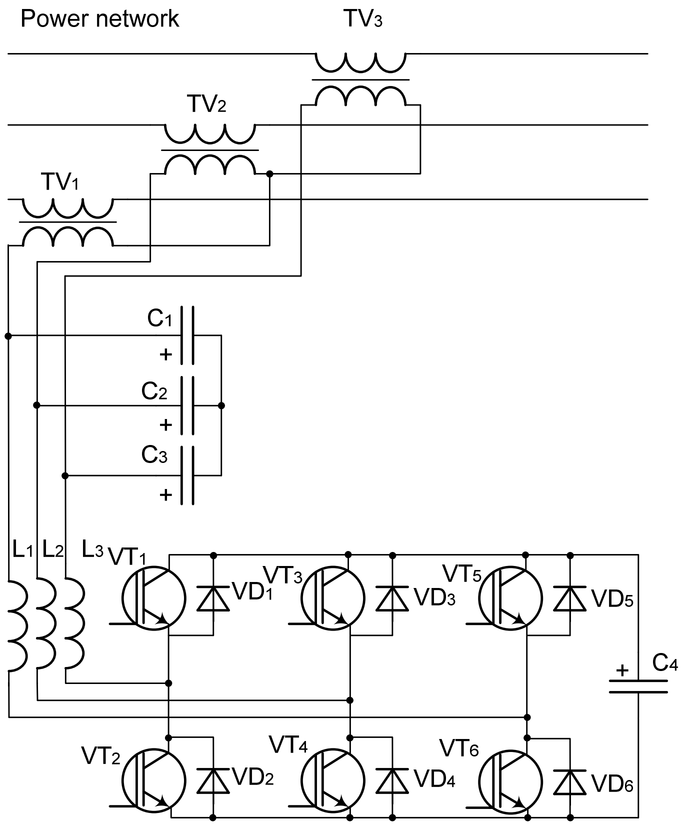


Fig. 5.6. The scheme of connection of serial AF to a network

The instantaneous power of a three-phase system in these coordinate systems is calculated by the formulas:

$$p(t) = u_A i_A + u_B i_B + u_C i_C = p_A + p_B + p_C = u_\alpha i_\alpha + u_\beta i_\beta + u_0 i_0 =$$
$$= p_\alpha + p_\beta + p_0 = p_{\alpha\beta} + p_0, \qquad (5.3)$$

where $p_{\alpha\beta}$ is the instantaneous active power, p_0 is the instantaneous power of the zero sequence.

The power of the zero sequence p_0 is compensated separately, for example by switching on the primary windings of the transformer by a triangle or by means of a balancing device. To compensate for the reactive power, its values are recorded through the values of currents and voltages on the α-β plane:

$$q(t) \approx u_\alpha i_\beta + u_\beta i_\alpha, \qquad (5.4)$$

or in the usual coordinate system:

$$q(t) \approx \left[(u_A - u_B) i_C + (u_B - u_C) i_A + (u_C - u_A) i_B \right] / \sqrt{3}. \qquad (5.5)$$

Expressions of instantaneous active and reactive power according to (5.3) and (5.4) have the following form:

$$\begin{bmatrix} p \\ q \end{bmatrix} \approx \begin{bmatrix} u_\alpha & u_\beta \\ -u_\beta & u_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}. \qquad (5.6)$$

The instantaneous active power $p(t)$ contains a constant component P and a variable component $p\sim$. To improve the operation of the power system, it is advisable to eliminate the return of energy from the load back to the source, which must compensate for the reactive power q and the variable component of active power $p_\sim =$

p - P, which are caused by nonlinear and reactive nature of the load. The equation for calculating the currents caused by the reactive power q and the variable component of the active power $p_{\sim}$, write similarly to (5.6):

$$\begin{bmatrix} p-P \\ q \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ -u_\beta & u_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \Rightarrow \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ -u_\beta & u_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p-P \\ q \end{bmatrix}. \quad (5.7)$$

To move to the coordinate system ABC use Clark transformations:

$$\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} u_\alpha & u_\beta \\ -u_\beta & u_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p-P \\ q \end{bmatrix}. \quad (5.8)$$

A low-pass filter carries out the selection of the average value of the active power P. To eliminate the exchange processes between the source and the load, it is sufficient to generate currents in antiphase with those obtained in (5.8).

The *d-q* method

The *d-q* method is a logical continuation of the theory of instantaneous power. From the α-β plane, by means of the Park transformation, the system of current and voltage vectors is represented in the d-q plane, which rotates with the network frequency.

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \begin{bmatrix} cos(\theta) & sin(\theta) \\ cos(\theta) & -sin(\theta) \end{bmatrix} \begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix}, \quad (5.9)$$

where $\theta = \omega t$ is the angle between the axes d and α.

If the vector d is combined with the voltage vector of the network u, we obtain: $u_d = u$, $u_q = 0$. The active and reactive power of a three-phase system are equal to:

$$\begin{bmatrix} p \\ q \end{bmatrix} = u_d \begin{bmatrix} i_d \\ -i_q \end{bmatrix}. \quad (5.10)$$

The purpose of AF, using the *d-q* method is:

1. Elimination of alternating currents i_d, i_q (harmonic suppression).

2. Elimination of the direct current component i_q (reactive power compensation).

3. Ensuring the implementation of the balance of active power between the source and the load: $P_S = P_{LOSS} + P_{LOAD}$, де N, where P_S - power consumed from the network, P_{LOSS} - power loss, P_{LOAD} - load power.

Thus, the operation of the AF should lead to the fact that the network current vector in the plane *d-q* i_{dq} should be equal to:

$$i_{dq} = \frac{P_{Load} + P_{Loss}}{u_d}, \quad (5.11)$$

and do not contain variable components, fig. 5.7. From this condition are the components of the output current AF i_d*, i_q*.

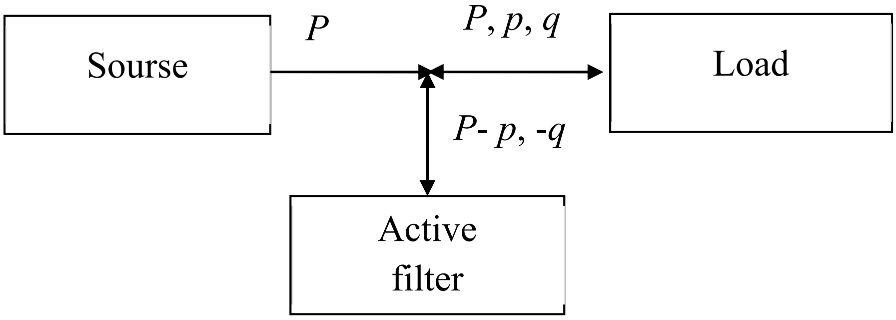


Fig. 5.7. The principle of AF

For the inverse transformation, the Clark transform (5.8) and Park are used:

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \begin{bmatrix} cos(\theta) & -sin(\theta) \\ sin(\theta) & cos(\theta) \end{bmatrix} \begin{bmatrix} f_d \\ f_q \end{bmatrix}. \quad (5.12)$$

Synchronous tracking method

If you use the method of forming the filter current can be carried out by two methods:

- from the condition of equality of the average value of power of phases $P_A = P_B = P_C$;

- from the condition of equality of equivalent resistances of phases $P_A = P_B = P_C$;

In the first case, the power is even ly distributed over the phases regardless of the value of the phase voltages.

$$i_A(t) = \frac{2u_A(t)\cdot P}{3U_{Am}^2};\ i_B(t) = \frac{2u_B(t)\cdot P}{3U_{Bm}^2};\ i_C(t) = \frac{2u_C(t)\cdot P}{3U_{Cm}^2}, \quad (5.13)$$

where U_{Af}, U_{Bf}, U_{Cf} - amplitudes of phase voltages, i_x(t), u_x(t) - instantaneous values of current and voltage of phase x of the network.

The constant value of the load power is calculated by the formula:

$$P = \int_t^{t+T} \left(p_A(t) + p_B(t) + p_C(t)\right)dt = \int_t^{t+T} \left(u_A(t)i_A(t) + u_B(t)i_B(t) + u_C(t)i_C(t)\right)dt, \quad (5.14)$$

where T is the period of the network frequency.

Frequency methods

Frequency methods are based on the apparatus of spectral analysis, mainly on discrete Fourier transform (DFT). The AF current is formed as follows:

1) calculate the spectral characteristics of the load current;

2) carry out the correction of the vector of the first harmonic;

3) take into account the delay of the reaction to the satisfactory action due to the presence of a power filter;

4) the transition to the time domain and the formation of control signals AF.

Calculation of AF elements

The minimum value of the inductance of the AF filters L_1-L_3, fig. 5.5 is calculated from the condition of compensation of reactive power of purely inductive load current I_{max}:

$$L_{\mathbf{min}} = \frac{\Delta U_{\mathbf{min}}}{2\pi f_M I_{\mathbf{max}}}, \tag{5.15}$$

where ΔU_{min} is the difference between the voltage of the capacitor AF and the current value of the mains voltage, f_M - network frequency.

In practice, the value of the inductance is several orders of magnitude greater and depends on the restriction on the amplitude of the current ripple of the source ΔI_{max}:

$$L = \frac{\Delta U_{max} T_{PWM}}{\Delta I_{\mathbf{max}}}. \tag{5.16}$$

The capacitance of the capacitor C AF must be calculated for reasons of providing a given voltage ripple factor on it. At times when it is necessary to change the amount of reactive energy AF, the energy of the capacitor changes by the difference between the initial and final amount of reactive energy ΔW:

$$\Delta W = \frac{3}{2}(LI_1^2 - LI_0^2). \tag{5.17}$$

The worst case is the transition from inductive load response compensation to capacitive compensation. Then the initial voltage on the capacitor U_{C0} will decrease to the value of U_{C1}.

$$\Delta W = \frac{1}{2}(CU_{C0}^2 - CU_{C1}^2) \approx CU_{C0}(CU_{C0} - CU_{C1}). \tag{5.18}$$

Equating (17) and (18), we obtain:

$$C = \frac{3L(I_1^2 - I_0^2)}{2U_{C0}^2 K_P}. \tag{5.19}$$

Hybrid filters

AF, due to its high cost, is used for low power power supply systems. To reduce the cost of filters, combined systems are used, which include low-power AF and multi-section PF. The disadvantage of PF - the inability to adjust their parameters under the condition of changing the mode of operation of consumers is eliminated in hybrid filters by installing active AF. In this case, the power of the active part of the circuit is reduced by an order of magnitude compared to PF, increases the stability of the passive part of the circuit in dynamic modes, which increases the quality factor PF and reduce losses.

Automatic correction of GF parameters has the following advantages:

- correction of frequency characteristics of the filter in static modes of network operation;
- reduction of the negative impact on the filtering properties of the network frequency deviation and filter parameters;
- elimination of resonant phenomena at higher current harmonics.

An example of a typical GF circuit is a combination of an AF, a three-phase transformer, two LC filters tuned to 5 and 7 harmonics, and a higher harmonic RLC filter. If you use the specified scheme GF to correct the parameters of electricity for the power supply system of the DC load through a diode rectifier with a capacity of 20 kW, it is sufficient to use AF with a capacity of 1.6 kVA and PF with a capacity of 5 kVA. The current harmonic coefficient of the system source does not exceed 5%. To achieve these parameters, the AF must have a capacity of about 15 kVA.

Questions

1. Describe the influence of converters on the power quality parameters of the network.
2. Describe the recommendations to be followed when designing multi-section passive filters.
3. Name the types of active filters of higher harmonics.
4. Describe the principle of operation of active filters of higher harmonics of parallel type.
5. State the reason for the active implementation of active filters recently.
6. Describe the method of controlling an active filter using the theory of instantaneous power.
7. List the methods of managing active filters.
8. List the benefits of using hybrid filters.

Lecture № 6. Balancing devices of three-phase power supply systems

Classification of balancing methods

In a set of measures aimed at improving the quality of electricity, the issue of propagation of asymmetry of voltages and currents in three-phase networks is essential. One of the simplest methods of reducing the asymmetry of voltages (currents) is the uniform distribution of single-phase loads between the phases. However, in practice this is a difficult task. Therefore, it is necessary to apply special methods and means of balancing of three-phase systems. One way to reduce voltage asymmetry is to increase the cross-sectional area of the wires and the power of substation transformers. In four-wire networks, it is advisable to reduce the resistance of the neutral wire. However, a more effective method is the use of special devices that eliminate currents of zero and reverse sequence. These methods can be divided into groups:

- methods based on the conversion of electrical energy parameters;
- methods based on cyclic switching of single-phase load to network phases;
- methods based on filtration;
- compensation methods that compensate for currents and voltages of the reverse and zero sequences.

In power supply systems, compensation methods are more often used because they have the best technical indicators: simultaneously with the asymmetry of currents, eliminate higher harmonics, compensate for reactive power. The synthesis of balancing devices (BD) is carried out based on the specified conditions of maintenance within the allowable limits of asymmetry of voltages and currents with the provision of a given power factor and the minimum power of the elements of the balancing devices. BD compensation type can be adjustable and unsettled. Unregulated BD can be used if the power consumption varies within narrow limits. Therefore, in practice, the vast majority use adjustable BD.

Method of symmetrical components

Special methods are used to calculate the level of voltage asymmetry. The most common of which is the method of symmetrical components. It is used to represent an arbitrary three-phase EMF system, voltage or currents in the form of the sum of three symmetric systems - forward, reverse and zero sequences, Fig. 6.1.

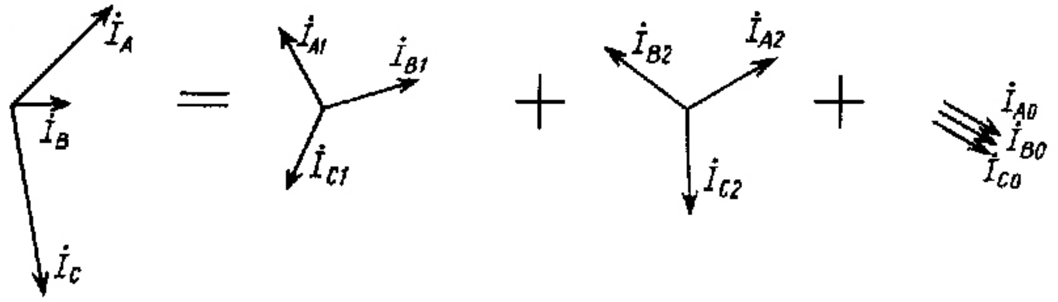


Fig. 6.1. Direct, inverse and zero sequences

The figure shows the decomposition of the three-phase system of currents I_A, I_B, I_C into components: direct sequence with currents I_{A1}, I_{B1}, I_{C1}, reverse I_{A2}, I_{B2}, I_{C2} and zero I_{A0}, I_{B0}, I_{C0}:

$$\begin{cases} \dot{I}_A = \dot{I}_{A1} + \dot{I}_{A2} + \dot{I}_{A0}; \\ \dot{I}_B = \dot{I}_{B1} + \dot{I}_{B2} + \dot{I}_{B0}; \\ \dot{I}_C = \dot{I}_{C1} + \dot{I}_{C2} + \dot{I}_{C0}. \end{cases} \tag{6.1}$$

The currents of the direct sequence I_{A1}, I_{B1}, I_{C1} have phase shifts of 120°, the direct order of alternation of the ABC phases. The reverse sequence IA2 I_{A2}, I_{B2}, I_{C2} has alternating phases of ACB. Zero-sequence currents have the same phase. The amplitudes of the currents of each sequence are equal to each other: $I_{A1} = I_{B1} = I_{C1}$, $I_{A2} = I_{B2} = I_{C2}$, $I_{A0} = I_{B0} = I_{C0}$.

An abbreviated notation with the rotation operator a - complex multiplier is used to record the individual components $a = e^{j2\pi/3} = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$.

The following relations are often used when simplifying formulas:

$$\begin{aligned} &a^2 = e^{j4\pi/3} = e^{-j2\pi/3} = a^{-1} = -\frac{1}{2} - j\frac{\sqrt{3}}{2}; \\ &a^3 = e^{j2\pi} = 1; \\ &a + a^2 + 1 = 0. \end{aligned} \tag{6.2}$$

The use of the operator a allows you to write the following relations for the line

$$\dot{I}_{B1} = a^2 \cdot \dot{I}_{A1}; \dot{I}_{C1} = a \cdot \dot{I}_{A1}, \tag{6.3}$$

reverse

$$\dot{I}_{B2} = a \cdot \dot{I}_{A2}; \dot{I}_{C2} = a^2 \cdot \dot{I}_{A2}, \tag{6.4}$$

and zero sequences

$$\dot{I}_{A0} = \dot{I}_{B0} = \dot{I}_{C0}. \tag{6.5}$$

Substitution of (6.3) - (6.5) in the (6.1) for calculation of the resulting currents allows to receive the following relations:

$$\begin{cases} \dot{I}_A = \dot{I}_{A1} + \dot{I}_{A2} + \dot{I}_{A0}; \\ \dot{I}_B = a^2 \cdot \dot{I}_{A1} + a \cdot \dot{I}_{A2} + \dot{I}_{A0}; \\ \dot{I}_C = a \cdot \dot{I}_{A1} + a^2 \cdot \dot{I}_{A2} + \dot{I}_{A0}, \end{cases} \tag{6.6}$$

or in matrix form:

$$\begin{bmatrix} \dot{I}_A \\ \dot{I}_B \\ \dot{I}_C \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{bmatrix} \begin{bmatrix} \dot{I}_{A1} \\ \dot{I}_{A2} \\ \dot{I}_{A0} \end{bmatrix}, \qquad (6.7)$$

from which the symmetrical components of phase A I_{A1}, I_{A2}, I_{A0} are expressed through the currents of the asymmetric system:

$$\begin{cases} \dot{I}_{A1} = \left(\dot{I}_A + a \cdot \dot{I}_B + a^2 \cdot \dot{I}_C\right)/3; \\ \dot{I}_{A2} = \left(\dot{I}_A + a^2 \cdot \dot{I}_B + a \cdot \dot{I}_C\right)/3; \\ \dot{I}_{A0} = \left(\dot{I}_A + \dot{I}_B + \dot{I}_C\right)/3. \end{cases} \qquad (6.8)$$

Similar relations are valid for symmetrical components of three-phase voltage and electric driving force systems. The schedule of asymmetric systems allows reducing the problem of calculation of an asymmetric three-phase network to the analysis of set of three symmetric modes of components of direct, return, zero sequences.

Consider the influence of direct, inverse and zero components on energy processes in the network. In a symmetric three-phase network with an asymmetric load, the voltage vectors are symmetric, they are described by a direct sequence: $E_A = a^2 \cdot E_B = a \cdot E_C$, and the currents are asymmetric, the analytical expression of which is as follows:

$$\begin{bmatrix} \dot{I}_A \\ \dot{I}_B \\ \dot{I}_C \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{bmatrix} \begin{bmatrix} \dot{I}_{A1} e^{-j\varphi 1} \\ \dot{I}_{A2} e^{-j\varphi 2} \\ \dot{I}_{A0} e^{-j\varphi 0} \end{bmatrix}, \qquad (6.9)$$

where φ is the phase shift between voltage and current of the forward, reverse and zero sequences. The instantaneous active power of the phases is equal to:

$$p_A = e_A sin(\theta)(i_{A1} sin(\theta - \varphi_1) + i_{A2} sin(\theta - \varphi_2) + i_{A0} sin(\theta - \varphi_0)); \qquad (6.10)$$

$$p_B = e_A sin(\theta - 2\pi/3)(i_{A1} sin(\theta - \varphi_1 - 2\pi/3) + i_{A2} sin(\theta - \varphi_2 - 4\pi/3) + \\ + i_{A0} sin(\theta - \varphi_0)); \qquad (6.11)$$

$$p_C = e_A sin(\theta - 4\pi/3)(i_{A1} sin(\theta - \varphi_1 - 4\pi/3) + i_{A2} sin(\theta - \varphi_2 - 2\pi/3) + \\ + i_{A0} sin(\theta - \varphi_0)); \qquad (6.12)$$

The average value of the active power of the phases depends on the angle of bias between current and voltage:

$$P_A = E_A I_{A1} cos(\varphi_1) + E_A I_{A2} cos(\varphi_2) + E_A I_{A0} cos(\varphi_0); \quad (6.13)$$
$$P_B = E_A I_{A1} cos(\varphi_1) + E_A I_{A2} cos(\varphi_2 + 2\pi/3) + E_A I_{A0} cos(\varphi_0 - 2\pi/3); \quad (6.14)$$
$$P_C = E_A I_{A1} cos(\varphi_1) + E_A I_{A2} cos(\varphi_2 - 2\pi/3) + E_A I_{A0} cos(\varphi_0 + 2\pi/3). \quad (6.15)$$

The active power of the three-phase network P is equal to the sum of the active capacities of the individual phases. Since the second and third terms in the power expressions of phases (6.13) - (6.15) form balanced vectors, the power of the network P is calculated by:

$$P = 3 E_A I_{A1} cos(\varphi_1). \quad (6.16)$$

Therefore, we can conclude that in an asymmetric three-phase network with symmetrical power supply, the active power is transmitted only by the active components of the currents of the direct sequence, which are the active components of the phase currents.

Let us investigate the influence of the forward, reverse, and zero sequences on the pulsation of the active power. We present the variable component of the instantaneous active power in the form of the sum of three components due to the forward, reverse and zero sequence:

$$\Delta p = p - P = \Delta p_1 + \Delta p_2 + \Delta p_0. \quad (6.17)$$

The pulsation Δp_1 due to the direct sequence for each phase is equal to:

$$\Delta p_{1A}(\theta) = \sqrt{2} E_A sin(\theta) \cdot \sqrt{2} I_{A1} sin(\theta - \varphi_1) = E_A I_{A1}(cos(\varphi 1) - cos(2\theta - \varphi_1)); \quad (6.18)$$
$$\Delta p_{1B}(\theta) = \sqrt{2} E_A sin(\theta - 2\pi/3) \cdot \sqrt{2} I_{A1} sin(\theta - \varphi 1 - 2\pi/3) =$$
$$= E_A I_{A1}(cos(\varphi 1) - cos(2\theta + 2\pi/3 - \varphi 1)); \quad (6.19)$$
$$\Delta p_{1C}(\theta) = \sqrt{2} E_A sin(\theta + 2\pi/3) \cdot \sqrt{2} I_{A1} sin(\theta - \varphi 1 + 2\pi/3) =$$
$$= E_A I_{A1}(cos(\varphi 1) - cos(2\theta - 2\pi/3 - \varphi 1)); \quad (6.20)$$

The instantaneous active power of the direct sequence of the three-phase network p1 is equal to the sum of the powers of the direct sequences of the phases. Summarizing the expressions (6.18) - (6.20), we obtain:

$$p_1 = 3 E_A I_{A1} cos(\varphi_1). \quad (6.21)$$

Therefore, the active power due to the direct sequence of currents is a constant value and has no pulsation $\Delta p_1 = 0$.

The active power ripple due to the reverse sequence of currents is calculated as follows:

$$\Delta p_{2A}(\theta) = \sqrt{2} E_A sin(\theta) \cdot \sqrt{2} I_{A2} sin(\theta - \varphi_2) = E_A I_{A2}(cos(\varphi_2) - cos(2\theta - \varphi_2)); \quad (6.22)$$
$$\Delta p_{2B}(\theta) = \sqrt{2} E_A sin(\theta - 2\pi/3) \cdot \sqrt{2} I_{A2} sin(\theta - \varphi_2 + 2\pi/3) =$$
$$= E_A I_{A2}(cos(\varphi_2 + 2\pi/3) - cos(2\theta - \varphi_2)); \quad (6.23)$$
$$\Delta p_{2C}(\theta) = \sqrt{2} E_A sin(\theta + 2\pi/3) \cdot \sqrt{2} I_{A2} sin(\theta - \varphi_1 - 2\pi/3) =$$
$$= E_A I_{A2}(cos(\varphi_2 - 2\pi/3) - cos(2\theta - \varphi_2)). \quad (6.24)$$

The instantaneous active power of the inverse sequence p_2 is equal to:

$$p_2(\theta) = -3 E_A I_{A2} cos(2\theta - \varphi_1), \quad (6.25)$$

and causes power ripple with double the network frequency.

The instantaneous power of the zero phase sequence is calculated by:

$$\Delta p_{0A}(\theta) = \sqrt{2}E_A sin(\theta)\cdot\sqrt{2}I_{A2}sin(\theta-\varphi_0) = E_A I_{A2}(cos(\varphi_0) - cos(2\theta-\varphi_0)) \text{;(6.26)}$$

$$\Delta p_{2B}(\theta) = \sqrt{2}E_A sin(\theta - 2\pi/3)\cdot\sqrt{2}I_{A0}sin(\theta-\varphi_0) =$$
$$= E_A I_{A2}(cos(\varphi_0 - 2\pi/3) - cos(2\theta-\varphi_0-2\pi/3)); \quad (6.27)$$

$$\Delta p_{2C}(\theta) = \sqrt{2}E_A sin(\theta + 2\pi/3)\cdot\sqrt{2}I_{A0}sin(\theta-\varphi_0) =$$
$$= E_A I_{A0}(cos(\varphi_0 + 2\pi/3) - cos(2\theta-\varphi_2+2\pi/3)). \quad (6.28)$$

From the analysis of formulas (26) - (28) we can conclude that the system of power vectors of zero sequence forms a balanced system of vectors, so $p_0 = 0$.

Thus, the active power is transmitted by the active components of the direct sequence, the inverse sequence of currents determines the ripple of the active power of the three-phase system, and the zero sequence does not affect the transmission of active power.

Passive balancing devices of three-phase network

When the asymmetry of voltage or current exceeds a certain value, it is necessary to use BD. The BD should not cause large power losses. This means that the balancing must be carried out through the use of reactive elements (LC) or by active methods (generators of electronic systems). In addition to balancing, such devices can also perform the function of reactive power compensation.

Low voltage networks are usually four-wire with a grounded neutral point. Medium or high voltage networks are three-wire.

Load balancing in the first case consists of two stages:

1) elimination of zero-sequence currents;

2) elimination of reverse sequence currents. In a three-wire circuit, only the reverse sequence currents must be eliminated.

First, consider the method of eliminating zero-sequence currents. In fig. 6.2 shows a three-phase power supply system with a neutral wire, to which an asymmetric load from the BD is connected. For this case, the balancing and compensation of the reactive current is to connect in parallel the asymmetric load of asymmetric reactive elements (chokes, capacitors) with the following values, which would meet the following conditions:

$$\dot{I}_{AM} + \dot{I}_{BM} + \dot{I}_{CM} = 0. \quad (6.29)$$

In scalar form, (6.29) will be rewritten as:

$$\begin{cases} \mathrm{Re}\left(\dot{I}_{AM} + \dot{I}_{BM} + \dot{I}_{CM}\right) = \mathrm{Re}\left(\dot{U}_A(jY_A + \dot{Y}_{AH}) + \dot{U}_B(jY_B + \dot{Y}_{BH}) + \dot{U}_C(jY_C + \dot{Y}_{CH})\right) = 0; \\ \mathrm{Im}\left(\dot{I}_{AM} + \dot{I}_{BM} + \dot{I}_{CM}\right) = \mathrm{Im}\left(\dot{U}_A(jY_A + \dot{Y}_{AH}) + \dot{U}_B(jY_B + \dot{Y}_{BH}) + \dot{U}_C(jY_C + \dot{Y}_{CH})\right) = 0. \end{cases} \quad (6.30)$$

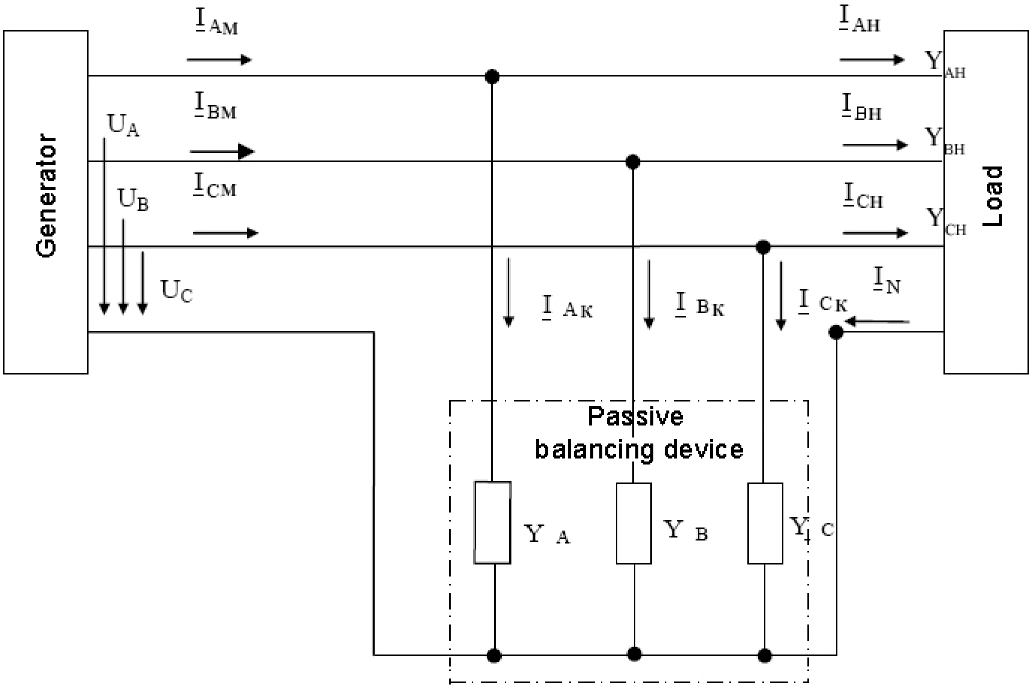


Fig. 6.2. The scheme of the joint venture to compensate for zero-sequence currents

An additional condition for calculating the parameters of the JV may be to ensure the required value of the power factor χ:

$$\chi = \frac{\mathrm{Re}\left(\dot{U}_A \overset{*}{I}_{AM}\right) + \mathrm{Re}\left(\dot{U}_B \overset{*}{I}_{BM}\right) + \mathrm{Re}\left(\dot{U}_C \overset{*}{I}_{CM}\right)}{\left|\dot{U}_A \overset{*}{I}_{AM} + \dot{U}_B \overset{*}{I}_{BM} + \dot{U}_C \overset{*}{I}_{CM}\right|}. \qquad (6.31)$$

Example 1. Given a system of three phase loads with power: P_A = 6.48 kW, Q_A = -5.15 kVA; P_B = 3.15 kW, Q_B = 4.44 kVA; P_C = 2.55 kW, Q_C = 4.2 kVA.

The loads are connected according to the "star" scheme and are powered by a three-phase network with a phase voltage U = 220 V.

Zero and reverse currents must be eliminated.

Solution:

1. Calculation of the conductivity of each phase:

$$\dot{Y}_{AH} = \frac{P_A}{U^2} + j\frac{Q_A}{U^2} = \frac{6480}{220^2} - j\frac{5150}{220^2} = 0.134 - 0.106j.$$

$$\dot{Y}_{BH} = \frac{P_B}{U^2} + j\frac{Q_B}{U^2} = \frac{3150}{220^2} + j\frac{4440}{220^2} = 0.065 + 0.0912j.$$

$$\dot{Y}_{CH} = \frac{P_C}{U^2} + j\frac{Q_C}{U^2} = \frac{2550}{220^2} + j\frac{4200}{220^2} = 0.053 + 0.087j.$$

2. Calculation of the current of each phase of the load:

$$\dot{I}_{AH} = \dot{Y}_{AH}\dot{U}_A = (0.134 - 0.106j)220 = 29.455 - 23.409j.$$

$$\dot{I}_{BH} = \dot{Y}_{BH}\dot{U}_B = (0.065 + 0.0912j)220e^{j2\pi/3} = -24.637 + 2.309j.$$

$$\dot{I}_{CH} = \dot{Y}_{CH}\dot{U}_C = (0.053 + 0.087j)e^{-j2\pi/3} = 10.738 - 19.583j.$$

3. Calculation of currents of forward, reverse and zero sequences:

$$\dot{I}_{A1}=\frac{\left(\dot{I}_A+a\cdot\dot{I}_B+a^2\cdot\dot{I}_C\right)}{3}=5.815\ -15.136j;$$

$$\dot{I}_{A2}=\frac{\left(\dot{I}_A+a^2\cdot\dot{I}_B+a\cdot\dot{I}_C\right)}{3}=18.455+5.288j;$$

$$\dot{I}_{A0}=\frac{\left(\dot{I}_A+\dot{I}_B+\dot{I}_C\right)}{3}=5.185\ -13.561j.$$

4. Calculation of the coefficient of asymmetry of the current zero k_0 and the reverse sequence k_2:

$$k_0=\frac{I_{A0}}{I_{A1}}\cdot 100\%=90\%;$$

$$k_2=\frac{I_{A2}}{I_{A1}}\cdot 100\%=118\%.$$

From the obtained values it can be concluded that the asymmetry of currents is significant and requires the connection of a balancing device.

5. Calculation of the load power factor χ:

$$\chi=\frac{\mathrm{Re}\left(\dot{U}_A\overset{*}{I}_{AH}\right)+\mathrm{Re}\left(\dot{U}_B\overset{*}{I}_{BH}\right)+\mathrm{Re}\left(\dot{U}_C\overset{*}{I}_{CH}\right)}{\left|\dot{U}_A\overset{*}{I}_{AH}+\dot{U}_B\overset{*}{I}_{BH}+\dot{U}_C\overset{*}{I}_{CH}\right|}=0.96.$$

6. Since the reactive power compensation is not performed at this stage, in condition (6.30) one of the conductivities of the balancing device can be equated to zero, for example $Y_c=0$. Then the system (6.30) will be simplified to the form:

$$\begin{cases} U_A\,\mathrm{Re}\left(\dot{Y}_{AH}\right)-\frac{\sqrt{3}}{2}U_BY_B-\frac{1}{2}U_B\,\mathrm{Re}\left(\dot{Y}_{BH}\right)- \\ -\frac{\sqrt{3}}{2}U_B\,\mathrm{Im}\left(\dot{Y}_{BH}\right)-\frac{1}{2}U_C\,\mathrm{Re}\left(\dot{Y}_{CH}\right)+\frac{\sqrt{3}}{2}U_C\,\mathrm{Im}\left(\dot{Y}_{CH}\right)=0; \\ U_AY_A+U_A\,\mathrm{Im}\left(\dot{Y}_{AH}\right)-\frac{1}{2}U_BY_B+\frac{\sqrt{3}}{2}U_B\,\mathrm{Re}\left(\dot{Y}_{BH}\right)- \\ -\frac{1}{2}U_B\,\mathrm{Im}\left(\dot{Y}_{BH}\right)-\frac{\sqrt{3}}{2}U_c\,\mathrm{Re}\left(\dot{Y}_{CH}\right)-\frac{1}{2}U_C\,\mathrm{Im}\left(\dot{Y}_{CH}\right)=0. \end{cases}$$

Where to get:

$$\begin{cases} Y_B=\dfrac{2\,\mathrm{Re}\left(\dot{Y}_{AH}\right)-\mathrm{Re}\left(\dot{Y}_{BH}\right)-\sqrt{3}\,\mathrm{Im}\left(\dot{Y}_{BH}\right)-\mathrm{Re}\left(\dot{Y}_{CH}\right)+\sqrt{3}\,\mathrm{Im}\left(\dot{Y}_{CH}\right)}{\sqrt{3}}; \\ Y_A=-\mathrm{Im}\left(\dot{Y}_{AH}\right)+\frac{1}{2}Y_B-\frac{\sqrt{3}}{2}\mathrm{Re}\left(\dot{Y}_{BH}\right)+\frac{1}{2}\mathrm{Im}\left(\dot{Y}_{BH}\right)+\frac{\sqrt{3}}{2}\mathrm{Re}\left(\dot{Y}_{CH}\right)+\frac{1}{2}\mathrm{Im}\left(\dot{Y}_{CH}\right). \end{cases}$$

If the conductivity is negative, Y < 0, then it is replaced by inductance, otherwise - capacitance.

In this case: Y_B = 0.08164 (capacity); Y_A = 0.2257 (capacity).

7. The phase current of the network after the elimination of zero-sequence currents:

$$\dot{I}_{AM} = (\dot{Y}_{AH} + jY_A)\dot{U}_A = 29.455+26.255j.$$

$$\dot{I}_{BM} = (\dot{Y}_{BH} + jY_B)\dot{U}_B = -40.192 \ -6.672j.$$

$$\dot{I}_{CH} = \dot{Y}_{CH}\dot{U}_C = 10.738 \ -19.583j.$$

8. Calculation of currents of forward, reverse and zero sequences:

$$\dot{I}_{A1} = \frac{\left(\dot{I}_A + a\cdot\dot{I}_B + a^2\cdot\dot{I}_C\right)}{3} = 11 - 1.575j;$$

$$\dot{I}_{A2} = \frac{\left(\dot{I}_A + a^2\cdot\dot{I}_B + a\cdot\dot{I}_C\right)}{3} = 18.455 + 27.830j;$$

$$\dot{I}_{A0} = \frac{\left(\dot{I}_A + \dot{I}_B + \dot{I}_C\right)}{3} = 0.$$

As can be seen from the calculations, the zero sequence current is eliminated.

To compensate for the reverse sequence currents, the BD is connected according to a three-wire circuit, Fig. 6.3.

Under the condition of a three-wire network, the balancing scheme shown in Fig. 3, obtained directly. In the case of a four-wire network, the zero-sequence current is eliminated first, as shown in the previous example.

After removing the neutral wire, the load ground can be disconnected from the generator ground without changing the currents and voltages of the system. The star load connection is then converted to a triangle connection.

$$Y_{ABH} = \frac{Y_{AH}Y_{BH}}{Y_{AH}+Y_{BH}+Y_{CH}};Y_{BCH} = \frac{Y_{BH}Y_{CH}}{Y_{AH}+Y_{BH}+Y_{CH}};Y_{ACH} = \frac{Y_{AH}Y_{CH}}{Y_{AH}+Y_{BH}+Y_{CH}}.\ (6.32)$$

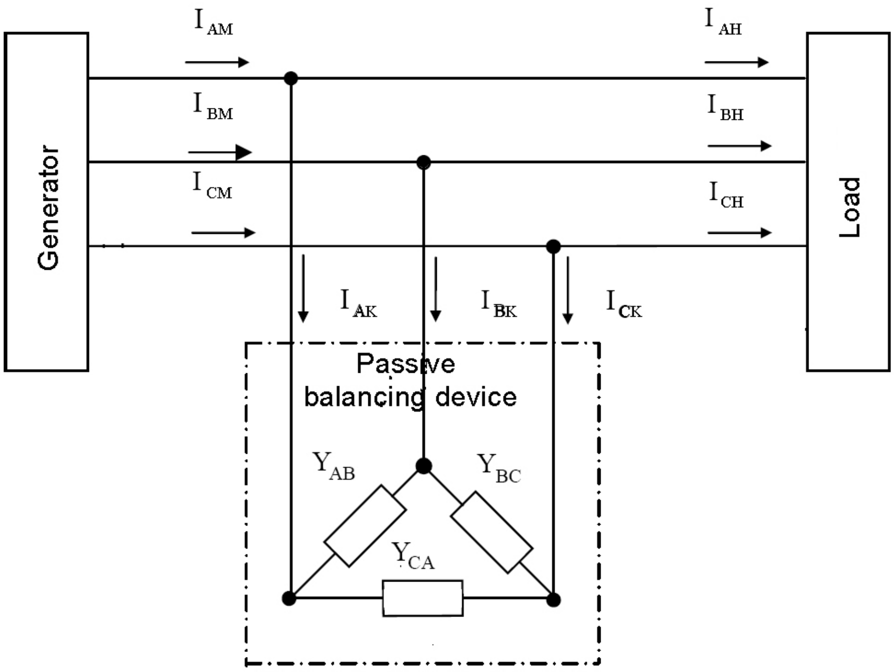


Fig. 6.3. Scheme of the joint venture to compensate for reverse sequence currents

After converting the equivalent load resistance into a triangle, the resistance of the joint venture is calculated:

$$\begin{cases} \operatorname{Im}\left(\dot{Y}_{AB}\right) = -\operatorname{Im}\left(\dot{Y}_{AB\,H}\right) - \dfrac{\operatorname{Re}\left(\dot{Y}_{AC\,H} - \dot{Y}_{BC\,H}\right)}{\sqrt{3}}; \\ \operatorname{Im}\left(\dot{Y}_{BC}\right) = -\operatorname{Im}\left(\dot{Y}_{BC\,H}\right) - \dfrac{\operatorname{Re}\left(\dot{Y}_{AB\,H} - \dot{Y}_{AC\,H}\right)}{\sqrt{3}}; \\ \operatorname{Im}\left(\dot{Y}_{AC}\right) = -\operatorname{Im}\left(\dot{Y}_{AC\,H}\right) - \dfrac{\operatorname{Re}\left(\dot{Y}_{BC\,H} - \dot{Y}_{AB\,H}\right)}{\sqrt{3}}. \end{cases} \qquad (6.33)$$

The power factor is calculated:

$$\chi = \frac{U_{AB}\operatorname{Re}\left(\dot{Y}_{AB\,H}\right) + U_{BC}\operatorname{Re}\left(\dot{Y}_{BC\,H}\right) + U_{BC}\operatorname{Re}\left(\dot{Y}_{BC\,H}\right)}{\left|U_{AB}\left(\dot{Y}_{AB\,H} + \dot{Y}_{AB}\right) + U_{BC}\left(\dot{Y}_{BC\,H} + \dot{Y}_{BC}\right) + U_{BC}\left(\dot{Y}_{AC\,H} + \dot{Y}_{AC}\right)\right|}. \qquad (6.34)$$

To ensure the required power factor $\chi_з$ to each arm of the balancing device is added a complex conductivity Y_0, which in a symmetrical system of voltages with a linear value of U is calculated:

$$\operatorname{Im}\left(\dot{Y}_{0}\right) = \frac{\sqrt{\left(\dfrac{1}{\chi_з^2} - 1\right)\operatorname{Re}\left(\dot{Y}_{AB\,H} + \dot{Y}_{BC\,H} + \dot{Y}_{AC\,H}\right)^2 - \operatorname{Im}\left(\dot{Y}_{AB\,H} + \dot{Y}_{BC\,H} + \dot{Y}_{AC\,H} + \dot{Y}_{AB} + \dot{Y}_{BC} + \dot{Y}_{AC}\right)^2}}{3}. \qquad (6.35)$$

Example 2. Eliminate the reverse sequence currents for the circuit of example 1 and provide a power factor $\chi = 0.8$.

1. Conversion of circuit parameters into a triangle by formula (32):

$$\dot{Y}_{ABH} = \frac{\left(\dot{Y}_{AH} + jY_A\right)\left(\dot{Y}_{BH} + jY_B\right)}{\dot{Y}_{AH} + jY_A + \dot{Y}_{BH} + jY_B + \dot{Y}_{CH}} = 0.04216 + 0.05952j;$$

$$\dot{Y}_{BCH} = \frac{\left(\dot{Y}_{BH} + jY_B\right)\dot{Y}_{CH}}{\dot{Y}_{AH} + jY_A + \dot{Y}_{BH} + jY_B + \dot{Y}_{CH}} = 0.01296 + 0.03920j;$$

$$\dot{Y}_{ACH} = \frac{\left(\dot{Y}_{AH} + jY_A\right)\dot{Y}_{CH}}{\dot{Y}_{AH} + jY_A + \dot{Y}_{BH} + jY_B + \dot{Y}_{CH}} = 0.02876 + 0.02778j.$$

2. Calculation of the parameters of the balancing device according to (33):

$$\dot{Y}_{AB} = -\ 0.06865j; \dot{Y}_{BC} = -\ 0.04694j; \dot{Y}_{AC} = -0.01091j.$$

3. Calculation of the parameters of additional conductivity to ensure the required power factor χ for (35):

$$\mathrm{Im}\left(\dot{Y}_0\right) = 0.02097.$$

From the analysis of materials of lectures 4 - 7 it is clear that to eliminate the negative impact on the AC network of nonlinear consumers and reactive power compensation it is necessary to install additional equipment - reactive power compensators, active filters, balancing devices. The advantage of DC power transmission is the reduction of additional equipment required for the operation of the network, so in certain circumstances, the use of DC transmission is justified.

Questions

1. Name the methods of balancing three-phase networks.
2. Describe the main theoretical provisions of the method of symmetric components.
3. Give the value of the phase shift between the vectors of the three-phase system of zero sequence.
4. Name the sequence of vectors of a three-phase reverse sequence system.
5. Indicate which components of power transmit forward, reverse and zero sequences.
6. Name the component that must first be compensated in three-phase networks with zero conductor.
7. Name the component that must first be compensated in three-phase networks without a neutral conductor.
8. Name the type of connection of loads of the balancing device in three-phase networks without a neutral conductor.

Lecture № 7. DC power supply systems. Experience and technical features of use

Prerequisites for the use of DC power supply systems

As you know, today for the generation of electricity, its transportation, distribution using alternating current, due to the simplicity of the transformation of alternating current voltage by transformers. However, from an energy point of view, it is more appropriate to use DC energy for generation and transportation. In the case of alternating current transmission, the parameters of the transmission line (specific inductance and line capacity, line length) determine the maximum energy transmitted by it. Thus, with increasing length of the overhead line, its inductive resistance ωL increases, which determines the maximum possible power of the line Smax (excluding line capacity):

$$S_{\mathbf{max}} = \frac{U_m^2}{\omega L}, \tag{7.1}$$

therefore, as the length of the line increases, its maximum power decreases. The capacity of the overhead line has almost no effect on the process of energy transfer by the line, but creates the so-called charging power of the line, which increases the effective value of the line current, causes heating of the wires and reduces efficiency. In addition, the charging current leads to an undesirable increase in voltage at intermediate points of the line and other negative phenomena. To eliminate these phenomena along the line it is necessary to install compensating devices, which increases the cost of the line.

If the transmission line operates on direct current, the reactive parameters of the line do not affect the energy transfer process and do not cause additional losses. In cable power transmission lines, DC has the same advantages. It should be noted that AC cable lines have a short length, which usually does not exceed 20 km, which is due to the large capacity of cable lines. DC cable lines can increase their length to hundreds of kilometers.

It is also advisable to use DC power supply systems as an interconnection of two or more AC power systems with different parameters. For example, 50 and 60 Hz AC power systems. Then the systems can work independently, but if necessary, exchange energy. An additional advantage of this approach is that emergencies in one system will not extend to another.

Today, DC power supply systems are divided into two groups. The first includes direct current transmission (DCT), which transmits electricity over a certain distance. An integral part of these systems is the overhead or cable line. The second group includes inserts of direct current (IDC), in which there is no power line. The IDC is located directly at the substation to which the AC power lines of the connected systems are connected.

Comparison of characteristics with alternating current systems

The cost of transporting electricity

The cost of transporting electricity consists of capital costs for transmission line pylons, wires, insulators, substation equipment, as well as operating costs. If the same insulation requirements are accepted, which depend on the current value of the overhead line voltage (OHL) DC and AC, the capacity of the DC overhead line is the same as that of the AC overhead line, provided that the cross section of the wires of both lines is the same. However, the support of the DC overhead line has a lower cost, less wires, the cost of insulation and it requires a sanitary zone of smaller width.

The simplest DC overhead line has only two wires designed for the same current value as the three AC overhead wires. Power losses are also two-thirds of the losses in an equivalent AC overhead line. The absence of AC displacement on the surface of the conductor (skin effect) during the power transmission of the DC overhead line significantly reduces power losses, and during the power transmission of the DC cable line significantly less dielectric losses. The DC overhead line also has significantly lower corona discharge losses than the AC overhead line. Other factors that affect the cost of the line are the cost of compensating devices and substation equipment. Therefore, the cost of a direct current line is 15-20% less than an alternating current line of the same power and length. However, the cost of substation equipment of direct current lines is more than alternating current lines, due to the use of semiconductor power converters and filters.

Comparison of the cost of AC and DC power transmission depending on the length of the line is shown in Fig. 7.1. From the graph of Fig. 7.1 shows that DC power transmission is cheaper than DC power transmission, starting with a certain line length, which is in the range of 400-700 km for overhead lines depending on the specific cost of power transmission per unit line length. For cable lines, this length is in the range of 25-50 km.

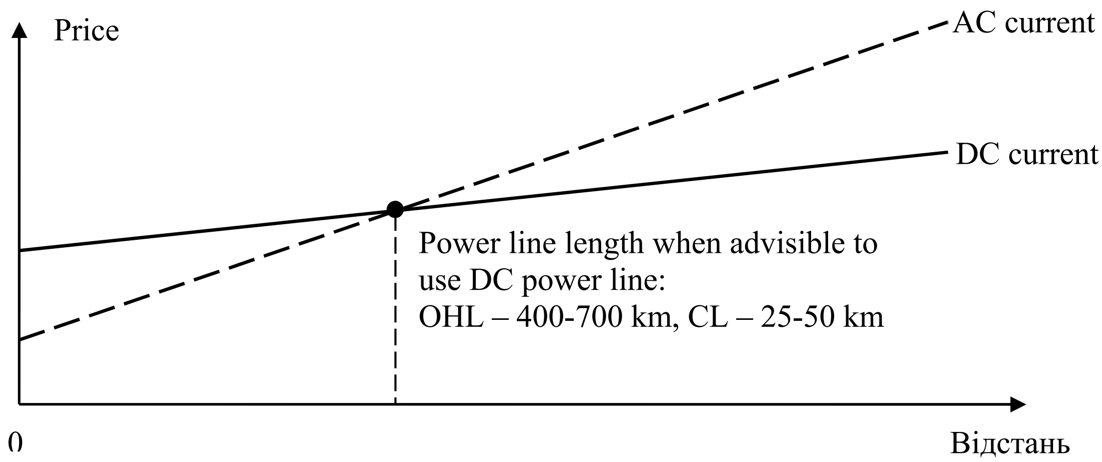


Fig. 7.1. Graph the cost of DC and AC lines depending on their length

Technical characteristics of direct and alternating current power transmission

Thanks to high-speed control, OHL allows complete control of the energy transport process, improve transients and dynamic stability in connected power systems, and limit short-circuit currents in the OHL.

Limit of static stability

The power transported by the AC line depends on the angle of bias between the voltage vectors on the busbars of the transmitting and receiving ends of the line. For a given value of transmitted power, this angle increases with increasing line length. The upper limit of transported energy is determined by static and dynamic stability. The capacity of the AC line is inversely proportional to the transmission length, and the capacity of the DC line does not depend on the length of the line.

Voltage regulation

Voltage regulation of alternating current lines is complicated due to the influence of the charging power of the line and the voltage drop along the line. The voltage on the AC line varies relatively little along the line only if the active power is transmitted. The voltage on the line varies depending on its load.

To maintain a constant voltage at the ends of the line, it is necessary to adjust the reactive power of the line when changing its load. The value of reactive power required for control increases with the length of the line. Although OHL converter substations consume reactive power when the line changes the transmitted power, the line itself does not consume reactive power.

The charging power of AC cables causes serious problems and reduces the length of the AC cable line to 50 km.

Line compensation

Compensation of parameters of the alternating current transmission line is used to solve the problems of the charging power of the line and increase the stability. Increasing the capacity and maintaining the line voltage is possible provided the use of shunt reactors, longitudinal compensation, static compensators STATKOM. No compensation is required for DC lines.

Problems of interconnection of alternating current transmissions

The AC overhead line connecting the two power systems requires the coordination of the excitation regulators of the generators of both power systems according to the transmitted power line and network frequency. But even with the coordination of power regulators, the parallel operation of interconnection AC transmission can be complicated by:

OHL an AC transmission line connecting two power systems requires the coordination of the excitation regulators of the generators of both power systems according to the transmitted power line and mains frequency. But even with the coordination of power regulators, the parallel operation of interconnection AC transmission can be complicated by:

1. Large power fluctuations that can lead to frequent line outages.
2. Increasing the short-circuit power in the integrated power system.
3. Transmission of emergency disturbances from one power system to another.

Good handling and short DCT adjustment time eliminate the above problems. Moreover, asynchronous communication between power systems is possible only with the use of DCT.

Disadvantages of DCT

1. High cost of conversion equipment.
2. Impossibility to use transformers for voltage regulation.
3. Generation of higher current harmonics.
4. The need to compensate for the reactive power consumed.
5. The complexity of the regulatory system.

In recent years, DCT technology has improved, which has overcome many of these shortcomings, with the exception of paragraph 2.

New achievements in the field of DCT

1. Improving the technology of manufacturing semiconductor valves and switches.
2. Increasing the number of phases of the converters to 12 and above.
3. Application of artificial switching of valve elements.
4. Application of digital control systems of converters.

Some of these advances have increased the reliability and reduced cost of DCT converters.

Use of direct current objects in modern electric power industry

The first DCT was built in 1954 between Sweden and the island of Gotland. By 2000, the world had 52 DCT and IDC with a total capacity of 25,000 MW. To date, 24 DCT and IDC with a total capacity of 12,500 MW have been built in Europe. In European countries, cable DCT are most often used to electrify island areas of land. The IDC is used to connect the power systems of neighboring countries. The largest of them are:

- DCT between England and France through the English Channel, which connects the energy systems of the countries. The capacity of this DCT is 2000 MW;
- Communication between Denmark and Norway via the Skagerrak, where three cable DCT lines with a total capacity of 1040 MW have been laid;
- cable double-chain DCT between Denmark and Sweden (670 MW);
- DCT between Finland and Sweden via the Gulf of Bothnia (500 MW);
- IDC in Vyborg between Russia and Finland (1400 MW);
- air-cable DCT Italy-Corsica-Sardinia (500 MW).

Over time, DC connections between Europe's public power systems will intensify.

There are a number of powerful DCT and IDC in North America. One of them is a two-chain DCT Nelson River - Winnipeg (Canada) with a capacity of 3600 MW and a length of 930 km. On the west coast of Canada, a 680 MW cable DCT has been built on the island of Vancouver, and there are two IDC in the eastern part of the country, which act as an asynchronous connection to the power systems of the northern part of the United States. One of them is the Il River River IDC (320 MW), the other is the Chategai IDC (1000 MW). In addition, in the early 1990s, a 1,500-kilometer multi-substation from the La Grand River DCT to Winnipeg with a capacity of 2,200 MW began operating.

More than ten DCT and IDC have been built in the United States. The largest of these are the Pacific DCT (3,100 MW, 1,362 km), Intermountain (1,600 MW, 788 km), and Butte Square (500 MW, 730 km).

The positive experience of the United States in creating interconnected asynchronous connections based on the IDC is used in other countries that have a large area. Of particular interest is India's energy system development plan, which provides for the division of the country's energy system into several parts that operate asynchronously and are interconnected by the DCT and IDC. A similar approach is planned in China.

There are several powerful DCT in Africa and Asia. In Africa, two DCT have been built: one from the Kabora Basa HPP (Mozambique) in South Africa (1920 MW, 1,400 km), and the other from Inga Shaba (Zaire, 1,120 MW, 1,700 km).

As already mentioned, DCT and IDC can be used to communicate systems with different nominal frequencies. There is no alternative to DC in this area. Such DCT and IDC operate in Japan and South America, where power systems with different AC frequencies operate.

In Japan, the boundary between systems operating at different frequencies runs along the island of Honshu. In the northern part of the island, the power system operates at a frequency of 50 Hz, in the south - at a frequency of 60 Hz. The systems are connected by three IDC with a total capacity of 1,200 MW. In addition, in the southern part of the island between the two systems operating on the same frequency is the IDC, which is used to regulate interconnection energy flows. In Japan, cable DCT operate. One is an asynchronous connection between the power systems of Hokkaido and Honshu, the other is used to connect to the power system of a power plant located on the island.

Brazil has built the most powerful Itaipu DCT, designed to transport energy from the Itaipu HES on the Parana River to Sao Paulo. This DCT consists of two lines with a capacity of 3150 MW and a length of 800 km. In addition, the Brazilian (60 Hz) power system is connected to the Paraguayan and Argentine (50 Hz) power systems by three IDC with a total capacity of 1,100 MW.

Several DCT and IDC have also been built in New Zealand and Australia. In New Zealand, the DCT integrates Washington's power systems, maintains a constant frequency, and dampens mains voltage fluctuations.

Ukraine has a DCT in the Luhansk region and several IDC that connect the power system of Ukraine with other countries for the possibility of unimpeded export of electricity abroad.

Based on the above, it can be concluded that DC facilities are widely used in world energy.

Principles of construction of direct current power transmission

The limited use of DC power transmission is primarily due to the technical difficulties of creating efficient low-cost high-voltage devices to convert AC to DC (at the beginning of the line) and DC to AC (at the end of the line). Their application is determined by the reliability of their work and specific technical characteristics. The first converters of direct current power lines, starting from 1954, used rectifiers on mercury valves. The first line with high-voltage thyristor valves was built in Canada in 1972. Since 2000, converters based on fully controlled IGCT thyristors and IGBT transistors have been actively introduced. With the improvement of the technology of production of controlled valves and methods of control of converters, the nominal voltage of direct current power lines increased, energy losses decreased and electricity quality parameters improved.

Block diagrams of DCT and IDC are shown in fig. 2.

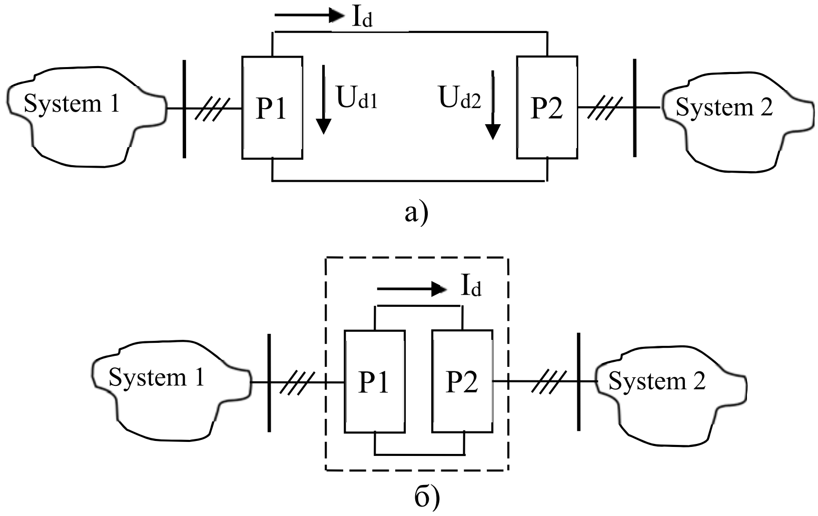


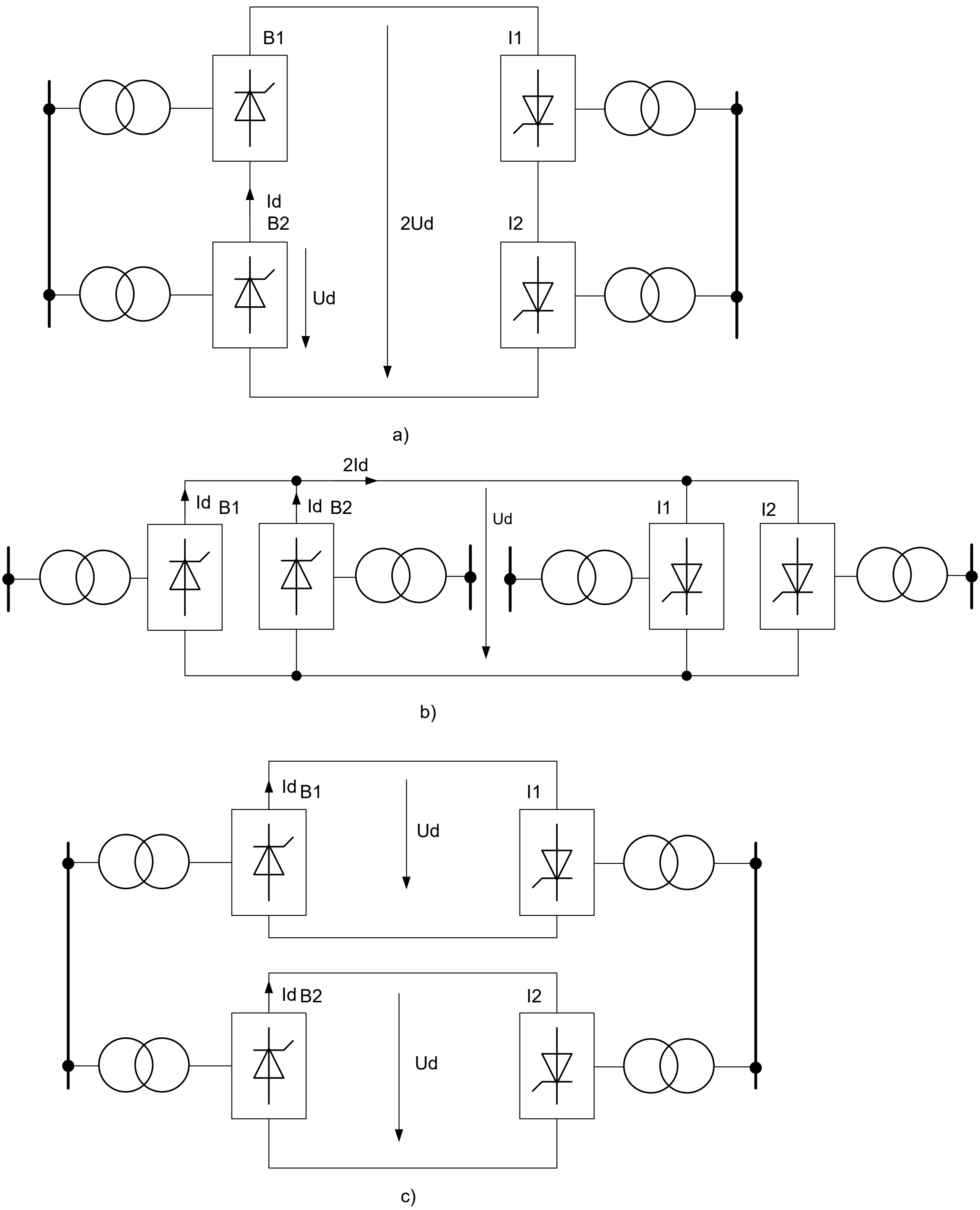
Fig. 7.2. Block diagrams of DCT (a) and IDC (b)

In DCT, a direct form of current is used to transport electricity from system 1 to system 2 and / or vice versa. If energy is transferred only from system 1 to system 2, the converter P1 converts AC energy into DC energy (rectifier), the converter P2 converts DC energy into AC energy (inverter). If energy can be transmitted in the opposite direction, converters P1 and P2 are reversible and perform both functions. The IDC performs the function of converting energy parameters without transporting energy, which allows systems 1 and 2 to operate independently of each other, but at the same time to exchange energy with each other.

Methods of connecting converters to power lines

The amount of energy in DC power lines is usually calculated in hundreds of megawatts - units of gigawatts, voltage - in tens, hundreds of kilovolts. However, the values of operating currents and voltages of thyristors do not exceed 10 kA and 10 kV, IGBT transistors - 500 A, 5 kV. Therefore, multi-section converters are often used to convert energy with such parameters. As a rule, for DCT converter modules are switched on in series to increase the line voltage and, consequently, to reduce transport losses, as shown in Fig. 7.3 a). The circuit of series-connected thyristors must be equipped with devices for uniform voltage distribution between them, cooling, supply channels of control pulses to each thyristor. Of great complexity is the process of transmitting control pulses, which must be applied with high accuracy over time to the potential of the valve relative to the potential of the earth. Fiber optics are now used for this purpose. If necessary, the converter unit is taken out of operation, and the modules, where there are damaged thyristors, are replaced with serviceable ones.

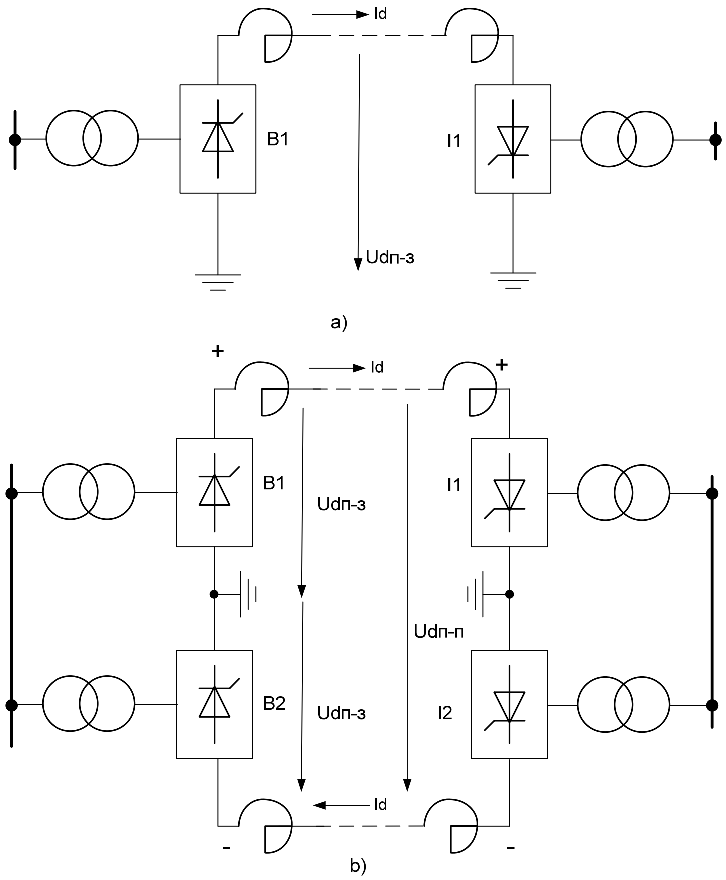
For the IDC there is no need to increase the voltage, so here the converters are often turned on in parallel, Fig. 7.3 b). At the same time, serial converters are also used to improve the current shape of the AC lines. Another option to increase power is to build a parallel line, Fig. 7.3 c).



a) increase in line voltage; b) increase the pole current; c) creation of a double-chain line

Fig. 7.3. Schemes of increasing the power of DCT

Since the AC and DC circuits of the DCT are not electrically connected, if the DC line is not grounded, its potential may change, which is unacceptable. Therefore, the DCT must be grounded at least one point. In practice, as a rule, carry out grounding at two points. This can be one of the poles (analog of the phase for alternating current transmissions) of the transmission or the midpoints of the converter substations. In the first case, when one of the transmission poles is grounded on both sides, the wire of this pole is usually absent and its role is performed by the ground. For direct current, the earth resistance is zero. Therefore, the resistance of a grounded pole depends on the spreading resistance of the grounding conductors that connect the pole to ground. This resistance is small (0.05-0.15 ohms) and does not affect the mode of operation of the DCT. Therefore, only one pole suspended on insulators is required for power transmission, if the line is overhead or single-core cable. Such transmissions are called unipolar. The scheme of unipolar DCT is shown in fig. 7.4.



a) unipolar DCT; b) bipolar DCT
Fig. 7.4. Schemes of DCT transmissions

Usually power lines of this type are built to cross large bodies of water, such as sea channels. To transfer energy from the rectifier to the inverter, you need to lay a single-core cable designed for pole-ground voltage. A number of power lines are connected according to this scheme: Italy - Sardinia in the Mediterranean Sea, Sweden - Denmark through the Skagerrak in the Baltic Sea, Sweden - Finland through the Gulf of Bothnia and a number of others. The Sweden-Finland power transmission, which is the most powerful of the unipolar transmissions, has a 200 km long cable with only one coupling.

The use of land to return electricity has its downsides. The most significant disadvantage here is the possibility of corrosion destruction of metal engineering structures laid in the ground near the ground - pipelines, cables. Part of the transmission current will be propagated by these structures and flowing from them, can cause damage due to electrolysis, which leads to the formation of holes in the pipes or cable sheaths.

Based on calculations and experimental studies, it is established that at a grounded pole current of 1 kA, the radius of the danger zone around the grounding conductor is about 5 km. Cathodic protection must be applied to underground structures located in this area. In some cases, when the line is laid in an area where there are many underground engineering structures, in order to avoid the spread of current through the ground, the grounded pole is made in the form of a cable whose core is grounded. The scope of unipolar DCT is the transmission of relatively small capacities (several hundred megawatts) over relatively short distances, mainly for crossing water obstacles.

For powerful power transmission, another scheme is used, where the line is made with two poles, each of which is isolated from the ground. Ground the middle points of the conversion substations located at the ends of the transmission. This transmission is called bipolar. The scheme of one circuit of such transmission - bipole is shown in Fig.4 b. If necessary, increase the transmission power build a second similar circuit. This is how the Itaipu DCT is designed, where the capacity of each DCT bipole is 3150 MW.

Because the middle points of the conversion substations are grounded, each bipole can be divided into two independent half-circuits. In normal modes, the current from the rectifier to the inverter is transmitted by the positive pole of the line and returned by the negative. Under the same load of both semicircles, the earth current is zero. However, in practice it is impossible to ensure the complete identity of the equipment parameters and the mode parameters of each of the semi-circuits. Therefore, there may be some imbalance and the ground current will not be zero. However, it is much smaller than the pole current. If one half-circuit fails, the other will continue to operate, but with the return of current through the ground. Then the transmission power is halved, but the transmission, although with reduced power, continues to work.

For high-power power transmission, where the pole current is several thousand amperes, the area of dangerous influence of ground current is significantly increased. Therefore, grounding points with the help of special lines are carried out at a distance of several tens of kilometers from the conversion substations where there are no underground engineering structures.

For bipolar transmissions, there are two types of line voltage: pole-ground voltage $U_{dp\text{-}g}$ and pole-pole voltage $U_{dp\text{-}p}$. It is obvious that the pole-pole voltage is 2 times higher than the pole-ground voltage. Therefore, a transmission with a voltage of, for example, ± 500 kV and a transmission of 1000 kV are the same transmission.

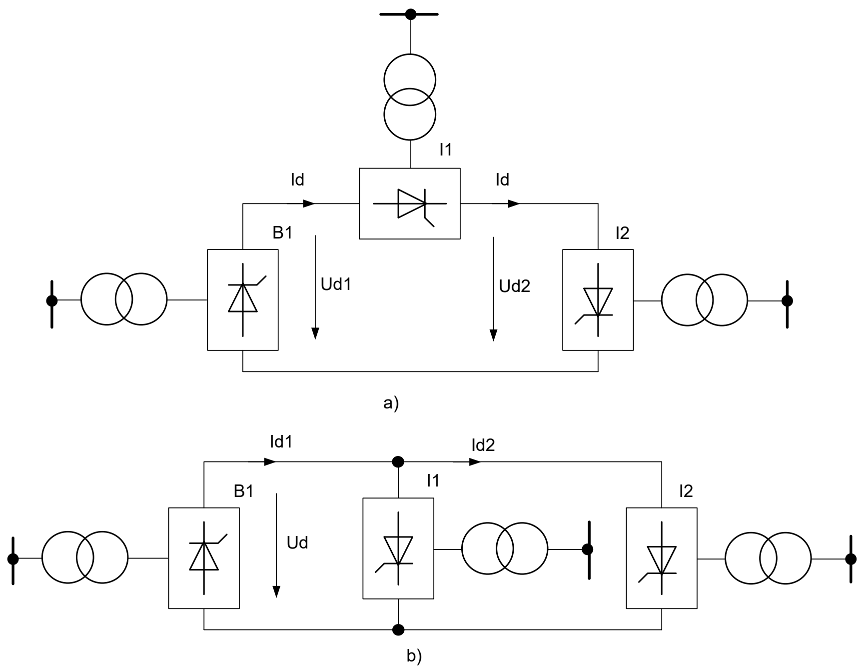
The scope of bipolar power transmission is the transmission of large powers over long distances. According to the bipolar scheme, all powerful and long-distance DC power lines have been built so far: Itaipu (Brazil), Pacific (USA), Cabora Bassa - Apollo (Mozambique-South Africa) and many others. It should be noted that before bipolar transmission is used in other cases, such as DCT England-France, laid across the English Channel, made as bipolar. One of the reasons that led to this decision was the desire to avoid the influence of the magnetic field of the unipolar line on the navigation devices of vessels passing through the strait.

DC lines, both unipolar and bipolar, do not have line switches. Controlled valves of the converter successfully perform their role. In the event of an emergency in the

DC line, it is sufficient to remove the control pulses from the rectifier valves to stop the power transmission. The valves can be closed both manually by the substation personnel on duty and by automatic protection devices that respond to damage.

The absence of line switches simplifies the design of the converter substation. However, such a decision can be made only for main power transmission, ie transmission that does not have intermediate substations. For transmissions with intermediate substations (DC networks) it is necessary to use DC switches designed to localize accidents that may occur in certain parts of the network.

Creating a high-voltage DC switch is a rather difficult technical task. For intermediate selection of power from the DCT, it is necessary to build a conversion substation at the sampling point. Under such conditions, it is necessary to be able to supply voltage from the local power system to ensure the operation of the inverter. This intermediate conversion substation can be connected to the line in series or in parallel, as shown in Fig. 7.5.



a) sequential power take-off scheme; b) the scheme of parallel power selection
Fig. 5. Power take-off schemes from DCT

Subject to sequential switching on, part of the conversion bridges is scattered along the line. Each of the intermediate substations can operate in both rectifier and inverter mode. Under the condition of operation in the rectifier mode, the energy of the intermediate system enters the DC line, in the inverter mode - is selected from the line and enters this intermediate system.

The disadvantage of the sequential power selection scheme is the dependence of all substations on each other. This is manifested in the difficulty of regulating the power of individual substations, as the current of the series circuit must remain constant for all its sections. Decommissioning of any of the substations as a result of an accident can lead to power outages and de-energization of all other substations. Therefore, intermediate substations must be equipped with bypass devices and bypass valves, which automatically switch on in the event of an accident at the substation.

Parallel switching on of intermediate substations, firstly, allows to carry out independent regulation of capacity at all substations and to change its direction of transportation, i.e. to pass on any of substations from the rectification mode to inversion mode and vice versa, secondly, parallel switching allows to pass to creation. high-voltage direct current network designed to communicate several intermediate power systems.

The disadvantage of the DCT circuit with parallel power selection is the need to use DC switches to disconnect damaged areas. Switches can be replaced by remote-controlled disconnects. But then you must first de-energize the entire transmission, then in a silent pause to turn off the damaged part of the transmission and turn on the disconnected again. De-energizing the transmission can be done by removing the control pulses from the converters operating on the rectifier. All this is done by means of protection and automation of power transmission. This is the method used in the five-substation Canada-US DCT. The same method is used for power transmission Italy - Corsica - Sardinia with power take-off on the island of Corsica.

If any converter substations in the circuit of their parallel connection must work in both rectifier and inverter mode, such substations must have a device for switching the polarity of the converter poles to change the direction of current in the converter while maintaining the polarity of the line voltage.

For the Air Force, as already mentioned, there is no need to increase the voltage and power of the conversion unit. Increasing the power of the insert is achieved by parallel connection of several units in the same way as it is done at power plants under the condition of parallel connection of generators. An example is the Russia-Finland DCT in Vyborg. It consists of four identical complete high-voltage converters with a capacity of 355 MW, each of which is connected on one side to 330 kV buses, where lines from the Lenenergo system, on the other - to 400 kV buses connected to the Finnish power system. Each converter is housed in a separate building, which also houses all the systems that serve the converters.

Questions

1. Describe the main advantages of using DC transmissions.
2. Give the main purpose of DC inserts.
3. Indicate the shortcomings of DC transmissions.
4. Describe the conditions under which it is advisable to use DC transmission from an economic point of view.
5. Describe the design differences between unipolar and bipolar DC power transmission.
6. Give the reason for the use of shunt devices in DC transmissions.
7. Explain the feasibility of using bipolar power lines.
8. List the methods of increasing the power of transmissions and inserts of direct current.

Lecture № 8. Equipment of direct current power supply systems

Main term and definitions

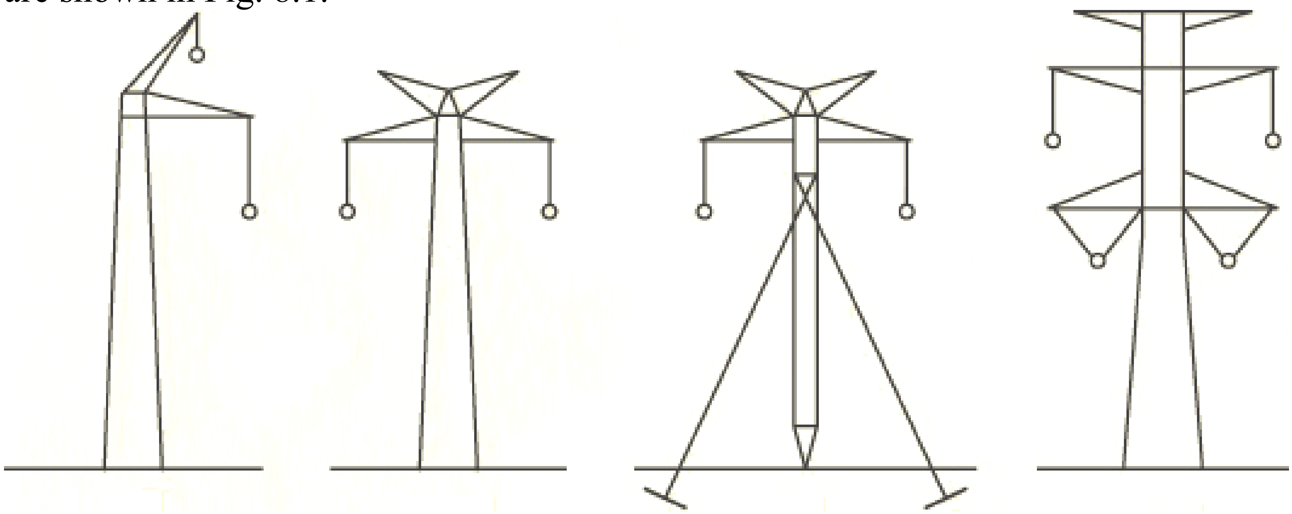
Neutral is the common point of the windings of generators or transformers that supply the network.

Deaf-grounded neutral is the neutral of the generator or transformer in three-phase current networks with voltage up to 1 kV, connected to the grounding device directly or through low resistance.

Insulated neutral is the neutral of the generator or transformer in three-phase current networks with voltage up to 1 kV, which is not connected to the grounding device.

Construction of overhead power lines

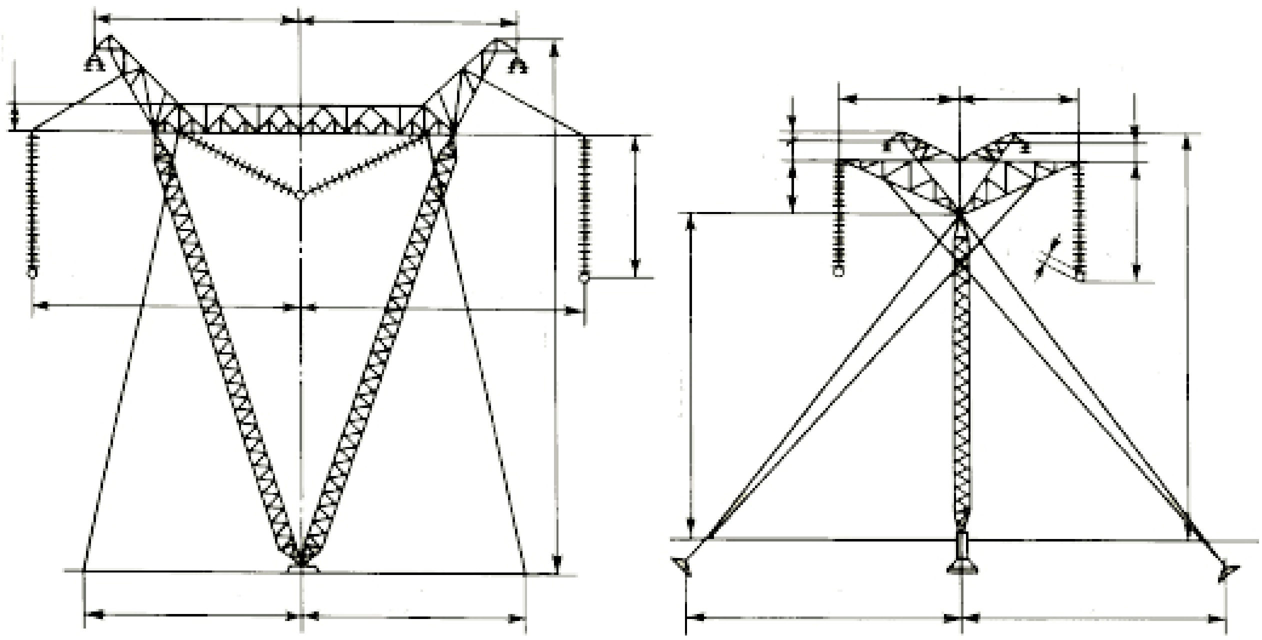
The direct current overhead line (OL) differs from the alternating current line by the design of the supports. Possible designs of supports for different types of OL lines are shown in Fig. 8.1.



a) unipolar OL; b) bipolar OL; c) bipolar OL with backstays; d) two-wire bipolar OL

Fig. 8.1. Designs of supports of power lines of a direct current

These supports require lower metal consumption and are simpler in design than AC line supports of the same voltage and capacity class. In fig. 8.2 shows the structures of the intermediate supports of the 1150 kV AC line and the ± 750 kV DC line, drawn on the same scale.



а) AC OL support 1150 kV, 5000 MW; б) DC OL support 750 kV, 6000 MW

Fig. 8.2. Schemes of intermediate supports of DC and AC power lines, made in one scale

OL, shown in Fig. 8.2, have approximately the same capacity (5000 and 6000 MW, respectively). The mass of the AC support is 19.8 tons, the DC support is 9.4 tons. Approximately the same ratios are valid for other AC and DC overhead lines. In addition, for the DC line, the width of the sanitary zone is 25-30% less than for the AC line. Therefore, the cost of a DC line is always less than an AC line of the same power.

The operating conditions of linear insulation on direct current are significantly different from the conditions of its operation on alternating current. In alternating current lines, the voltage distribution along the insulator garland is determined mainly by the own capacitances of each insulator, the capacitances between the insulator and the conductor, and the insulator and ground. Therefore, surface contamination of insulators has relatively little effect on the voltage distribution along them. In DC lines, the capacitors of the insulators do not participate in the voltage distribution along the garland. This distribution depends on the resistance of insulators, the value of which depends on the degree of contamination of their surfaces. Under conditions of clean dry insulators, the voltage distribution along them is uniform, but under the condition of contamination or humidification of individual insulators, this uniformity is violated, which can lead to failure of insulators. The solution to this problem is to use insulators of a special shape or increase their number in garlands.

The design of the pole of the DC line is identical to the design of the phase of the AC line. Split conductors are also used here for two reasons. The first is the large currents of the pole, which causes a large total cross section of the pole conductors (several thousand square millimeters). Conductors with such a cross-section do not produce plants, because their delivery to the route and subsequent installation is extremely difficult. Therefore, use a bundle of conductors with a smaller cross-sectional area. The second reason is the need to eliminate the corona effect, which requires reducing the electric field strength on the surface of the conductor. For this purpose, the conductors included in the beam are placed at a certain distance from each other on the vertices of a regular polygon. As a result, the possibility of a common corona is eliminated and power losses to the local corona are reduced, which are significantly less for DC lines than for AC lines.

Different types of cables can be used for DC cable lines: cables with paper and oil insulation, cables with oil under pressure, cables with gas under pressure. Experience has shown that it is best to use cables with paper insulation and viscous impregnation for this purpose. The electrical strength of such a cable is much higher than an AC cable with the same insulation thickness. Therefore, these cables are most widely used in the construction of DC cable lines. Currently, a cable for a voltage of 400 kV and a current of 1.25 kA has been created. Its outer diameter is 128 mm. Because cable lines run through water obstacles, one of the important tasks in reducing the cost and reliability of the line is to reduce the number of couplings that are a source of increased danger. For this purpose, use special vessels conductors. The maximum length of the cable line constructed by such a vessel is 200 km with one coupling in the middle. The first cable lines were laid directly on the seabed, but they were often damaged by fishing trawls or ship anchors. Modern technologies allow laying the cable underwater in a trench up to 1.5 m deep.

Features of substation equipment operation

The main equipment of converter substations includes semiconductor converters, transformers and phase compensation devices (PCS). FCPs include high-harmonic current filters, linear (smoothing) reactors, capacitor banks, synchronous compensators or static reactive power sources. The expediency of placing higher harmonic filters at one or another point of the circuit is largely determined by the parameters of the AC network and its frequency characteristics. When it comes to synchronous compensators and capacitor banks, they are structurally identical to similar devices of alternating current networks.

PPP semiconductor converters are designed using network-driven semiconductor rectifiers and inverters that operate in the current source mode. If such converters are connected to the AC mains, a current with a shape close to rectangular flows in it, fig. 8.3.

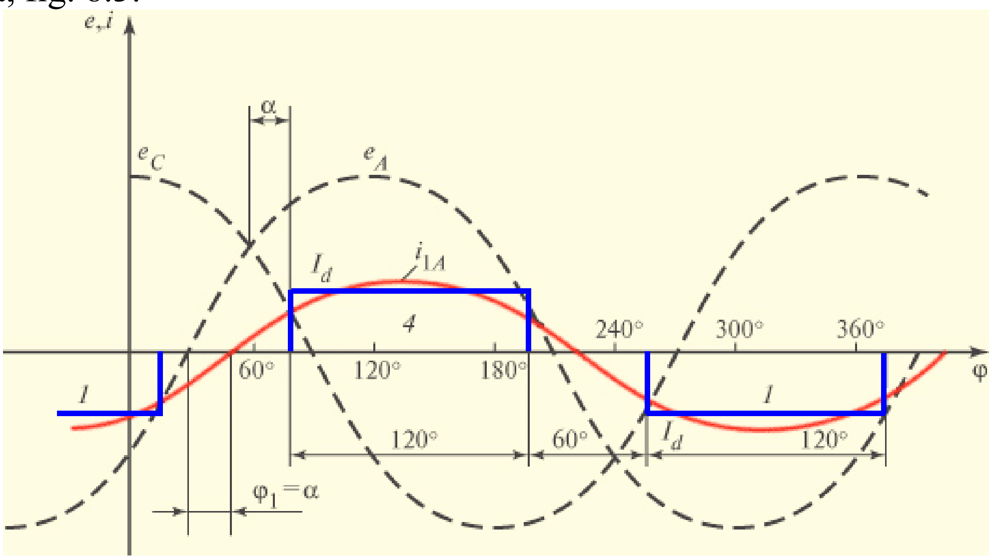


Fig. 8.3. The form of current of AC power network

Energy from the AC network to the DC network is transmitted by the first harmonic. Higher harmonic currents create distortion power, which leads to heating of the equipment and other undesirable consequences. The offset of the first harmonic of the current relative to the phase voltage of the AC network depends on the control angle of the thyristors of the converter and determines the amount of reactive power consumed from the network. The phase shift angle between current and voltage φ is approximately estimated by the formula:

$$\varphi = \alpha + \gamma / 2, \tag{8.1}$$

where α is the opening angle of the thyristors;
γ is the switching angle.

These angles have the following meanings:

- for the rectifier α = (5-15) °, γ = (20-25) °;
- for the inverter δ = (15-20) °, γ = (20-25) °.

The power consumed by the rectifier is 30-50% of the transmitted power *P*, the power consumed by the inverter - 40-60%. Therefore, the amount of reactive power generated by the DC power network has the order of line power, which increases the load on the elements of the converter. Compensating devices are installed at the DC power network connection point to compensate for reactive power. The use of fully controlled thyristors and high-voltage IGBT transistors to convert the parameters of electrical energy allows to form the required mains current curve and significantly reduce the amount of reactive power consumed. However, this does not completely solve the problem of higher harmonic currents. Active and passive harmonic filters are used for additional compensation of higher harmonic currents. Also, to significantly reduce the amplitude of the higher current harmonics, a cascade connection of converters with different connection of transformer windings is used, for example, one transformer is connected in a star-star scheme, the other is a star-triangle, which provides phase shift between secondary transformer windings by 30º , Fig. 8.4.

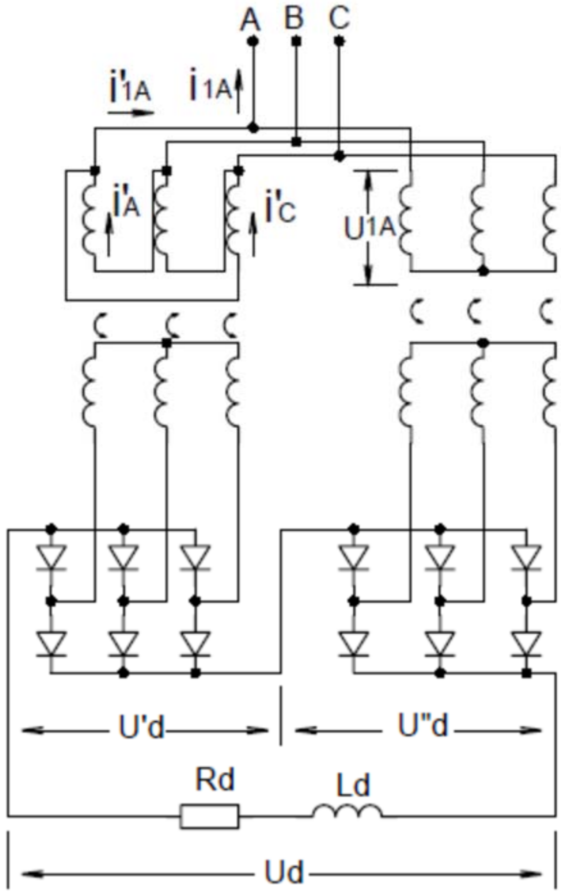


Fig. 8.4. Cascade connection of rectifiers

As a result of such connection of converters currents 5 and 7 harmonics compensate. Time diagrams of currents of separate converters - i_1 and i_2 accordingly, and also current of a network $i_1 + i_2$ are shown in fig. 8.5.

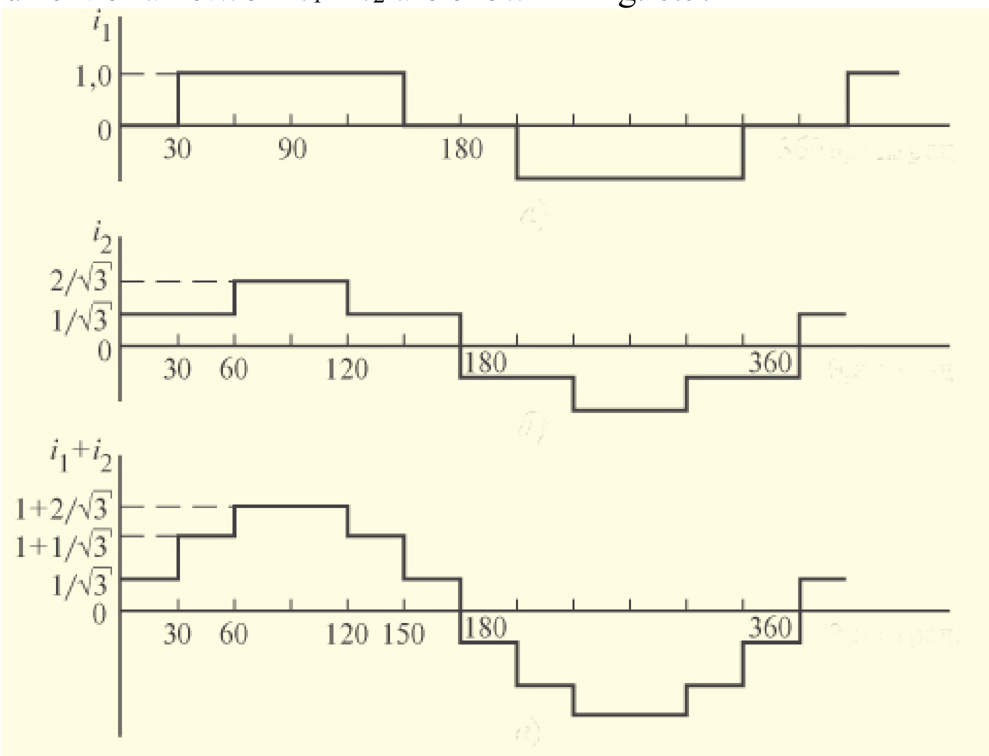


Fig. 8.5. Time diagrams of converter currents

As can be seen from the time diagrams shown in Fig. 8.5, the mains current has a shape close to a sinusoid, which facilitates further filtering of higher harmonics.

As a rule, resonant filters tuned to the eleventh and thirteenth harmonics are installed in the DC power network, other higher harmonics are suppressed by one broadband filter.

DC power network efficiency is determined from energy losses in the elements of converter substations and direct current power lines. The relative energy losses in substation equipment and energy consumption for own needs as a percentage of nominal capacity are given below:

Transformers…………………….………………………...1,3-1,5 %.
Power converters…………………………………………….0,5-0,7 %.
High harmonics filters…………….………………………0,018-0,020 %.
Linear reactors………………………………………………0,17-0,20 %.
Energy consumption for own needs ………..……………………...0,1 %.
Total…………………………………………………………..…2,1-2,5 %.

From the given data it is possible to draw a conclusion that the converting substation from the point of view of losses is rather economic device.

The main power network losses are losses in the ΔP_L line, which are calculated by the formula:

$$\Delta P_L = 2 I_d^2 r_0 l, \qquad (8.2)$$

where I_d is the pole current,
l is power line length, km,
r_0 is specific pole resistance per 1 km of length.

The resistivity of the line is determined from its design. An important factor in determining losses is the length of the line. Given a relatively short line (up to 900 km), the losses in it are 4-5% of the nominal power, for the line 2-2.5 thousand km, the losses increase to 8-10%.

Given the above, we can identify the properties of PPP, which does not have in the AC lines:

- in the power network there is no restriction on the amount of transported energy according to the stability of the power supply system;
- the power network is flexible, controlled elements of the power system, which allows to increase the reliability and stability of the coordinated operation of AC systems;
- converter substations consume a significant amount of reactive power and can generate higher harmonics in the AC network, compensation for this effect requires the use of higher harmonic filters, which increases the cost of converter substations.

Another important unit of conversion equipment is the transformer. The transformer can be double- or multi-winding. Usually use transformers with three or four windings. In the latter case, one winding is connected to the AC mains, two to the cascaded rectifiers, and another winding can be connected to higher harmonic filters or a synchronous compensator.

Converter transformers operate in more severe conditions than conventional AC mains transformers because the currents flowing through the transformer windings contain higher harmonics. If the transformer is idling with connected high-pass filters or capacitor banks, resonant phenomena are possible, which lead to significant overvoltages lasting several seconds. The insulation of transformers must be designed for these overvoltages. All this leads to the need to significantly strengthen the internal insulation of the transformer, increase the mechanical strength of the windings, as well as to increase the cross-sectional area of the conductors of the windings and the core of the transformer. As a result, the consumption of active materials (steel and copper) for converter transformers is approximately 1.5 times higher than for conventional transformers of the same voltage and power class. A distinctive feature of converter transformers is their higher reactance than conventional transformers of the same power. The increase in the resistance of the transformer, on the one hand, due to the peculiarities of its design, on the other - it is necessary to limit the rate of change of current in the valves during their operation in both normal and emergency modes. The total power of the transformer usually exceeds the power of the rectifier bridge by 20-25%, due to the consumption of reactive power and increased losses of active power from currents of higher harmonics. Valve windings of transformers have the strengthened isolation concerning the earth for separation of circuits of direct and alternating currents. Converter transformers are equipped with voltage regulation devices under load, which is necessary to reduce the consumption of reactive power by the bridge. All together leads to an increase in the mass and dimensions of transformers. The maximum power of converting transformers today is 500 MV · A per phase.

Linear reactors are connected to each pole of the line. They are multifunctional elements of power transmission - reactors not only smooth out the ripple of the pole current, but also provide a given rate of change of line current during short circuits in the line and inverter malfunctions. In addition, the reactors are designed to protect the converters from overvoltages that may occur on the AC side. The reactor winding must be insulated from the ground, the electrical strength of the insulation must be designed for the pole voltage. In addition to this constant component on the insulation of the winding in normal modes and the variable component of the rectified voltage. The latter depends on the control angles with which the thyristor converter works, and increases with their increase. These two voltage components create different loads on the reactor insulation. The magnetic system of the reactor is performed without an inner core, but with magnetic shunts and a large number of air gaps to eliminate the saturation of the reactor with direct current. The reactor winding and its magnetic system are placed in a tank filled with transformer oil.

The scheme and equipment of the substation neutral depends on the allowable value of the current that can flow through the ground for a long time. This rule determines the design and cost of the working ground, the area of its location relative to the converter substation, the presence or absence of additional conductor for the passage of asymmetry current. For unipolar PPPs it is always necessary to install a special working ground. Then the neutral circuit of the converter substation can be performed in two ways:

- with an additional phase of the transmission line, which creates a neutral line, and switches to convert ground current to neutral. In this case, the working ground has a simplified design;

- circuit with remote working grounding and two grounding lines.

In both cases, capacitor banks, arresters and DC switches are connected to the substation neutrals.

The operating modes of substation equipment largely depend on the type of installed transducers. The use of transducers on fully controlled valves allows to minimize the amount of generated reactive power and improve the spectral composition of the current consumption.

Questions

1. Specify the design features of the supports of direct current power lines in comparison with the resistances of alternating current.
2. Describe the features of the calculation of the insulation of DC transmission lines in comparison with AC lines.
3. Name the design features of conductors and DC cables.
4. Explain the factors that contribute to the generation of reactive power by the DC transmission line.
5. List the measures that reduce the amount of reactive power generated by the DC transmission line.
6. Specify the sources of energy loss in the transmission of direct current.
7. Describe the properties of DC transmissions that are not present in AC lines.
8. Specify the purpose of the reactors in the DC transmission lines.

Lecture № 9. Intelligent power supply systems. Smart grid concept

Main terms and definitions

Smart Grid is a concept of the electric network, which is able to combine the modes and actions of generators, storage devices, consumers to ensure cost-effective and sustainable operation of the power system with minimal losses, the required quality and reliability of power supply.

Context is information used to describe the state of a control object.

Optimization is the process of finding the most favorable characteristics, relationships. The optimization problem is formulated if given: the optimality criterion, the parameters whose values are regulated to solve the optimization problem, the mathematical model of the process and the constraints that must be taken into account when solving the problem.

The introduction of intelligent power supply networks dates back to the 70s of the twentieth century. Such networks are called "Smart grid" (Self Monitoring Analysis and Reportin Technology). The Smart Grid concept combines electrical networks, consumers and electricity producers into a single automated system that allows you to control and optimize the operation of the grid. The active development of this concept began in the early 90s of the last century, when the problem of integrating renewable energy sources into the existing power supply system, which had a centralized structure. The solution to this problem is the transition from a centralized to a distributed power supply system, which has certain features due to the presence in the network of several different sources of electricity and energy storage systems. Taking into account these features makes it possible to improve the quality of power supply by forming active and adaptive properties of networks, such as the possibility of self-diagnosis and self-recovery. A necessary condition for the implementation of the Smart Grid concept is the modernization of modern power grids, which makes it possible to provide:

- bidirectional exchange of electricity;
- work with different types of electricity sources;
- the possibility of accumulating electricity;
- adaptability of grid properties for efficient operation in changing conditions of electricity generation and consumption;
- network self-recovery;
- openness of the system in information and energy aspects;
- taking into account current data on energy consumption and generation, which ensures high reliability and quality of energy transportation.

The following key components of the Smart Grid concept are identified:

- electricity metering devices;
- technologies of bidirectional energy regulation on alternating FACTS and direct FACDS current, SST semiconductor transformers, VSD electric drives, SS FID semiconductor isolating devices;

- control theories and technologies: nonlinear control, artificial intelligence, neural networks, model predictive control, distributed decision making systems;

- network technologies, broadband wired and wireless networks, power line communications (PLC).

All these technologies form the power electrical, information and communication components of Smart grid, the purpose of which is to increase the efficiency of power grid management as a whole.

With the modernization of power grids, the scope of use of power electronics devices is being expanded. Primarily for generating set levels of active and reactive power (static thyristor compensators and STATCOM) and improving the quality of electricity (active filters and balancing devices).

The specification of the Smart grid concept depends on the technical level of the power system. Therefore, in practice, the definition of Strong Smart Grid (SSG) for networks with voltage higher than 110 kV, Regional Smart Grid (RSG) - for networks with voltage (3-110 kV) and Micro Smart Grid (MSG) - for networks with voltage -3) kV. Data on the functional purpose of networks are given in table. 9.1.

Table 9.1. Functional purpose of Smart grid networks

Subordinate network	Main network		
	SSG	RSG	MSG
SSG	SSG ⇄ SSG* - digital substations; - parameters matching (compensators, DC inserts); -switching; - power generation control	RSG Switch to control mode in case of SSG network failures	MSG Switch to control mode in case of SSG and RSG networks failures
RSG	SSG ⇄ RSG - load with adjustable parameters of consumption and energy generation; - reactive power generation; - damping transients in SSG; - formation of virtual generating capacities; - energy accumulation	RSG ⇄ RSG - determining the most energy-intensive RSG network and giving it the status of the main network; - task solving in SSG ⇄ RSG	MSG Transition to independent work in the event of an emergency in the network RSG

MSG	SSG ⇄ RSG⇄ MSG - consumer with adjustable power; - task solving in SSG ⇄ RSG.	RSG ⇄ MSG - determination of the most suitable networks for formation of the set parameters of quality of the electric power	MSG ⇄ MSG - determining the most energy-intensive MSG network and giving it the status of the main network; - task solving in RSG ⇄ MSG

* arrows indicate the interaction of systems with possible energy exchange.

Practical implementation of the Smart grid concept is possible on the basis of power electronics. The choice of type and structure of semiconductor converters must be made taking into account the nature of changes in the parameters of the electrical energy of the system. A feature of SSG, RSG and MSG electric transmissions is the oscillation in a wide range of electrical parameters. The most stable from this point of view is the SSG system. In power transmissions of the RSG type there are changes of values of parameters of the electric power caused by switching of loadings. MSG low-voltage networks are a connection point for RES and a wide class of loads, so the change in the values of electricity parameters is the largest here.

According to the Smart grid concept, adjacent electrical systems have a hierarchical interaction relative to each other: one of them is the main one, the others are subordinate. In addition, all systems dynamically change their parameters to adjust their configuration to the changing energy flows generated by the dispersed generators and the loads consumed. Therefore, the interaction of the components of the Smart grid network, generators and loads switched on at specified times, is carried out by power electronics devices by implementing the following functions:

1. Configuration of the power grid structure with the provision of certain modes of operation of generating devices. Network configuration is carried out both by contactors with solid-state switches, which accelerate the switching process with simultaneous unloading of mechanical contactors, which allows to provide galvanic isolation and increase their service life. Controlled rectifiers and inverters provide switching with simultaneous provision of the necessary mode of operation, realization of the necessary form of voltage or current. For example, in system interface nodes, semiconductor converters, which are regulators of active and / or reactive power parameters, provide synchronization and coordination of their operation. Smart grid systems can also not be subordinated to each other, but can be organized independently if they are connected by DC inserts.

2. Providing the necessary modes of operation - voltage sources, current sources, sources of constant power, stabilization of electricity parameters. This feature is especially important in MSG networks, to which most RES are connected.

3. Optimization of operating modes of individual generators and the network as a whole, which allows to ensure the coordination of operating modes of generators with the load.

Electric power converters are installed at the output of generators or at the point of their connection - to adjust the parameters of one or a group of generators. If you need to adjust the parameters of the grid in general - use converter substations, which connect the individual converters and power lines between them. Control complexes of a group of terroir-distributed converters or converter substations have a multilevel structure. At the highest (third) level of the hierarchy, the control commands of the power grid as a whole are formed (increase / decrease the total capacity of electricity generators, increase / decrease the capacity of electricity consumers, increase / decrease $cos\varphi$). Based on the commands of the highest level, the commands of the middle (second) level of the control hierarchy are formed, which arrive at separate power supply units (switch the power supply unit to power / voltage / current generator mode, switch on / off the power supply unit, etc.). At the lowest (first) level, control signals are generated by individual power parameter converters and controlled switches in accordance with the operating modes of the respective power supply units and load groups.

Power system management is associated with the complexity of analyzing the current situation of the Smart grid environment due to the large number of generators and loads and the constant change of their modes of operation. Therefore, to describe the state of the grid using the concept of context, which allows to narrow the amount of processed information. Integration into the context of information obtained from energy sources allows you to obtain a model of the current state of the system and generate many possible setting effects on the converters connected to the power nodes of the network.

Building a converter control system in a common information space, taking into account the necessary context parameters, does not reduce to the simple use of several systems that jointly solve the control problem, because the context parameters can be interdependent or contradictory. The inability to relate a specific context parameter to each setpoint action further complicates the construction of multi-parameter control systems. Another problem is the difficulty of formalizing context parameters. Therefore, in general, the task of intelligent control of the power grid is to adequately take into account the many external factors that affect the parameters of the context of the system.

In the information aspect of Smart grid control, it is necessary to pay attention to the problem of data reliability associated with the need to measure contextual data with the above interference from switching power keys, which take the form of abrupt changes in contextual data. A predictive data model is used to assess the reliability of the data.

After verifying the authenticity of the context data, they are used to control the power supply system. The control task is multi-parameter, so finding a solution is quite time consuming. To reduce the amount of calculations it is necessary to narrow the space of possible solutions to the problem, which can be done on the basis of inference rules, and then use optimization control algorithms based on a specific objective function.

Depending on the power of the power system, the number and type of consumers and generators connected to the network, network management has some differences. Consider the features of managing a low-power network (tens of kilowatts) to which renewable energy sources are connected. As a rule, low-power power supply systems are distributed, they include renewable energy sources (photovoltaic panels PV, wind turbines WT), storage capacity (battery AB) and backup power systems (diesel generator DG). Distributed power supply systems can be connected to a centralized power supply system or operate autonomously. On the other hand, various electrical equipment is connected to the network - microclimate systems (heating, ventilation, air conditioning), alarms, lighting, pool equipment, access control, etc. All power units of the system, including loads, are connected to the network by electrical energy converters (CON). To improve the parameters of electricity quality, specialized conversion equipment is used - reactive power compensators, higher harmonic filters, power factor correctors, stabilizers.

The structure of the power supply system is shown in Fig. 9.1.

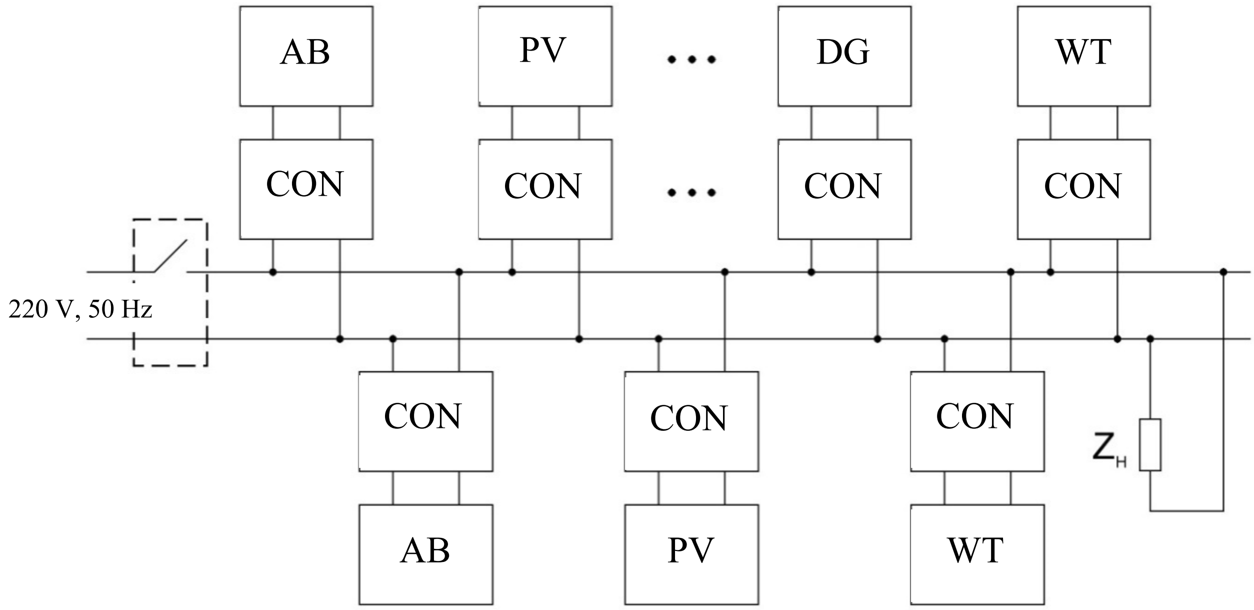


Fig. 9.1. The structure of low-power distributed power supply system

In general, electricity converters (CON) and switches (Sw) combine all electrical devices into a single system to ensure the required quality of electricity consumption parameters. That is, they perform a system-forming function, which allows to combine in one network heterogeneous on the physical principle of operation of generators and loads, Fig. 9.2.

The use of semiconductor power converters allows to solve the following problems:

1) change the modes of operation of generators and loads;

2) to ensure uniformity of electric energy parameters, for which use: bidirectional power correctors, which provide consumption and generation of reactive power; "DC voltage - sinusoidal voltage" or "DC voltage - sinusoidal current" converters, which are installed at the output of renewable energy sources; converters "reactance - active resistance", which provide the consumption of sinusoidal current with zero phase shift relative to the mains voltage; "voltage-to-current" charging converters, which are installed to charge batteries; bit converters "DC voltage - sinusoidal current" or "DC voltage - sinusoidal voltage". There are also possible

implementations of charging converters "voltage - voltage", "voltage - constant power";

3) adjust the power factors in the power supply network and ensure the sinusoidality of currents and voltages consumed by generators;

4) to compensate for the influence of asymmetric regimes;

5) select the maximum amount of energy from renewable energy sources.

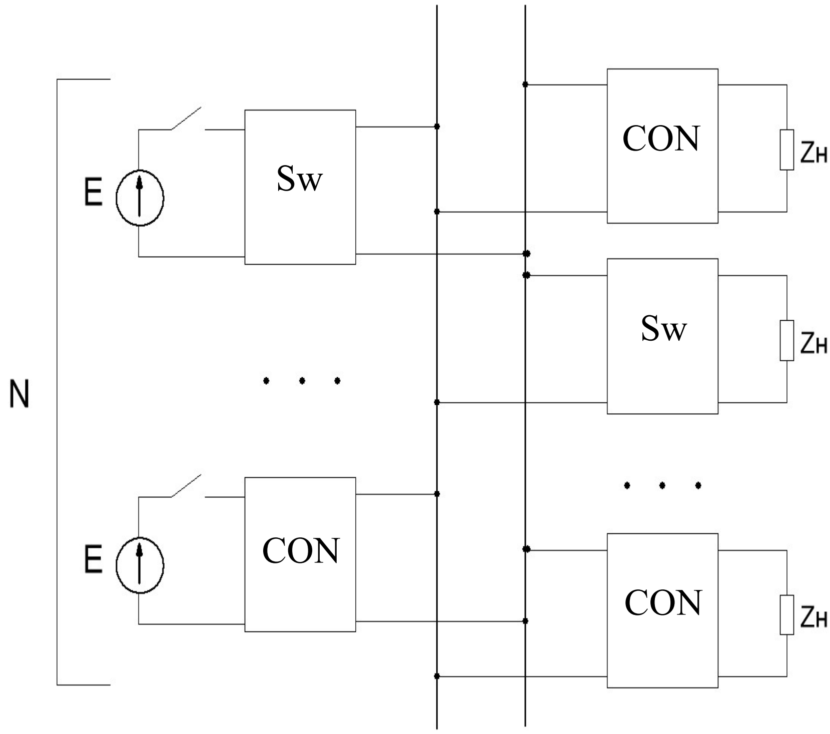


Fig. 9.2. Use of converters for connection of generators and loadings to a network

The use of converters provides the conversion of mechanical, light, thermal energy into electrical energy with the necessary parameters.

The main task of the control system of such power supply system is control and regulation of power quality parameters according to the existing standard (total power S, reactive power Q, active power P, power factor χ, shear angle between current and voltage φ, etc.), which is possible taking into account system context parameters. On the one hand - the parameters that affect the operation of generators (light level, wind direction and speed, battery level, etc.). On the other - the modes of operation of consumers.

The components of the microgrid infrastructure are territorially distributed and managed independently at different intervals. The infrastructure area that contains the controlled converters is the core. The state of operation of the microgrid and its individual core zones depends on the modes of power consumption and a number of external factors (temperature, wind force and direction, light level, etc.), which are measured by the sensor system and form the context as an information component of the microgrid infrastructure.

Based on the context, the grid management system sets the modes of operation of the system's power units according to a certain parameter or group of parameters based on rules. Then the systems optimize the operation of each power unit separately.

An example of the formation of the power system control rule is shown in Fig. 9.3. To form a rule, use the following parameters: the presence of connection to the network, the value of the power balance, the charge level of the batteries, the tariff, the phase shift of the voltage and load current cosφ, load capacity. As a result of combining the parameters of logical connections, it is possible to form network management rules, such as reducing / increasing the power of generators, return / consumption of network energy, etc.

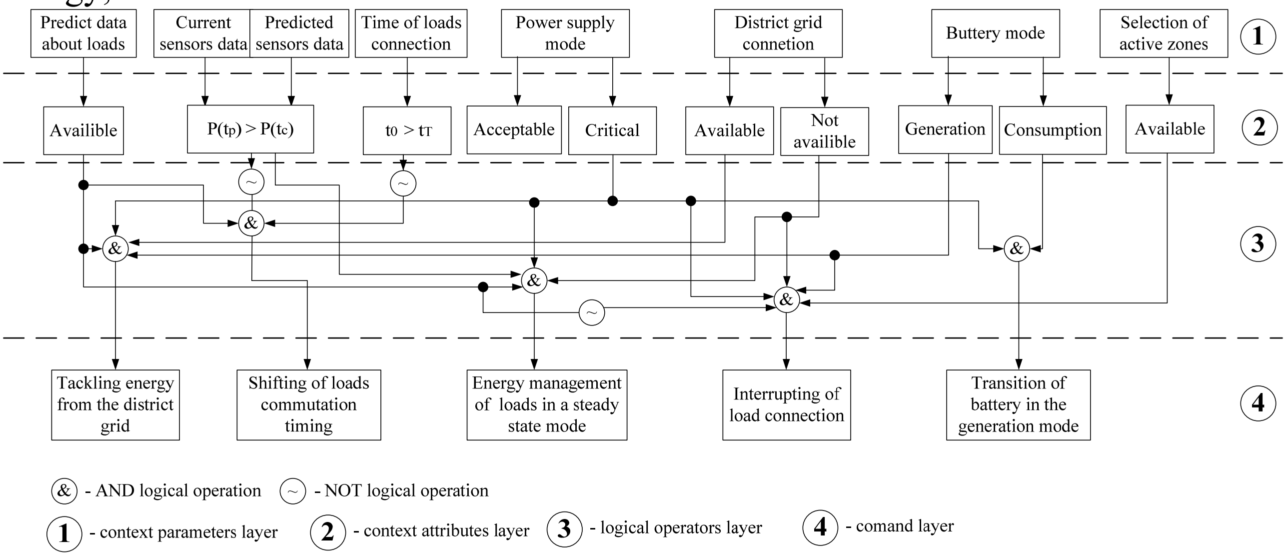


Fig. 9.3. An example of forming a power control rule

The concept of power supply system, which combines intelligent control algorithms and power electronics devices, allows to control electricity consumption, improve its parameters, reduce losses, which allows to move to a qualitatively new level of relations between seller and buyer in the electricity market.

Questions

1. Identify new opportunities to manage the power grid, provided the implementation of the concept of Smart grid.
2. List the necessary conditions for the implementation of the concept of Smart Grid.
3. List the key components of the Smart Grid concept.
4. Describe the functions performed by power converters in the Smart Grid.
5. Define the term "context".
6. Describe the features of the Micro Smart Grid.
7. List the tasks solved by converters in the Smart Grid network.
8. Describe the procedure for using context data by the Smart Grid control system.

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