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

PRACTICE NOTES

Tutorial

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"

Compiler: I. V. Verbytskyi

Electronic online educational publication

Kyiv

Igor Sikorsky Kyiv Polytechnic Institute
2022

Reviewer *Shvaichenko V.B.*, Doctor of Philosophy, Associate Professor, Associate Professor of Department of Acoustic and Multimedia Electronic Systems of Igor Sikorsky KPI

Responsible editor *Romashko V.Ya.,* Doctor of Science, Professor

tamp assigned Methodical Council of Igor Sikorsky Kiev Polytechnic Institute
(Protocol № 6 of 24.06.2022)
at the request of the Academic Council of the Faculty of Electronics
(Protocol № 5/22 of 31.05.2022)

The practice notes contain basic theoretical information, practical tasks, solution examples and tasks for themselves solution in the discipline "DC and AC networks with alternative energy sources - 2". The presented tasks allow to gain practical skills, more thoroughly master the theoretical material of the course, prepare for tests and practical classes. The manual was prepared at the Department of Electronic Devices and Systems and is intended for students in speciality 171 "Electronics", educational program "Electronic Components and Systems".

Registr. № 21/22-844. Size 4.5 auth. sheet
National Technical University of Ukraine
“Igor Sikorsky Kyiv Polytechnic Institute”
Peremohy av., 37, Kyiv, 03056
https://kpi.ua
Certificate of inclusion in the State Register of Publishers, Manufacturers
and Distributors of Publishing Products ДК № 5354 from 25.05.2017

CONTENT

Introduction

The purpose of the practice notes is to deepen practical skills in the discipline "DC and AC power grids with alternative energy sources - 2". They discusses the 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 devices to improve energy efficiency of power grids. 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 methods of calculation of power electronics devices designed to increase the energy efficiency of power grids are given.

After solving the tasks listed in the manual, students will gain skills in:

- calculation of modes of operation of primary energy sources that provide maximum output power or efficiency;
- determination of capacity and losses in overhead and cable power lines;
- methods of calculating the parameters of electricity quality and assessing the impact on them of parameters and modes of operation of electricity consumers;
- design of reactive power compensators based on reactors and capacitor banks;
- methods of load balancing of three-phase networks;
- calculation of parameters of active filters;
- calculation of parameters and losses in DC power lines.

The practice notes are a supplement to the lecture course and contains solutions to typical problems that are submitted for practical classes and tests of the course. A brief description of the theoretical material at the beginning of each practical lesson allows you to use the notes to obtain basic knowledge in the discipline " DC and AC power grids with alternative energy sources - 2".

Practice lesson № 1. Modes of transmission of electrical energy in electric power systems

Theory

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}:

$$R_{out} = -\Delta U_{out} / \Delta I_{out}, \qquad (1.4)$$

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 ROUT source and load resistance R_L.

Dependence of EED η_E and P_H load power on the ratio of R_L and R_i resistances for the model on voltage sources E, P_L load power:

$$\eta_E = \frac{P_L}{P_E} = \frac{E^2 R_L / \left(R_i + R_L\right)^2}{E^2 / (R_L + R_i)} = \frac{R_L}{\left(R_i + R_L\right)} \qquad (1.5)$$

To simplify further calculations, we introduce the variable $k = R_L/R_i$:

$$\eta_E = k / (1 + k). \qquad (1.6)$$

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

$$P_{L\max} = \frac{E^2}{\left(R_i + kR_i\right)^2} kR_i = \frac{E^2}{4R_L} \qquad (1.7)$$

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

$$P_L = \frac{J^2 R_i^2}{\left(R_i + R_L\right)^2} R_L = \frac{J^2 R_i^2}{\left(R_i + kR_i\right)^2} kR_i = J^2 R_i \frac{k}{\left(1 + k\right)^2} \qquad (1.8)$$

Taking into account (1.8), the parameter η_E is equal to:

$$\eta_E = \frac{P_L}{P_E} = \frac{J^2 R_i^2 R_L / \left(R_i + R_L\right)^2}{J^2 R_i R_L / (R_i + R_L)} = \frac{R_i}{\left(R_i + R_L\right)} = \frac{1}{1 + k} \qquad (1.9)$$

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. 1.1.

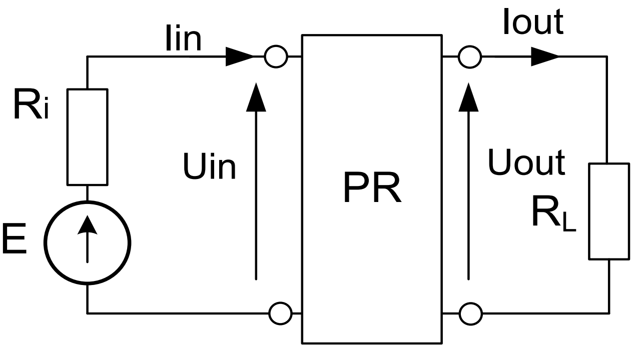


Fig. 1.1. Scheme of matching the parameters of the constant current source and load

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:

$$R_{in} = U_{in} / I_{in} = n^2 U_{out} / I_{out} = n^2 R_L \tag{1.10}$$

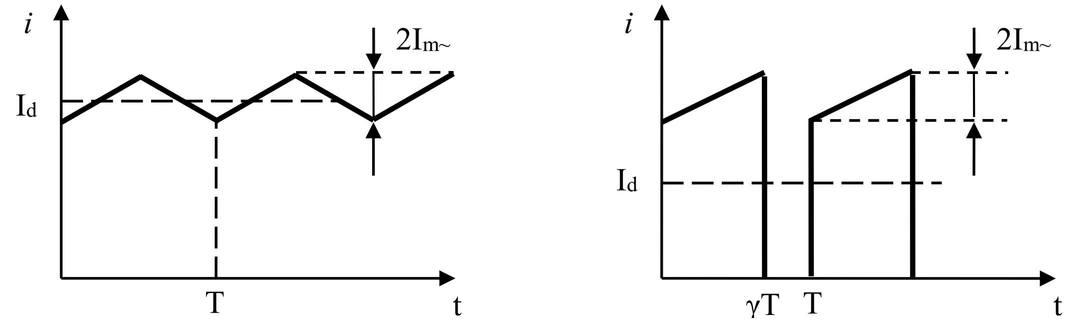
As a rule, the voltage ripple is insignificant, but in some PR, for example, in buck converters, the amplitude of the variable component of the input current is commensurate with its average value, which significantly reduces the EED of energy sources. An increase in the ripple amplitude does not affect 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. 1.2 a), calculate:

$$I = I_d \sqrt{1 + \frac{1}{3}\left(\frac{I_{m\sim}}{4I_d}\right)^2}. \tag{1.11}$$

From the analysis of (1.12), 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. 1.2 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. 1.2 b). The effective value of the current of the specified form is calculated:

$$I = \frac{I_d}{\sqrt{\gamma}} \sqrt{1 + \frac{1}{3}\left(\frac{I_{m\sim}}{4I_d}\right)^2}. \tag{1.12}$$

Comparing (1.11) and (1.12) we can conclude that the current pulse shape is much more effective value than continuous current.



a) b)

Fig. 1.2. 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:

$$s(t) = u(t)i(t) = U_m I_m \sin(\omega t)\sin(\omega t + \varphi) = UI\cos(\varphi) - UI\cos(2\omega t + \varphi). \quad (1.13)$$

Graphs of instantaneous values of current, voltage and power are shown in Fig. 1.3.

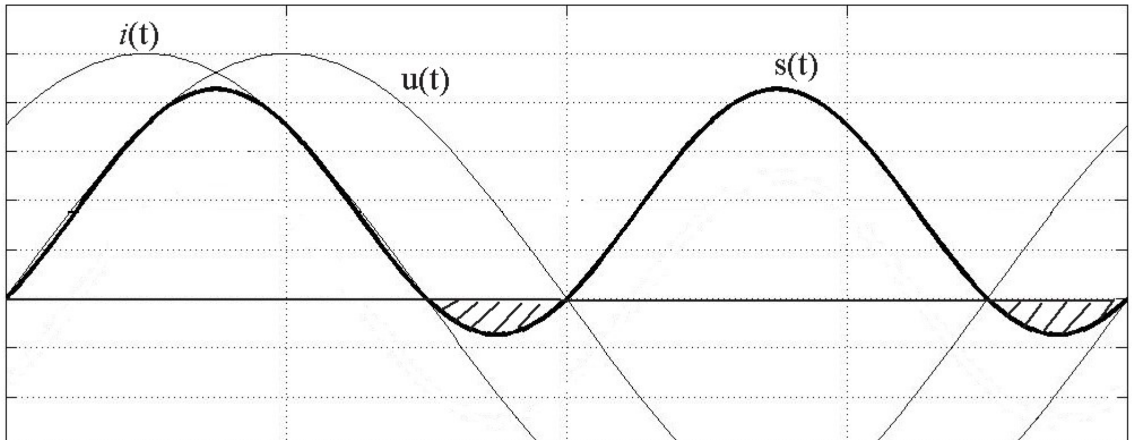


Fig. 1.3. Diagrams of electromagnetic processes in a linear circuit

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:

$$P = U \cdot I\cos(\varphi). \quad (1.14)$$

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

$$Q = U\,I\sin(\varphi). \quad (1.15)$$

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

$$S = \sqrt{P^2 + Q^2}\,. \tag{1.16}$$

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:

$$S = U \cdot I. \tag{1.17}$$

As can be seen from (1.14) and (1.17), 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 (1.13):

$$s(t) = UI(1 - \cos(2\omega t)) \geq 0. \tag{1.18}$$

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:

$$S = \sqrt{P^2 + Q^2 + T^2}\,. \tag{1.19}$$

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

$$\nu = I_{(1)} / I. \tag{1.20}$$

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:

$$\chi = \nu \cdot \cos(\varphi_1), \tag{1.21}$$

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.

Task solution examples

Task № 1

An energy source with voltage E = 25 V and inner resistance R_i = 10 Ohm via power converter with efficiency η = 0.95 is connected to load R_L = 25 Ohm, Fig. 1.4.

Define:

1. Efficiency of electricity delivering η_E without the power converter.
2. Efficiency of electricity delivering η_E of the energy source without the power converter that operates in maximum power point and provide a constant input source current without ripple.

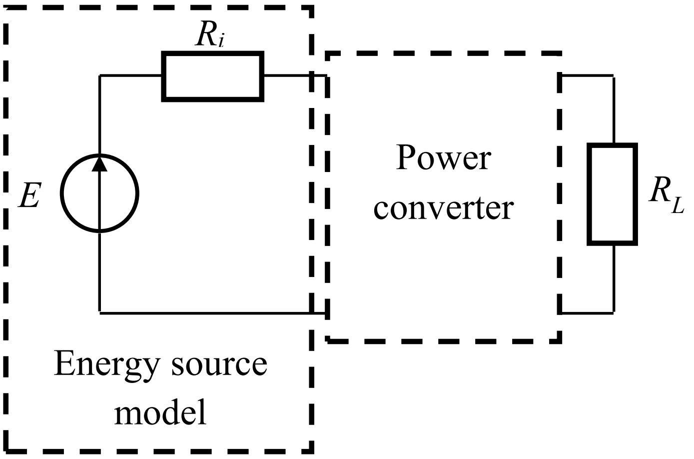


Fig. 1.4. Power supply model

Solution:

1. Efficiency of electricity delivering η_E is defined as the relation of load power P_L and maximum possible power $P_{L\max}$.

$$\eta_E = \frac{P_L}{P_{L\max}}. \tag{1.22}$$

Without the power converter load power P_L is defined as:

$$P_L = \left(\frac{E}{R_L + R_i} \right)^2 R_L. \tag{1.23}$$

If matching condition $R_L' = R_i$ is satisfied than maximum load power $P_{L\max}$ is equal to:

$$P_{L\max} = \left(\frac{E}{R_L^{/} + R_i} \right)^2 R_L^{/} = \frac{E^2}{4R_i}. \tag{1.24}$$

After substituting (1.23) and (1.24) to (1.22) we get an expression for efficiency of electricity delivering η_E:

$$\eta_E = \frac{P_L}{P_{L\max}} = \frac{4R_i R_L}{(R_L + R_i)^2} = \frac{4 \cdot 10 \cdot 25}{(25+10)^2} \approx 0.81.$$

2. Efficiency of electricity delivering η_E with power converter is defined with (1.22). If converter operates in maximum power point, power load calculated as follows:

$$P_L = \eta P_{L\max}. \tag{1.25}$$

After substituting (1.25) in (1.22), we get:

$$\eta_E = \frac{P_L}{P_{L\max}} = \eta = 0.95.$$

Answer: Efficiency of electricity delivering η_E without power converter is equal to $\eta_E = 0.81$, with power converter is $\eta_E = 0.95$.

Task № 2

Calculate how much the losses will increase if instead of constant current in Task № 1, power converter is used with input current shape shown in Fig. 1.5.

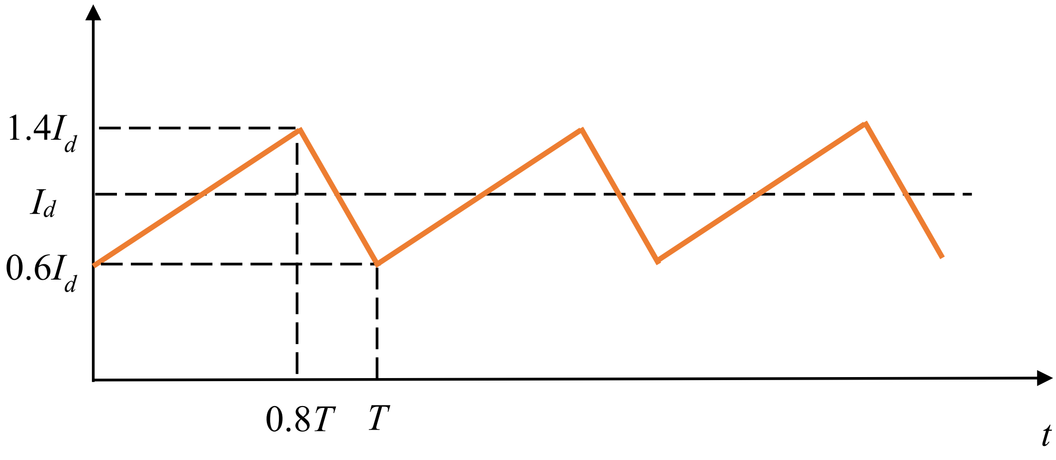


Fig. 1.5. The source current shape with power converter

Solution:

RMS current value I shown in Fig. 1.5, calculated by the formula:

$$I = \sqrt{\frac{1}{T}\int_0^T i^2 dt} =$$

$$I_d \sqrt{\frac{1}{T}\left(\int_0^{0.8T}\left(0.6+\frac{t}{T}\right)^2 dt + \int_{0.8T}^{T}\left(1.4-\frac{0.8(t-0.8T)}{0.2T}\right)^2 dt\right)} =$$

$$= 1.026 I_d.$$

If case of constant current, the power loss of internal resistance is equal

$$P_{Ri} = R_i \cdot I_d^2.$$

If current ripple appears, power loss is increased to value

$$P_{Ri} = R_i \cdot I^2 = R_i \cdot 1.026^2 \cdot I_d^2 = 1.053\ R_i \cdot I_d^2.$$

Hence, with constant input power $P = E \cdot I_d$, the power loss of internal resistance is increased on value 0.053 $R_i \cdot I_d^2$.

Answer: power loss is increased on value 0.053 $R_i \cdot I_d^2$.

Tasks for themselves solving

Task № 1

Calculate how much the losses will increase in power supply system shown in Fig. 1.4, if instead of constant current, power converter is used with input current shape shown in Fig. 1.6.

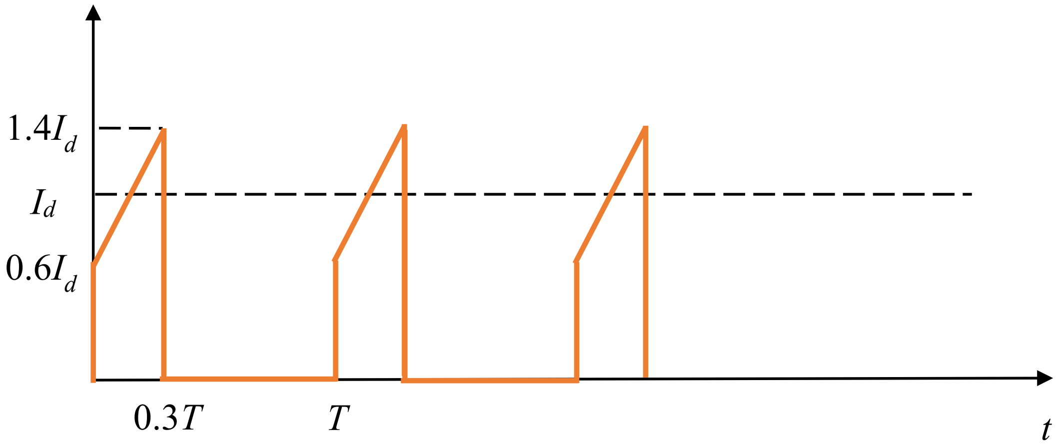


Fig. 1.6. Energy source current shape with power converter

Task № 2

Determine the type of pulse regulator (buck, boost, buck/boost), which can be used for maximum power point tracking in the system shown in Fig. 1.4, if $E = 25$ V, $R_i = 10$ Ohms, the load resistance R_H varies within $R_H = 5..12$ Ohms. For the selected type of regulator to determine the range of change of duty cycle γ.

Task № 3

Fig. 1.7 shows the behaviour of the output power of the wind turbine system depend on the speed of rotation of the engine shaft for different wind speeds υ, $P_{nom} = 5$ kW, $f = 50$ Hz.

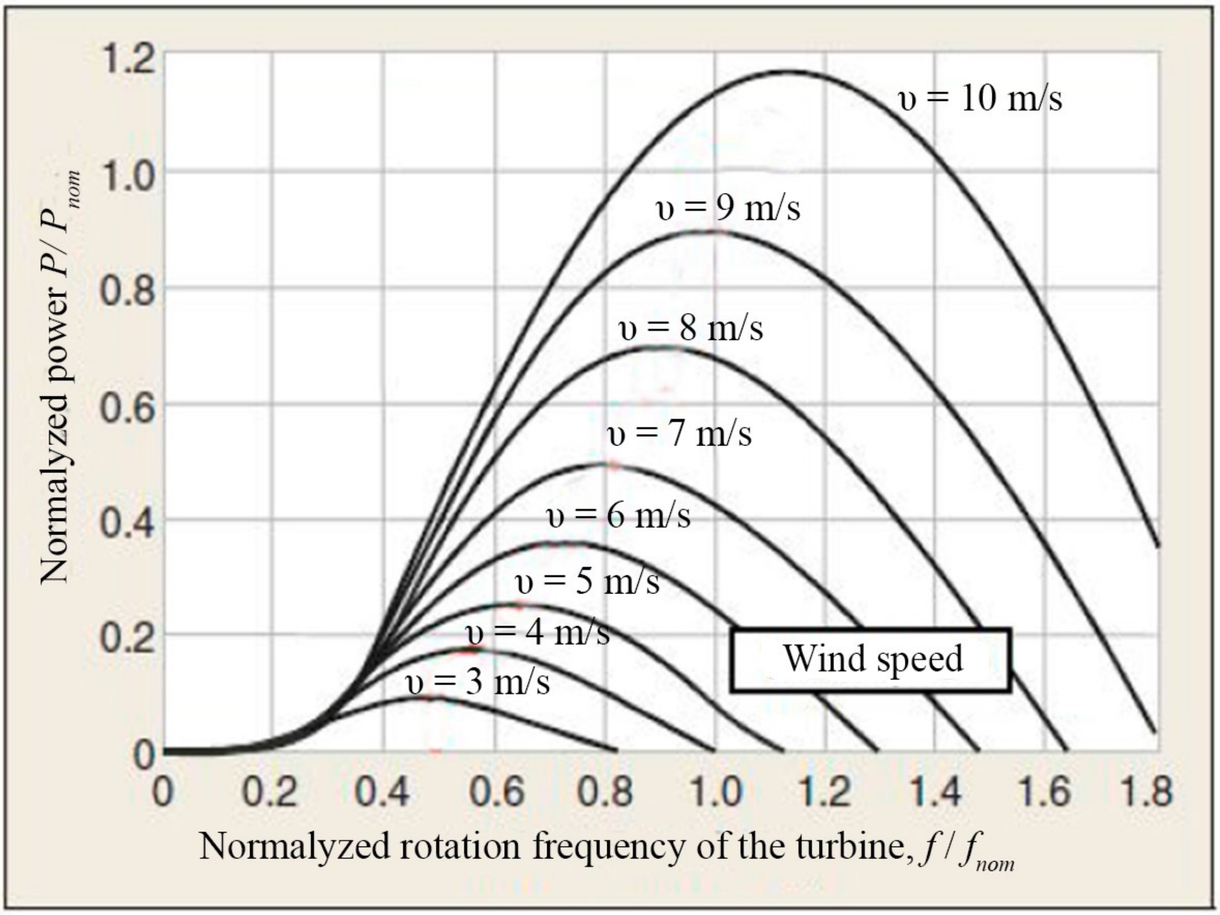


Fig. 1.7. Dependence of the output power of the wind turbine system on the speed of rotation of the engine shaft

Determine the average output power of a wind farm (WF) that is directly connected to a power grid with a frequency of 50 Hz, Fig. 1.8.

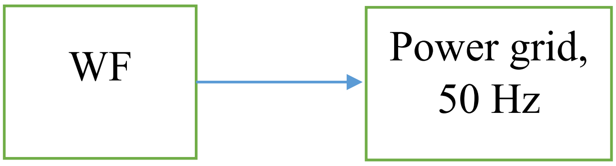


Fig. 1.8. Wiring diagram of the wind farm

If wind speed schedule shown in Fig. 1.9.

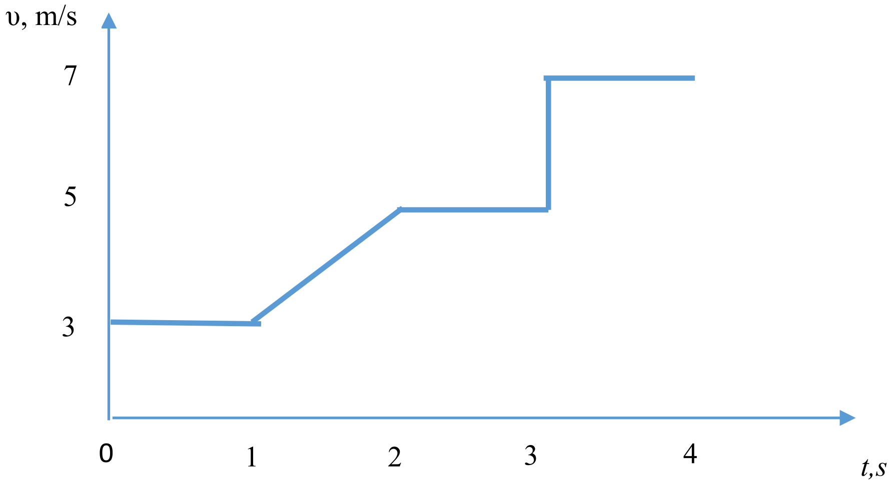


Fig. 1.9. Wind speed schedule

Task № 4

Fig. 1.7 shows the dependence of the output power of the wind turbine system on the speed of rotation of the engine shaft for different wind speeds υ, P_{nom} = 5 kW, f_{nom} = 50 Hz. Determine the average output power of WF, which is connected to the network through the DC link and the inverter, which perform the function of maximum power point tracker, Fig. 1.10.

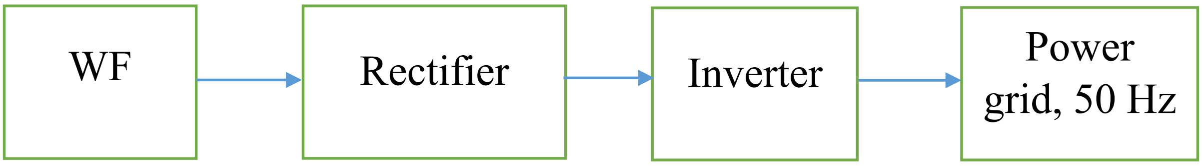


Рис. 1.10. Connection circuit of the wind farm to the power grid

If wind speed schedule shown in Fig. 1.11.

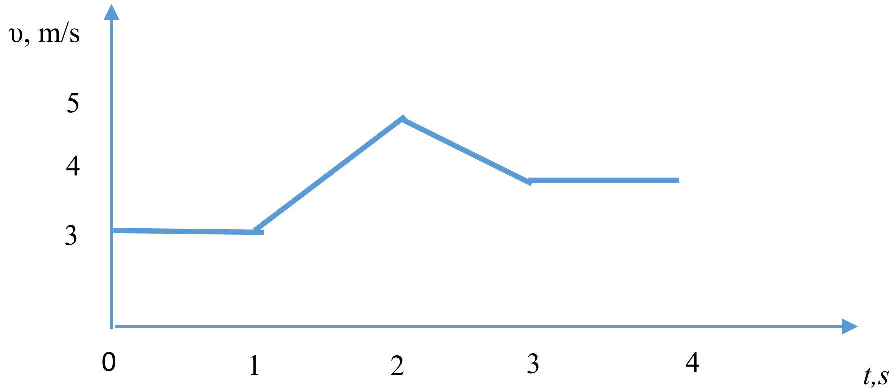


Fig. 1.11. Wind speed schedule

Task № 5

In a linear single-phase AC power supply system 220 V, 50 Hz, reactive power of inductive type Q = 10 kV·Ar circulates, the power factor of the system is χ = 0.6, which causes power loss in the power line P_W = 150 W. Which capacitance must be connected in parallel with the load to fully compensate of reactive power? By how much the power loss is reduced ?

Practice lesson № 2. Design and parameters of AC power lines

Theory

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.

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. The advantages of OHL with insulated wires compared to non-insulated ones include the absence of insulators on the supports.

Cable lines

Cable lines (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. 2.1.

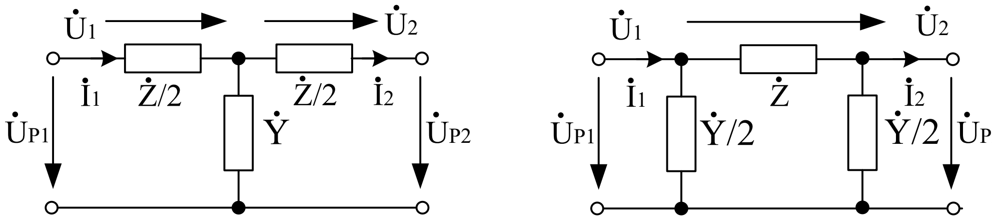


Fig. 2.1. T and R-shaped substitution schemes with concentrated parameters

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:

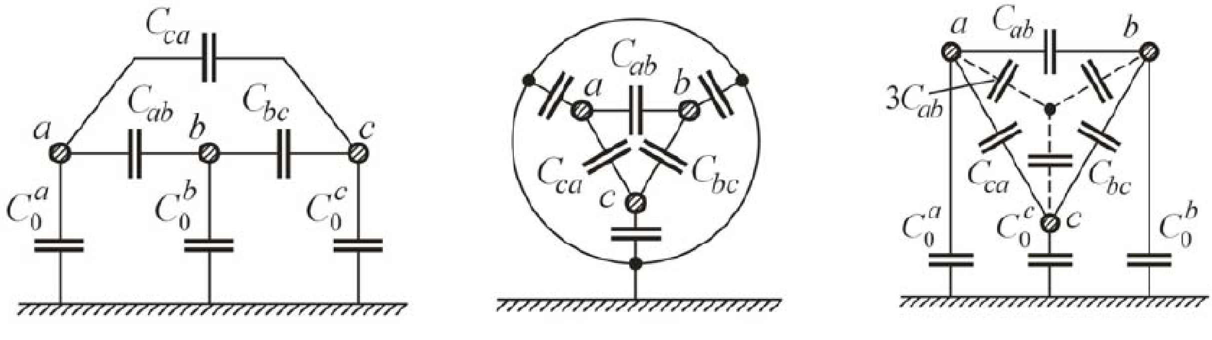
$$X_0 = \omega L_0 = \omega\left(0.46\,\mathbf{lg}\frac{D_{av}}{r_d} + 0.05\mu\right)\cdot 10^{-3}, \tag{2.1}$$

магнітна 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 frequency 50 Hz, (2.1) has the following form:

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

Capacitive conductance is due to the capacitance between phases, phase conductors and earth. In Fig. 2.2 a) and 2.2 b) show the capacitive conductivity of overhead lines and cable lines, in Fig. 2.2 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:

$$C_0 = \frac{0.024}{\lg \frac{D_{av}}{r_d}} \cdot 10^{-6} \tag{2.3}$$

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:

$$B_0 = \omega C_0. \tag{2.4}$$

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

$$B_{0\_50} = \frac{7.58}{\lg \frac{D_{av}}{r_d}} \cdot 10^{-6} \text{ Sm/km}. \tag{2.5}$$

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:

$$I_{C0} = U_{\Phi} \cdot B_0 \text{ кA/km}, \tag{2.6}$$

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

$$Q_{C0} = 3U_{\Phi} \cdot I_{C0} = 3U_{\Phi}^2 \cdot B_0, \tag{2.7}$$

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:

$$Q_C = \frac{1}{2}(U_1^2 + U_2^2) \cdot B_0 \cdot l = \frac{1}{2}(U_1^2 + U_2^2) \cdot B, \tag{2.8}$$

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

$$Q_C = U_{nom}^2 \cdot B. \tag{2.9}$$

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:

$$G_0 = \frac{\Delta P_{\Phi}}{U_{nom}^2} \tag{2.10}$$

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

$$E_L = 24{,}5m\delta\left[1+0{,}63/(r_0\delta)^{0{,}4}\right]\ 10^{-5}\ \text{V/m}, \tag{2.11}$$

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, $m = 0.82$.

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

$$G_0 = \omega C_0 tg\delta = B_0 tg\delta, \tag{2.12}$$

and the corresponding surge current:

$$I_{СП} = U_{Ф} \cdot B \cdot tg\delta = U_{Ф} \cdot G. \tag{2.13}$$

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

$$\Delta P_{loss} = 3I_{loss}^2 \frac{1}{\omega C \cdot tg\delta} = U^2 \cdot G. \tag{2.14}$$

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. 2.3.

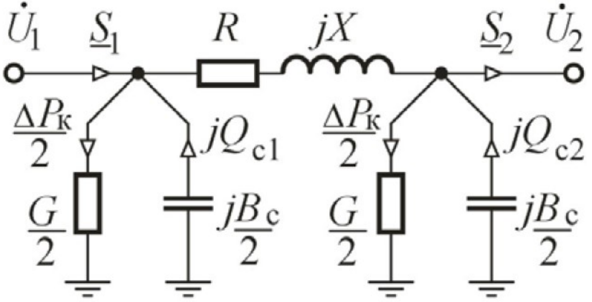


Fig. 2.3. Scheme of replacement of an electric line

The following are methods of calculating simple electrical networks. Consider the scheme of replacement of the electrical networks, Fig. 2.4.

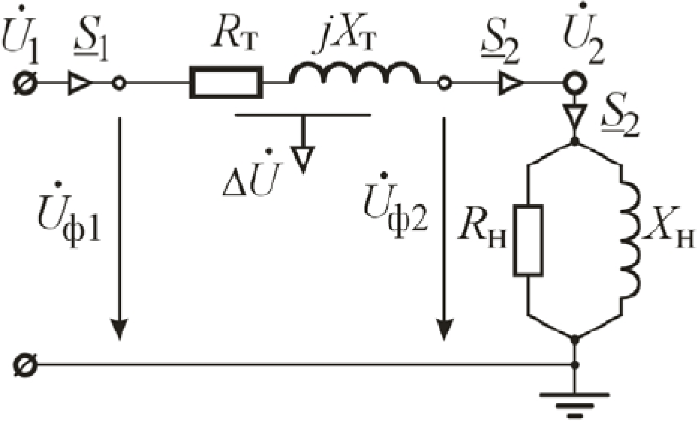


Fig. 2.4. Scheme of phase replacement of the network section

The section of the network feeds a symmetrical three-phase load, which is set at the end of the section by current I or power of three phases S_2, which consumes the load with active resistance R_H and reactive resistance X_H. 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. Given the calculation of symmetric 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 form:

$$\dot{U}_{P2} = U_{P2\_a} - jU_{P2\_p} = U_{P2}e^{-j\delta 2}, \dot{I}_P = I_{P\_a} - jI_{P\_r} = I_P e^{-j\varphi}. \tag{2.15}$$

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:

$$\begin{gathered}\dot{U}_{P1} - \dot{U}_{P2} = \Delta\dot{U} = \dot{I}_P \cdot \dot{Z} = (I_{P\_a} - jI_{P\_r}) \cdot (R_T - jX_T) = \\ = I_{P\_a}R_T + I_{P\_r}X_T + j(I_{P\_a}X_T - I_{P\_r}R_T).\end{gathered} \tag{2.16}$$

From (2.15) 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:

$$\delta_1 = arctg\left(\frac{I_{P\_a}X_T - I_{P\_r}R_T - U_{P2\_r}}{I_{P\_a}R_T + I_{P\_r}X_T + U_{P2\_a}}\right). \tag{2.17}$$

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_P current at the beginning of the section is equal to:

$$\dot{I}_P = \frac{\overset{*}{S}_1}{3U_{P1}} = I_{P\_a} - jI_{P\_r}. \tag{2.18}$$

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

$$\Delta S = 3I_P^2 Z = 3(I_{P\_a}^2 + I_{P\_r}^2)(R + jX), \tag{2.19}$$

or provided that the full power value is used:

$$\Delta S = \frac{S_1^2}{3U_{P1}^2}Z = \frac{P_1^2 + Q_1^2}{3U_{P1}^2}(R + jX) \tag{2.20}$$

and calculated the loss of active and reactive power:

$$\Delta P = 3(I_{P\_a}^2 + I_{P\_r}^2)R = (P_1^2 + Q_1^2)R / 3U_{P1}^2; \tag{2.21}$$

$$\Delta Q = 3(I_{P\_a}^2 + I_{P\_r}^2)X = (P_1^2 + Q_1^2)X / 3U_{P1}^2. \tag{2.22}$$

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

$$S_2 = S_1 - \Delta S = P_1 - \Delta P + j(Q_1 - \Delta Q). \tag{2.23}$$

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 $I_P^{(0)}$:

$$I_P^{(0)} = \overset{*}{S}_2 / \dot{U}_{P2}^{(0)} = I_{P\_a}^{(0)} - jI_{P\_r}^{(0)}. \tag{2.24}$$

According to the values of current and line resistance, the power losses $\Delta S^{(1)}$ are found by (2.19). 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 (2.18) 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.

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.

Task solution examples

Task № 1

Calculate the parameters of the cable line replacement scheme and the total power that can be transmitted through it. Line parameters: line length l = 40 km, nominal voltage U_{nom} = 3 kV, wire diameter d = 60 mm, material - copper (18 Ohm·mm² / km), inductive resistance of wire per 1 km of length X_0 = 0.25 Ohm / km, reactive power generated by line capacity per unit length q_0 = 4 kVar / km.

Solution:

To replace the cable line, a U-shaped replacement scheme is used, shown in Fig. 2.5.

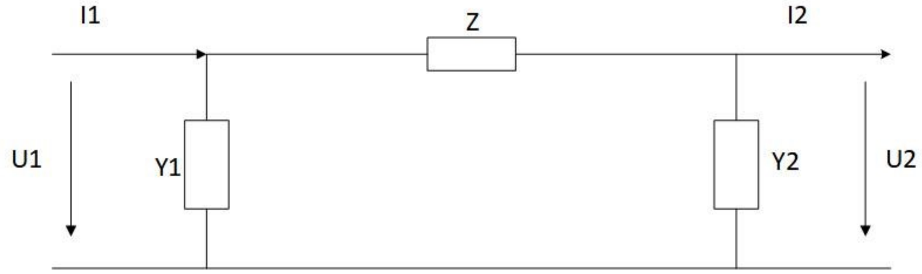


Fig. 2.5. U-shape replacement scheme of the cable line

1. Replacement scheme parameters:

Impedance Z:

$$Z = R + jX.$$

Active resistance:

$$R = \frac{\rho l}{S}.$$

Reactance:

$$X = X_0 \cdot l.$$

After substitution in the formula, we obtain the values of active and reactive resistance:

$$R = \frac{18 \cdot 40 \cdot 4}{3600 \cdot \pi} = \frac{0.8}{\pi} = 0.255 \text{ Ohm};$$

$$X = 0.25 \cdot 40 = 10 \text{ Ohm}.$$

Impedance:

$$Z = 0{,}255 + j10 \text{ Ом}.$$

The conductivity Y is determined from the formula of reactive power Q:

$$Y = \frac{Q}{U^2}.$$

After substituting the original values to the expression, we obtain:

$$Y = \frac{4 \cdot 10^3}{(3 \cdot 10^3)^2} = 1.33 \cdot 10^{-3} \text{ Sm}.$$

Parameters Y_1 and Y_2 of the substitution scheme are equal $Y_1 = Y_2$ and are defined as $Y_1 = Y_2 = Y/2$.

The maximum line capacity is limited by a series resistance Z. If the maximum total power $S_{\max}$ is estimated without reactive power compensation, it is achieved if the resistance Z is equal to the load resistance Z_l, $Z = Z_l$:

$$S_{\max} = \frac{U^2}{4Z} = \frac{(3 \cdot 10^3)^2}{4 \cdot 10} = 225 \text{ kVA}.$$

Under the condition of full reactive power compensation, the maximum active power of the $P_{\max}$ line is equal to

$$P_{\max} = \frac{U^2}{4R} = \frac{(3 \cdot 10^3)^2}{4 \cdot 0.255} = 35.3 \text{ MW}.$$

Answer: 1) $Z = 0.255 + j10$ Ohm; $Y = 1.33 \cdot 10^{-3}$ Sm;

2) $S_{\max} = 225$ kVA, $P_{\max} = 35.3$ MW.

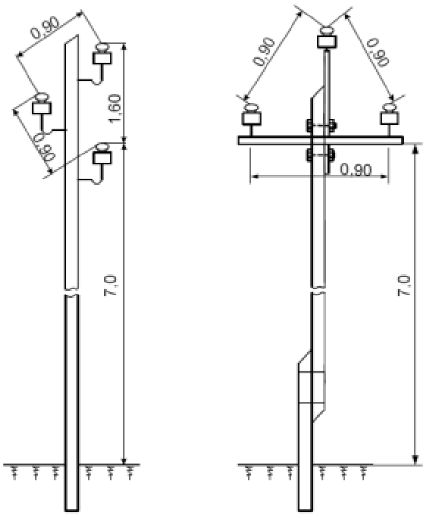
Tasks for themselves solving

Task № 1

Calculate the parameters of the cable line replacement scheme and total power that can be transmitted over it. Line parameters: line length $l = 5$ km, nominal voltage $U_{nom} = 25$ kV, wire diameter $d = 25$ mm, material - copper (18 Ohm · mm^2 / km), wire resistance per 1 km of length: $X_0 = 0.1$ Ohm / km, $q_0 = 9$ kVAR / km.

Task № 2

Due to the reconstruction of the network on the section of the 10 km line, it is planned to replace the 6 kV transmission line with a 15 kV line, the area of the line wire remains unchanged and is equal to $S = 60$ mm^2, aluminum material (30 Ohm·mm^2/ km). After the reconstruction, it is planned to change single-rack wooden supports with wires placed at the vertices of an isosceles triangle, to single-rack wooden supports with reinforced concrete attachments with wires placed at the vertices of an equilateral triangle, Fig. 2.5. Assess the bandwidth and parameters of line replacement schemes before and after reconstruction.



a) b)

Fig. 2.5. Illustration on the reconstruction of the transmission line: a) before the reconstruction; b) after reconstruction

Task № 3

The power supply of the enterprise is carried out by cable and overhead lines with a voltage of 35 kV. The length of each line $l = 10$ km. Cable line wire parameters: $R_0 = 0.5$ Ohm / km, $X_0 = 0.2$ Ohm / km, $q_0 = 90$ kVAR / km. The parameters of the overhead line wire: $R_0 = 0.4$ Ohm / km, $X_0 = 0.5$ Ohm / km, $b_0 = 2.8 \cdot 10\text{-}6$ Sm / km. Determine the parameters of line substitution schemes.

Task № 4

For a 220 kV overhead line with a longitudinal resistance $Z = 10 + j10$ Ohm and a capacitive conductivity $B_C = 10^{-3}$ Sm known power and voltage at the end of the line $S_2 = 200 + j100$ MVA, $U_2 = 215$ kV. Calculate the current and voltage at the beginning of the line.

Task № 5

For an overhead line with a longitudinal resistance $Z = 10 + j10$ Ohm and a capacitive conductivity $B_C = 10^{-3}$ cm known power and voltage at the beginning of the line $S_1 = 200 + j300$ MVA, $U_1 = 215$ kV. Calculate the current and voltage at the end of the line.

Task № 6

For an overhead line with a longitudinal resistance $Z = 15 + j10$ Ohm and a capacitive conductivity $B_C = 10^{-2}$ Sm known current and voltage at the beginning of the line $I_1 = 150 + j100$ kA, $U_1 = 215$ kV. Calculate the phase difference between the input and output voltage.

Practice lesson № 3. Long-distance AC power lines

Theory

Long-distance transmission lines (LDTL) are considered to be power lines (transmission lines) longer than 300 km. The electromagnetic processes that occur in LDTL are described by electromagnetic equations valid for long lines. To accurately calculate the transients in the LDTL, it is necessary to take into account the wave processes that occur along the line and are associated with a limited speed of propagation of electromagnetic radiation c = 300,000 km / s. For a network frequency f = 50 Hz, the length of the electromagnetic wave Λ propagating along the transmission line is equal to:

$$\Lambda = c / f = 300000 / 50 = 6000 \text{ km}, \tag{3.1}$$

therefore, if the voltage at the beginning of the line has a phase of 90°, which for household networks corresponds to the maximum phase voltage $u_P(90°) = 220\sqrt{2}$ V, at a distance of 3000 km from this point the voltage has a phase of 270 °, which corresponds to the phase voltage $u_P(270\,°) = -\ 220\sqrt{2}$ V. Calculation of operating modes of such transmission line with the help of linear substitution schemes would give a qualitatively erroneous result. Therefore, the processes in LDTL are described through the equation of a long line. To do this, use the secondary parameters of the long line - the wave resistance Z_C and the voltage transfer coefficient γ.

The equation of a long line through secondary parameters in the general form has the form:

$$\begin{cases} \dot{U}_1 = \dot{U}_2\, ch(\gamma) + \dot{I}_2\, ch(\gamma) Z_C; \\ \dot{I}_1 = \dot{U}_2\, ch(\gamma) / Z_C + \dot{I}_2\, ch(\gamma). \end{cases} \tag{3.2}$$

Secondary parameters of the line γ and Z_C can be expressed through the primary parameters of the line per 1 km of length: R_0, X_0, G_0, B_0 - active and reactive resistance, active and reactive conductivity, respectively. The primary parameters are grouped into the complex longitudinal resistance Z_0 and the complex transverse conductivity Y_0:

$$\dot{Z}_0 = R_0 + jX_0; \quad \dot{Y}_0 = G_0 + jB_0. \tag{3.3}$$

In real transmission lines, the specific parameters of the line are of the following order: $X_0 \approx 0.3$ Ohm / km, $B_0 \approx 3 \cdot 10^{-6}$ Sm / km, $R_0 << X_0$, $G_0 \approx 0$. The values of the specific secondary parameters of the line Z_{C0} and γ_0 are calculated by formulas:

$$Z_{C0} = \sqrt{\frac{Z_0}{Y_0}}; \tag{3.4}$$

$$\gamma_0 = ln\left(ch(\gamma_0) + sh(\gamma_0)\right) \approx ln\left(1 + \sqrt{Z_0 Y_0}\right). \tag{3.5}$$

Given the ratio $\sqrt{Z_0 Y_0} << 1$, expression (3.5) transforms to:

$$\gamma_0 \approx ln\left(1 + \sqrt{Z_0 Y_0}\right) \approx \sqrt{Z_0 Y_0}. \tag{3.6}$$

A long line has the following properties:

1. The characteristic resistance of the Z_C line does not depend on its length and can be recorded due to its primary parameters:

$$Z_{C0} = \sqrt{\frac{Z_0}{Y_0}} = \sqrt{\frac{Z_0 l}{Y_0 l}} = \sqrt{\frac{Z}{Y}}. \qquad (3.7)$$

2. In the agreed mode, the ratio between current and voltage is constant along the line U_i / I_i = const.

The power of the line in the agreed S_{HT} mode is called natural:

$$\dot{S}_{HT} = \dot{U}_2^2 / Z_C. \qquad (3.8)$$

The current in the line in the coordinated I_{HT} mode is also called natural:

$$\dot{I}_{HT} = \dot{U}_2 / \dot{Z}_C. \qquad (3.9)$$

The calculation of the secondary parameters of the entire LDTL is carried out according to the formulas:

$$\gamma = l \ln\left(\dot{U}_{IN1} / \dot{U}_{IN2} \right) = l\gamma_0 = l\sqrt{Z_0 Y_0} = \sqrt{ZY}. \qquad (3.10)$$

Operation modes of lines without power loss

Consider the modes of operation of the line without power losses, which is called the ideal line. In an ideal line, the primary parameters conductivity, line resistance and damping coefficient are zero $G_0 = R_0 = \alpha = 0$, and the secondary parameter γ has an imaginary value:

$$\gamma = \gamma_0 l = l\sqrt{jX_0 jB_0} = jl\sqrt{X_0 B_0} = jl\lambda_0 = j\lambda. \qquad (3.11)$$

The parameter λ is called the wavelength of an ideal line, and the parameter λ_0 is called the coefficient of propagation of an electromagnetic wave. The parameter λ characterizes the shift of the voltage and current phase at the end of the line relative to the current and voltage at the beginning of the line under the condition of natural power transmission. In the ideal line, the wave resistance Z_C and the natural power of the P_{HT} have active values:

$$Z_C = \sqrt{\frac{X_0}{B_0}}; \; P_{HT} = \frac{U_2^2}{Z_C}. \qquad (3.12)$$

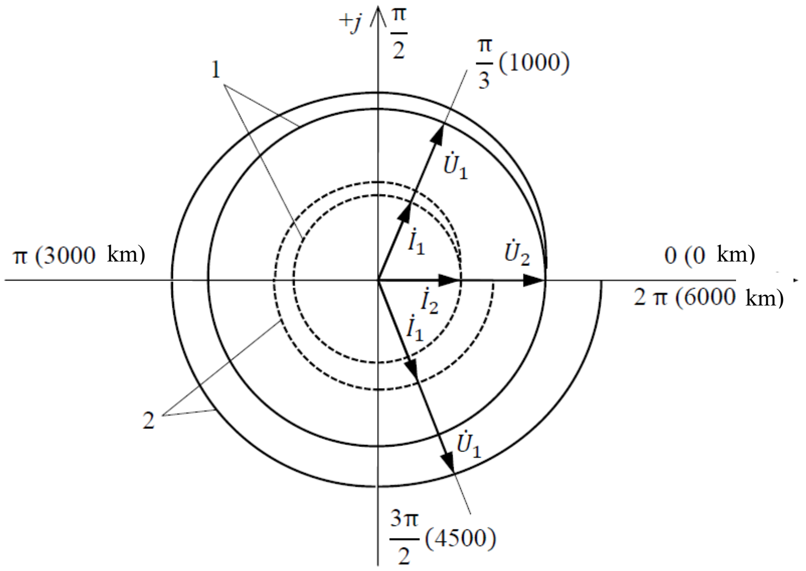
The equations that describe the processes in an ideal line are as follows:

$$\begin{cases} \dot{U}_1 = \dot{U}_2 cos(\lambda) + j\dot{I}_2 sin(\lambda) Z_C; \\ \dot{I}_1 = j\dot{U}_2 sin(\lambda) / Z_C + \dot{I}_2 cos(\lambda). \end{cases} \qquad (3.13)$$

Consider the mode of active power transmission ($P_2 = P_{HT}$, $I_2 = I_{HT} = U_2/Z_C$). In this mode, the processes in the line are described by equations:

$$\begin{cases} \dot{U}_1 = \dot{U}_2 cos(\lambda) + j\dot{U}_2 sin(\lambda) = \dot{U}_2 e^{j\lambda}; \\ \dot{I}_1 = j\dot{I}_2 sin(\lambda) + \dot{I}_2 cos(\lambda) = \dot{I}_2 e^{j\lambda}. \end{cases} \qquad (3.14)$$

System (3.14) describes a circle in the complex plane, which indicates the same phase shift of voltage and current at the beginning of the line, which is equal to λ. Since the active load is connected to the line, along the line the phase shift φ between current and voltage is zero φ = 0. Given the losses (R_0> 0, G_0> 0), the equations of the line are described by spirals, Fig. 3.1.



1 – ideal line, 2 – line with power loss

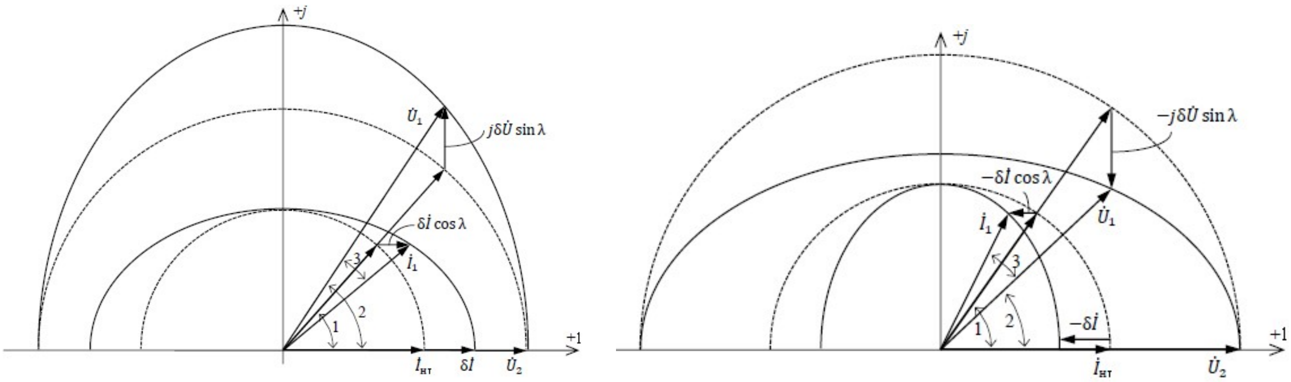
Fig. 3.1. Vector diagram of currents and voltages in the line

The absence of phase shift between current and voltage in the presence of reactive line elements: longitudinal inductive resistance and transverse capacitive resistance, indicates the equality of reactive power consumption Q_L inductive line resistance and generated reactive power Q_C capacitive resistance line Q_L = Q_C. Therefore, the generator, which operates on a coordinated line, generates only active power P_1, which is equal to the natural $P_1 = P_{HT}$. In the line with losses, the generator must generate power P that exceeds the natural by the amount of active losses in the line $P_1 = P_{HT} + \Delta P$.

Consider the modes of transmission of active power other than natural. Let the current at the end of the line be equal to $I_2 = I_{HT} + \Delta I$, where I_{HT} is the line current under the condition of natural power transfer of P_{HT}. Then the current and voltage at the beginning of the line are equal:

$$\begin{cases} \dot{U}_1 = \dot{U}_2 cos(\lambda) + j\dot{Z}_C \left(\dot{U}_2 / \dot{Z}_C + \Delta\dot{I} \right) sin(\lambda) = \dot{U}_2 e^{j\lambda} + j\Delta\dot{U}_2 sin(\lambda); \\ \dot{I}_1 = j\dot{I}_{HT} sin(\lambda) + (\dot{I}_{HT} + \Delta\dot{I}) cos(\lambda) = \dot{I}_{HT} e^{j\lambda} + \Delta\dot{I} cos(\lambda). \end{cases} \tag{3.15}$$

Equations (3.15) describe ellipses. The voltage ellipse has a smaller radius on the real axis, which is equivalent to the mode of natural power transmission $P_2 = P_{HT}$. On the imaginary axis, the ellipse has a larger radius by value Usin(λ). The current ellipse has the opposite dependence - a smaller radius on the imaginary axis and a larger one on the value of cosIcos (λ) on the real one. Deviation of the load power from the natural value leads to a violation of the equality of voltage modules at the beginning and end of the line. Vector diagrams of line currents and voltages are shown in Fig. 3.2.



а) larger than natural ($P_2 > P_{HT}$, $\Delta I > 0$) б) less than natural ($P_2 < P_{HT}$, $\Delta I < 0$)

1 – phase and voltage phase shift λ relative to the end of the line in the mode of natural power transmission; 2 – phase shift between voltages at beginning U_1 and at the end U_2 of line; 3 – phase shift between voltage U_1 and current I_1 at beginning of line

Fig. 3.2. Vector diagram of currents and voltages of line

The ratio of voltage modules at the beginning of U_1 and the end of line U_2 is described by the following formula:

$$\dot U_1 = U_2\sqrt{\cos^2(\lambda)+\left(\dot Z_C/\dot Z_2\right)^2\sin^2(\lambda)}, \tag{3.16}$$

where Z_2 is load resistance connected to the end of line.

According to formula (3.16), the deviation of the load from the agreed value leads to a deviation of the voltage at the beginning of the line by the value of $\Delta U\sin(\lambda)$. If $P_2 > P_{HT}$, $U_1 > U_2$, for example for $P_2 = 1.5P_{HT}$ and LDTL 1000 km long ($\lambda = \pi / 3$) $U_1 = 1.4U_2$, ie the voltage at the beginning of the line U_1 is less than at its end $U_1 < U_2$. The largest voltage deviation at the beginning of the U_1 line is observed in the quarter-wavelength lines. For the voltage frequency $f = 50$ Hz, the line length is $l = 1500$ km.

Despite the active load resistance, which causes the lack of reactive power at the end of the line, at the beginning of the line reactive power is non-zero. Therefore, in this mode the equality of inductive and capacitive reactive powers $Q_L \neq Q_C$ is not achieved and in lines with losses to provide close to one value of the voltage transfer coefficient $M = U_1 / U_2$ it is necessary to generate reactive power of capacitive or inductive type.

Line voltage control modes

To analyze the voltage control modes, we convert the first equation of the system (3.13) to the form:

$$\dot U_1 = \dot U_2\cos(\lambda) + jZ_C\frac{\dot I_2 U_2}{\overset{*}{U}_2}\sin(\lambda). \tag{3.17}$$

After transforming the second term of the right-hand side of expression (3.17), we obtain:

$$\dot U_1 = \dot U_2\cos(\lambda) + jZ_C\frac{P_2 - jQ_2}{\overset{*}{U}_2}\sin(\lambda). \tag{3.18}$$

Directing the voltage vector of the end of the line U_2 along the real axis and using the angle θ, we express the voltage at the beginning of the line U_1, then equation (3.18) will look like this

$$U_1 cos(\theta) + jU_1 sin(\theta) = U_2 cos(\lambda) + Z_C \frac{Q_2}{U_2} sin(\lambda) + jZ_C \frac{P_2}{U_2} sin(\lambda). \quad (3.19)$$

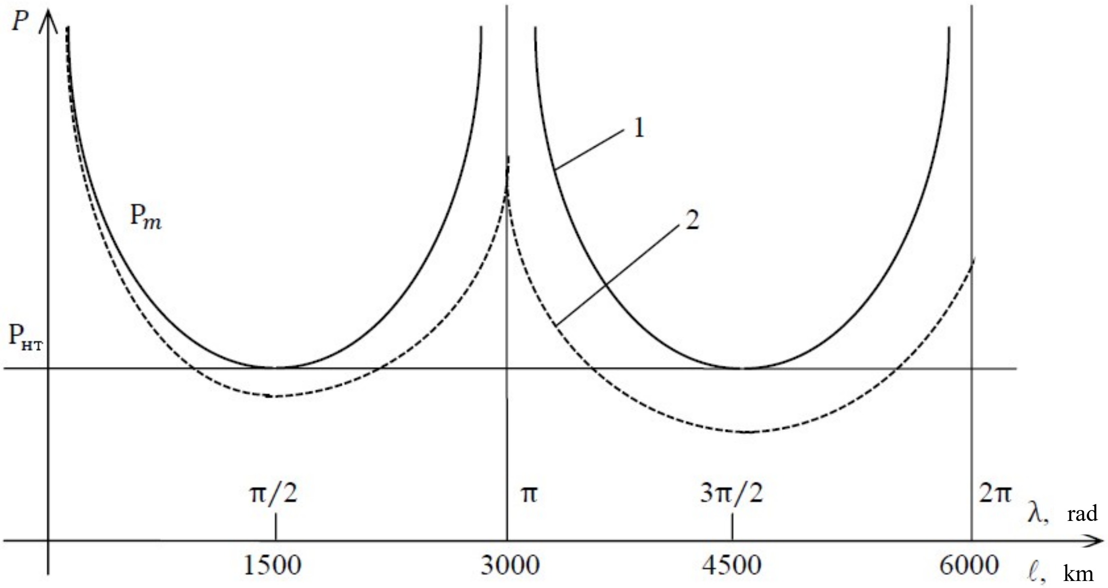
Let's compare the imaginary components of the equation (3.19):

$$U_1 sin(\theta) = Z_C \frac{P_2}{U_2} sin(\lambda). \quad (3.20)$$

From equation (3.20) we express the active power of the line:

$$P_2 = \frac{U_1 U_2}{Z_C sin(\lambda)} sin(\theta) = P_m sin(\theta). \quad (3.21)$$

The maximum value of the active power of the line P_m depends on the wavelength of the line $P_m = f(\lambda)$, the graph of this dependence is shown in Fig. 3.3



1 – ideal line; 2 – line with power loss

Fig. 3.3. Graph of maximum line power P_m

From fig. 3.3 it can be concluded that the minimum value of active power is a line with a quarter wavelength $l = \Lambda / 4$. For a voltage with a frequency of 50 Hz, the length of the line is l = 1500 km. Ideal half-wavelength lines $l = \Lambda / 2$ have unlimited bandwidth. In half-wave loss lines, the line power is limited, but this limit is several times higher than the natural power of P_{HT}. Lines with a length of $l = \Lambda / 8$ .. $3\Lambda / 8$ (750-2250 km) have reduced bandwidth.

Analysis of the real components of expression (3.19) makes it possible to calculate the reactive power:

$$U_1 cos(\theta) = U_2 cos(\lambda) + Z_C \frac{Q_2}{U_2} sin(\lambda). \quad (3.22)$$

Consider the mode of voltage regulation of the line, which maintains the equality of input and output voltage $U_1 = U_2$. Then the reactive power at the end of the line is calculated by the formula:

$$Q_2 = \frac{cos(\theta) - cos(\lambda)}{sin(\lambda)} P_{HT}. \tag{3.23}$$

The value of the reactive power of the line, normalized by the value of natural power $q_2 = Q_2 / P_{HT}$ is as follows:

$$q_2 = (cos(\theta) - cos(\lambda)) / sin(\lambda). \tag{3.24}$$

It is also possible to calculate the value of reactive power at the beginning of the line

$$q_1 = (cos(\lambda) - cos(\theta)) / sin(\lambda) = -q_2. \tag{3.25}$$

Thus, under voltage regulation, the reactive powers at the beginning and end of the line are numerically equal to each other and have opposite signs. If the power at the end of the line is greater than the natural $P_2 > P_{HT}$, the voltage in the middle of the line is less than at its ends, Fig. 3.4. Otherwise, the voltage in the middle of the line is greater than at the ends. At zero active power, overvoltage can be critical.

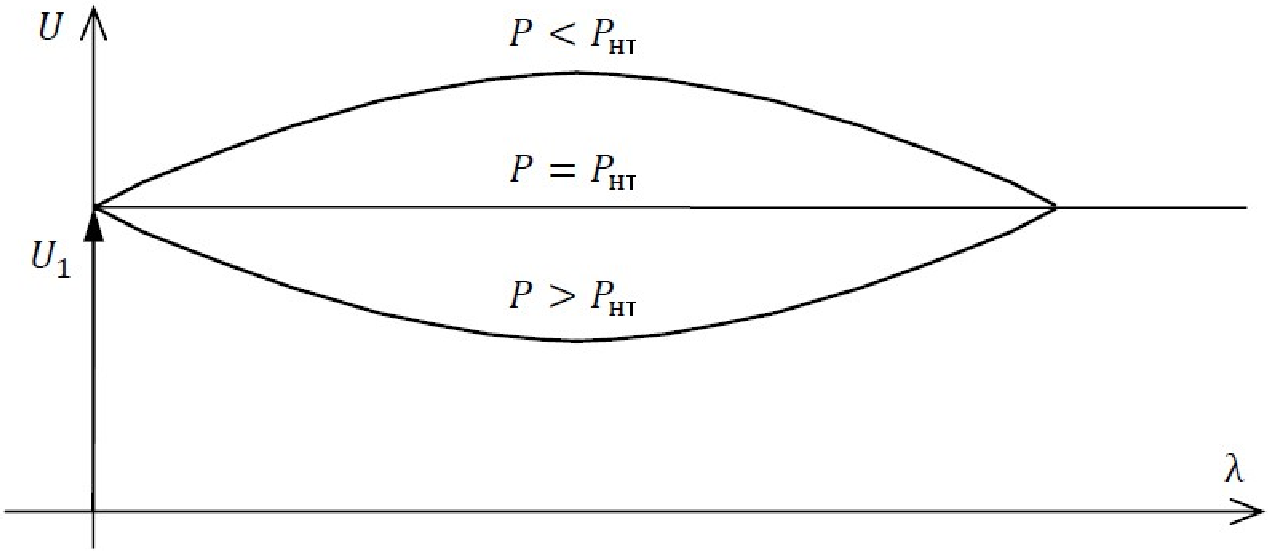


Fig. 3.4. Voltage along the line

Consider the processes in the lines of a quarter and a half wave in more detail.

A quarter wave line

A line of a quarter of a wavelength has the lowest bandwidth $P_m = U_1U_2/Z_C$. On the other hand, in idle mode $I_2 = 0$ the voltage at the end of the line is equal:

$$U_2 = U_1 / cos(\lambda). \tag{3.26}$$

Since cos (π / 2) = 0, connecting to the beginning of the line of the voltage generator in idle mode will theoretically lead to an unlimited increase in voltage at the end of the line. In real lines, the voltage will increase several times compared to the nominal. Therefore, the idle mode of the line length of a quarter of a wave is unacceptable. The same applies to lines whose length is in the range $l = \Lambda / 8..3\Lambda / 8$ (750-2250) km. Idling mode is also dangerous for generators installed at the beginning of the line due to the increase in reactive power of the line, which is equal to:

$$Q_1 = -U_1^2 tg(\lambda) / Z_C. \tag{3.27}$$

Fig. 3.5 shows the dependence of the voltage at the end of the line and the reactive power at the beginning of the line depending on the parameter λ in idle mode for two cases - the ideal line U_2, Q_1 and the real line U_2^P, Q_1^P.

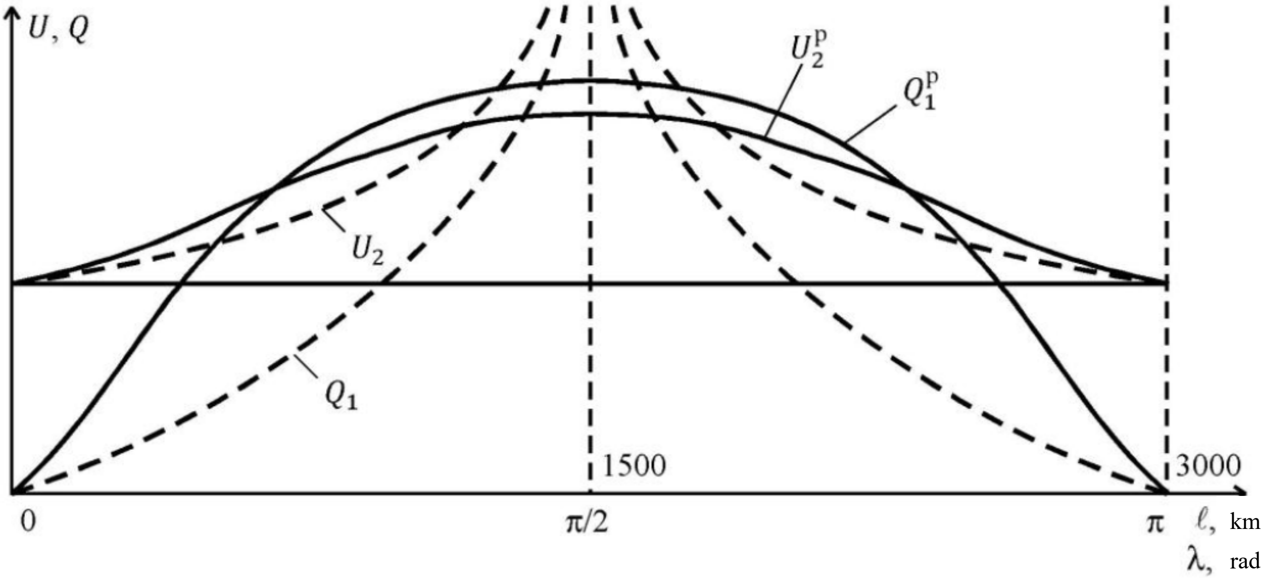


Fig. 3.5. Dependence of voltage and reactive power in idle mode

In the energy transfer mode, the quarter-wave line equations are as follows:

$$\begin{cases} \dot{U}_1 = j\dot{I}_2 sin(\lambda) Z_C; \\ \dot{I}_1 = j\dot{U}_2 sin(\lambda) / Z_C. \end{cases} \tag{3.28}$$

That is, the voltage at the end of the line U_2 does not depend on the voltage of its beginning U_1, and the load current I_2 does not depend on the current of the generator I_1. Moreover, changing the load resistance at the end of the line Z_C without changing the voltage at the end of the line U_2 can be done only due to the load current I_2, which in turn will change the voltage at the beginning of the line U_1. Since the range of voltage change at the beginning of the line is usually 10%, the possibilities for regulating the power of the line are small.

A half wave line

LDTL half-wavelengths theoretically have unlimited bandwidth and do not have the disadvantages inherent in LDTL quarter-wavelength. The following relations are valid in such lines:

$$\dot{I}_1 = -\dot{I}_2; \; \dot{U}_1 = -\dot{U}_2. \tag{3.29}$$

Therefore, in any mode, even in idle mode, the current and voltage at the beginning of the line are shifted relative to the current and voltage at the end of the line by 180°. The voltage U_{CP} and the current I_{CP} in the middle of the line is calculated taking into account that for this point the parameter λ = π / 2:

$$\dot{U}_{CP} = jZ_C \dot{I}_2; \; \dot{I}_{CP} = j\dot{I}_{HT}. \tag{3.30}$$

The values of current and voltage along the line in different modes are shown in Fig. 3.6.

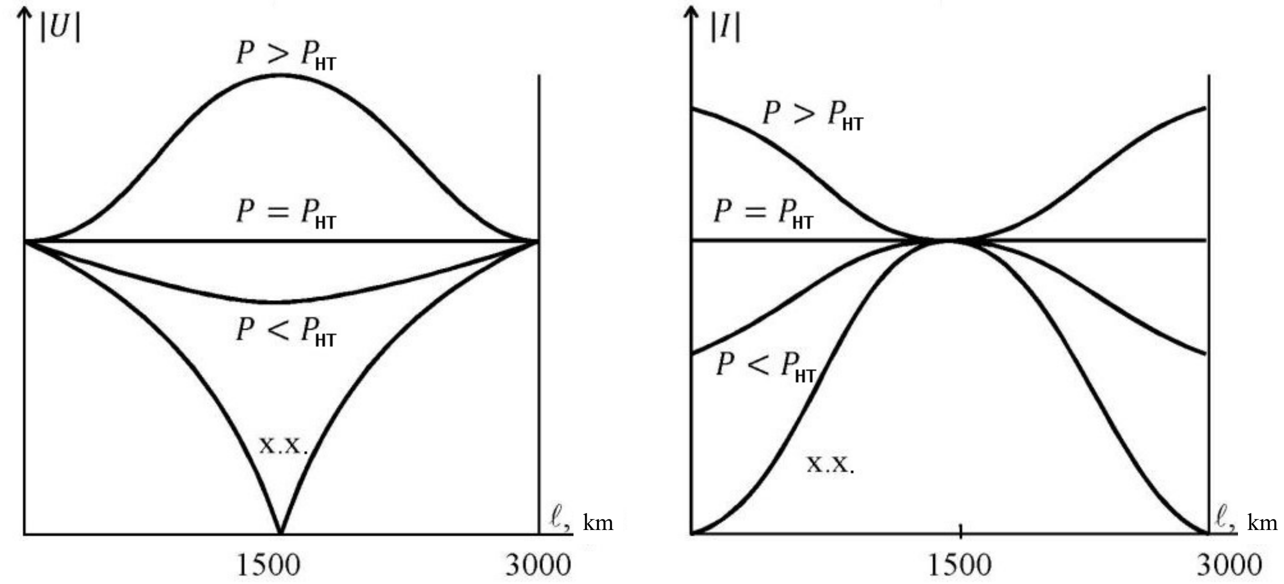


Fig. 3.6. Values of current and voltage in the middle of the line in different operating modes

From Fig. 3.6 it can be concluded that the idling mode has no negative consequences for the equipment of the half-wave line. In power transfer mode, the amount of power is not limited by the line itself. For clarity, consider the example of the power supply system, the replacement scheme of which is shown in Fig. 3.7.

Fig. 3.7. Power supply system replacement scheme

According to the substitution scheme shown in Fig. 3.7, the system contains:

- generator with output voltage E and reactance X_1;
- a line half a wavelength, the input voltage of which is equal to U_1, the output - U_2;
- receiving substation with resistance X_2, the output voltage of which is maintained at the level of U_C.

In the vector diagram shown in Fig. 3.8, shows the phase shift between currents and voltages of the power supply system. According to the vector diagram, we compose an equation that connects the voltage of the generator E and the voltage at the output of the receiving substation U_C:

$$\dot{E} = -\dot{U}_C - j\dot{I}_2(\dot{X}_1 + \dot{X}_2). \tag{3.31}$$

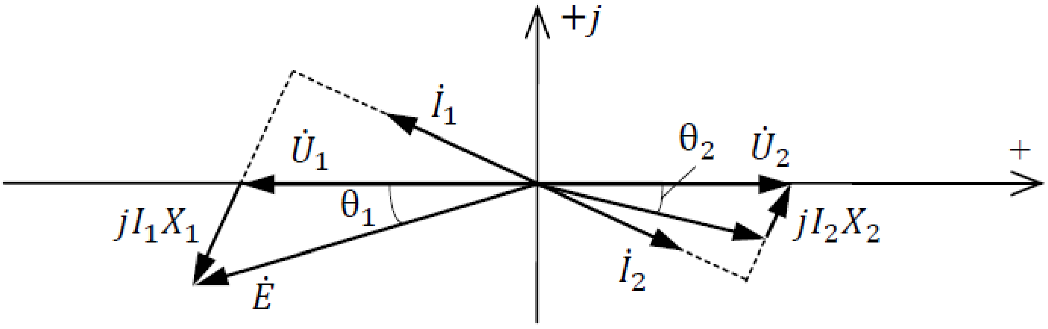


Fig. 3.8. Vector diagram of currents and voltages of the power supply system

From formula (3.31) express the current at the end of the line:

$$\dot{I}_2 = j(\dot{E}+\dot{U}_C)/(\dot{X}_1+\dot{X}_2). \tag{3.32}$$

The active power *P* at the output of the receiving substation is equal:

$$P = \mathrm{Re}(\dot{S}) = \mathrm{Re}(I_2\dot{U}_C) = \mathrm{Re}(j(E\dot{U}_C+\dot{U}_C^2)/(\dot{X}_1+\dot{X}_2)). \tag{3.33}$$

Taking into account that $\overset{*}{E} = -E\cos(\theta_1) + jE\sin(\theta_1)$ i $\dot{U}_C = U_C\cos(\theta_2) - jU_C\sin(\theta_2)$, we get:

$$P = EU_C(\sin(\theta_1)\cos(\theta_2)+\sin(\theta_2)\cos(\theta_1))/(X_1+X_2) = EU_C\sin(\theta_1+\theta_2)/(X_1+X_2). \tag{3.34}$$

A similar result can be obtained for the power supply system without taking into account the power line, the substitution scheme of which is shown in Fig. 3.9.

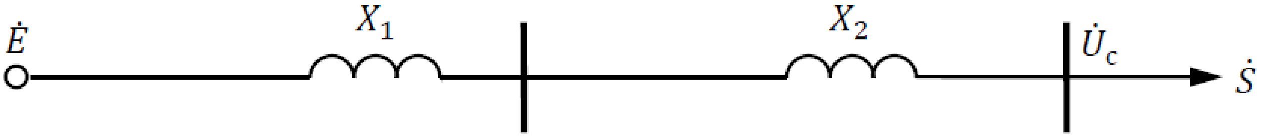


Fig. 3.9. Power supply system replacement scheme

The obtained result testifies to the absence of influence of the power line on the power transmitted by it. The parameters of power lines affect the parameters of electricity quality, which are regulated by state standards, so electricity suppliers must control the modes of operation of the system in accordance with this standard.

Task solution examples

Task № 1

A voltage source $u_1(t) = 500\sin(1000t)$ is connected at the input of the cable line $l = 55.5$ km long. Current at the input of the line at short circuit $i_{sc} = 1\cdot\sin(1000t + 21.5°)$, and at idle - $i_{id} = 1\cdot\sin(1000t + 68.5°)$. Calculate the primary parameters of the line, as well as the instantaneous values of currents and voltages at the end of the line at the agreed load. It is known that the line length l is less than half the wavelength λ, $l < \lambda / 2$.

Solution:

Line input resistance in case of short circuit, Z_{sc}:

$$Z_{sc} = \dot{l} \quad {}^{0^\circ}_{5^\circ} - 500e^{-j21.5^\circ} \text{ Ohm.}$$

Input line resistance at idle, $Z_{кз}$:

$$Z_{id} = \dot{l} \quad {}^{0^\circ}_{5^\circ} - 500e^{-j68.5^\circ} \text{ Ohm.}$$

Secondary line parameters are calculated by formulas:

- impedance Z_c:

$$Z_c = \sqrt{Z_{id} Z_{sc}} = 500e^{-j45^\circ} \text{ Ohm;}$$

- propagation coefficient γ:

$$th(\gamma \cdot l) = \sqrt{\frac{Z_{sc}}{Z_{id}}} = e^{j23.5^\circ}.$$

Because

$$th(\gamma l) = \frac{e^{\gamma l} - e^{-\gamma l}}{e^{\gamma l} - e^{-\gamma l}} \Rightarrow e^{2\gamma l} = \frac{1 + th(\gamma l)}{1 - th(\gamma l)} = 4.74e^{j(90^\circ \ldots)}.$$

the damping coefficient α is calculated by the formula:

$$\alpha = \frac{\ln(4.74)}{2l} = 1.41 \cdot 10^{-2} \text{ Np/km,}$$

phase coefficient β:

$$\beta = \frac{90^\circ \ldots n}{2l} = 1.41 \cdot 10^{-2} \text{ rad/km.}$$

Primary parameters of the line:

$$\begin{cases} R_0 + j\omega L_0 = \gamma Z_C = 10 \text{ Ohm/km;} \\ G_0 + j\omega C_0 = \gamma / Z_C = j40 \cdot 10^{-6} \text{ Sm/km.} \end{cases}$$

Thus, R_0 = 10 Ohm/km; L_0 =0; G_0 = 0; C_0 = 40 nF.

Instantaneous values of voltage and current on the load in the agreed mode:

$$u_2(t) = U_{1m} e^{-\alpha l} \sin(\omega t - \beta l) = 229.36 \sin(\omega t - 45^\circ, \ . ,$$

$$i_2(t) = \frac{U_{1m}}{|Z_c|} e^{-\alpha l} \sin(\omega t - \beta l + 45^\circ, \quad .46 \sin(\omega t) \text{ A.}$$

Answer: R_0 = 10 Ohm/km; L_0 =0; G_0 = 0; C_0 = 40 nF;

$$u_2(t) = U_{1m} e^{-\alpha l} \sin(\omega t - \beta l) = 229.36 \sin(\omega t - 45^\circ, \ . ,$$

$$i_2(t) = \frac{U_{1m}}{|Z_c|} e^{-\alpha l} \sin(\omega t - \beta l + 45^\circ, \quad .46 \sin(\omega t) \text{ A.}$$

Task № 2

Calculate the line input resistance without loss and the load resistance, if the reflection coefficient from the beginning of the line $n_1 = -e^{j45^\circ}/3$, the line length $l = 9\lambda/16$ and the wave resistance Z_c = 400 Ohm are known.

Solution:

Input impedance of the line Z_1 is calculated by formula:

$$Z_1 = \frac{\dot{\iota}}{\dot{}} \qquad \frac{n_1}{n_1} = 556 - j295 \text{ Ohm.}$$

Express the reflection coefficient from the end of the line n_2 through n_1:

$$n_2 = \frac{\dot{\iota}}{\dot{\iota}} \qquad \dot{} \qquad n_1 e^{j2\beta l}.$$

Expression 2βl is calculated by formula:

$$2\beta l = 2 \frac{2\pi}{\lambda} \frac{9\lambda}{16} = \frac{\pi}{4}.$$

Hence,

$$n_2 = n_1 e^{j\pi/4} = \frac{1}{3}.$$

Therefore, load resistance Z_l equals:

$$Z_l = Z_c \frac{1 + n_2}{1 - n_2} = 800 \text{ Ohm.}$$

Answer: Z_1 = 556 - j295 Ohm; Z_l = 800 Ohm.

Tasks for themselves solving

Task № 1

For cable lines due to the close location of the conductors in the low frequency range (300-6000 Hz) the inductive resistance ωL_0 is much lower than the resistivity R_0, $\omega L_0 << R_0$, and the capacitive conductivity ωC_0 is much higher than the active conductivity G_0, $\omega C_0 << G_0$. Therefore, in the specified frequency range we can assume that $L_0 \approx 0$, $G_0 \approx 0$. Given the simplifications, calculate the phase coefficient β of the cable line at a frequency f = 1000 Hz, if the attenuation coefficient α = 6·10-2 Np / km. And also determine the coefficient of propagation γ at a frequency f = 4000 Hz.

Task № 2

The cable line has the following primary parameters: R_0= 40 Ohm/km, $G_0 \approx 0$, $L_0 \approx 0$, $C_0 = 50 \cdot 10^{-9}$ F/km. In the coordinated mode at the frequency ω = 1000 rad/s the active power P_1 = 100 W is selected from the source, and at the load the power P_2 = 6 W is dissipated. Calculate the length of the line l, currents and voltages at the input and output of the line I_1, U_1, I_2, U_2, as well as the phase shift between the input and output voltages.

Task № 3

At the input of the cable line with the primary parameters: R_0 = 20 Ohm/km, $G_0 = 0.5 \cdot 10^{-6}$ Sm / km, L_0 = 2·10-3 H / km, $C_0 = 40 \cdot 10^{-9}$ F / km voltage $u_1(t)$ = 500·sin(5000t) is supplied, line length l = 50 km. Assuming that the line operates in a coordinated mode, calculate the active power P_2 dissipated in the load and the power loss P_{loss}, as well as the energy transfer efficiency of the line η. How will the values of the parameters P_2, P_{loss}, η change after connecting the additional inductance line length for each kilometer to achieve the transmission mode without distortion?

Task № 4

At the input of a homogeneous line with parameters R_0 = 5 Ohm / km, G_0 = $1.5 \cdot 10^{-6}$ Sm/km, $L_0 = 2 \cdot 10^{-3}$ H/km, $C_0 = 40 \cdot 10^{-9}$ F/km and length $l = \lambda$ voltage source $u_1(t) = 200 \cdot \sin(6000t)$ is connected. The line operates in a coordinated mode. Calculate the instantaneous values of current and voltage at the output i_2, u_2 and the current at the input of the line i_1 also the phase shift between the input and output voltage. Plot graphs of voltage distribution along the line for time points: $t_1 = 0$, $t_2 = \pi/4\omega$, $t_3 = \pi/2\omega$, $t_4 = \pi/\omega$.

Task № 5

A voltage source $u_1(t) = 200 \cdot \sin(100t)$ is connected to the input of the lossless line with parameters $L_0 = 2 \cdot 10^{-3}$ H/km, $C_0 = 10 \cdot 10^{-9}$ F/km with length l = 100 km. By the end of the line, three types of loads are connected: 1) coordinated; 2) short circuit; 3) idling. For these loads, determine the wave resistance Z_c and wavelength λ, write the expressions of the instantaneous values of currents and voltages i_2, u_2 of load.

Task № 6

A voltage source $u_1(t) = 200 \cdot \sin(100t)$ is connceted to the input of the lossless line with parameters $L_0 = 4 \cdot 10^{-3}$ H/km, $C_0 = 5 \cdot 10^{-9}$ F/km with length l = 100 km. By the end of the line, three types of loads are connected: 1) coordinated; 2) short circuit; 3) idling. Determine how many times the voltage amplitude at the end of the line will change if the frequency of the voltage source has changed by 3%.

Task № 7

The input resistance of the line length l = 62.5 km with a wave resistance Z_c = 500 Ohm is Z_1 = j100 Ohm. Wavelength λ = 6000 km. Determine the modulus and type of the load resistance.

Practice lesson № 4. Quality standards of electric energy parameters

Theory

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 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. 4.1.

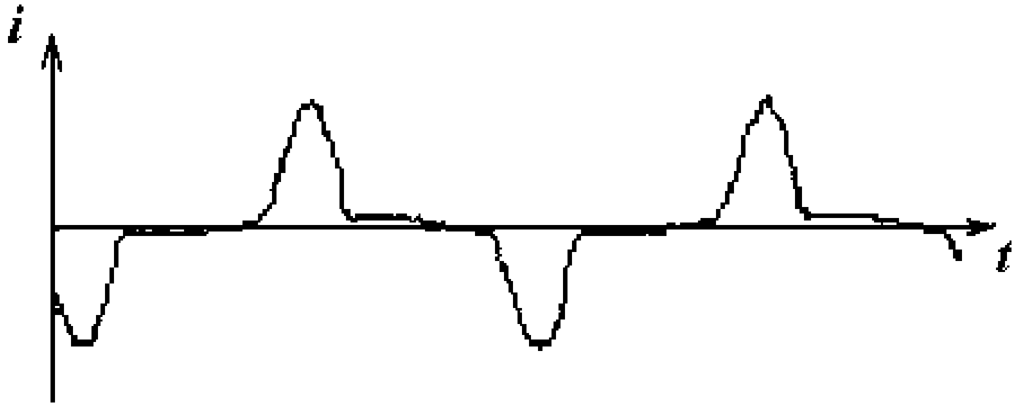


Fig. 4.1. The form of the input current of the pulse converter with the input capacitive filter

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. 4.2.

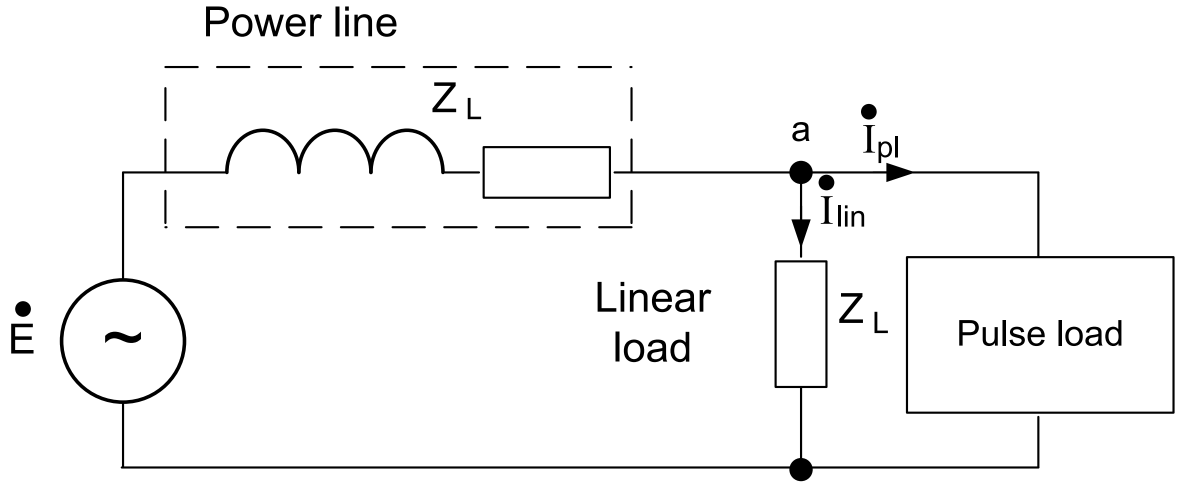


Fig. 4.2. Model of AC power supply system with nonlinear load

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:

$$\Delta\dot{U} = \dot{I}_{lin} X_L . \qquad (4.1)$$

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:

$$\Delta\dot{U}_n = \dot{I}_{imp(n)}(jn\omega L + R_L), \qquad (4.2)$$

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

From the analysis of (4.2) 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:

$$I_0 = 3\sqrt{I_3^2 + I_9^2 + I_{15}^2 + \ldots}\,. \qquad (4.3)$$

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.

The list of parameters of quality of the electric power which are influenced by the maintenance of higher harmonics is resulted in tab. 4.1.

Table 4.1. Electricity quality parameters

Quality parameters	Calculation formula
1. RMS value, Y	$Y = \sqrt{\frac{1}{T}\int_0^T y(t)^2 dt} = \sqrt{\sum_{k=0}^{\infty} Y_i^2}$, where Y_k – harmonic k RMS value
2. Mean value, Y_d	$Y_d = \frac{1}{T}\int_0^T \lvert y(t)\rvert dt$ - for AC current $Y_d = \frac{1}{T}\int_0^T y(t)dt = Y_0$ - for DC current
3. Shape factor, K_f	$K_f = \frac{Y}{Y_d}$
4. Amplitude factor, K_{Am}	$K_{Am} = \frac{Y_{\max}}{Y}$, where $Y_{\max} = \max\lvert y(t)\rvert$
5. Non- sinusoidality factor, K_H	$K_H = \frac{Y_1}{Y}$, where Y_1 is first harmonic RMS value
6. Total harmonic distortion, K_{HC}, (THD)	$THD = K_{HC} = \frac{\sqrt{Y^2 - Y_1^2}}{Y_1}$
7. Total interharmonic distortion, $TIHD$	$TIHD = \frac{\sqrt{\sum_{k\in\Lambda} Y_k^2}}{Y_1}$, Λ is set of interharmonic
8. Harmonic factor, K_G	$K_G = \frac{\sqrt{Y^2 - Y_1^2}}{Y}$
9. Coefficient of relative content of harmonics, K_{Bn}	$K_{Bn} = \frac{Y_n}{Y_1}$, where Y_n is harmonic n RMS value
10. Rejection factor, K_{Rn}	$K_{Rn} = n^2 \frac{Y_1}{Y_n}$
13. Harmonic n ripple factor, K_{Rpn}	$K_{Rpn} = \frac{Y_n}{Y_d}$
14. Instability, δ_H	$\delta_H = \frac{Y_{d\max} - Y_{d\min}}{Y_{dnom}}$, wher $Y_{d\max}$, $Y_{d\min}$, Y_{dnom} are maximum, minimum and nominal average values for a certain time T

Task solution examples

Task № 1

Rectangular current with a phase shift of + 30 ° and an amplitude of 10 A is consumed from the 220 V, 50 Hz AC network. Calculate the power factor χ of the consumer that consumes the current.

Solution:

Since the current has a non-sinusoidal shape and contains higher harmonics, its power factor is calculated by the formula:

$$\chi = \frac{I_{in1}\cos(\varphi)}{I_{in}},$$

where I_{in1} is RMS value of current first harmonic, φ is shift angle between input voltage and current first harmonic, I_{in} is RMS value of non-sinusoidal current.

Since the current has a rectangular shape, its effective value is calculated by the following formula:

$$I_{in} = \sqrt{\frac{2}{T}\int_{0}^{T/2} i(t)^2\,dt} = \sqrt{\frac{2}{T}\int_{0}^{T/2} 10^2\,dt} = 10\text{ A}.$$

The rectangular signal is decomposed into a Fourier series as follows:

$$i_{in}(t) = I_{max}\frac{4}{\pi}\sum_{n=1}^{\infty}\frac{\sin(2\pi(2n-1)ft)}{2n-1}.$$

Hence,

$$I_{in1} = \frac{4}{\pi}\frac{I_{max}}{\sqrt{2}} = \frac{40}{\pi\sqrt{2}};$$

$$\chi = \frac{I_{in1}\cos(\varphi)}{I_{in}} = \frac{40\cos(30°)}{10\pi\sqrt{2}} = 0.78.$$

Answer: $\chi = 0.78$.

Tasks for themselves solving

Task № 1

A bridge rectifier with an inductive filter (the inductance of the filter goes to infinity) and an active load *R* = 50 Ohm is connected to the 220 V, 50 Hz AC network.

The equivalent circuit of the power line consists of inductance L_M = 10 mH and resistance R_M = 0.3 Ohm. Calculate the first 30 non-zero harmonics of the mains voltage at the point of load connection and plot it.

Task № 2

A bridge rectifier with a capacitive filter C = 200 μF and an active load R = 50 Ohm is connected to the 220 V, 50 Hz AC mains. The equivalent circuit of the power line consists of inductance L_M = 10 mH and resistance R_M = 0.3 Ohm. Calculate the first 30 non-zero harmonics of the mains voltage at the point of load connection and plot it.

Calculate the current of a rectifier with a capacitive filter use the book:

В. Мелешин. Транзисторная преобразовательная техника, розділ 10.6.

Task № 3

A rectangular current with a phase shift of + 20 °, a pulse filling factor $\gamma = 0.8$ and an amplitude of 5 A is consumed from the 220 V, 50 Hz AC network. Calculate the power factor χ of the consumer consuming the current.

Task № 4

A triangular current with a phase shift of + 15 ° and an amplitude of 15 A is consumed from the 220 V and 50 Hz AC mains. Calculate the power factor χ of the consumer that consumes the current.

Task № 5

From the AC mains 220 V, 50 Hz with equivalent active-inductive resistance R = 0.2 Ohm, L = 1 mH is consumed current containing higher harmonics: the fifth - with an amplitude of 7 A, the seventh - with an amplitude of 5 A, and the eleventh - with an amplitude of 2 A. Calculate the coefficient of nonlinear voltage distortion at the point of connection of consumers.

Task № 6

Calculate the voltage drop on a zero wire with a resistance of 1 ohm, three-phase symmetric system, the load of each of which consumes a rectangular current with an amplitude of 10 A (take into account the values of the first 50 harmonics).

Practice lesson № 5. Reactive power compensators

Theory

In general, reactive power sources (RPS) is a multifunctional device and 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.

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).

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 $0{,}95U_{\text{nom}} \le U_{\text{G}} \le 1{,}05U_{\text{nom}}$. The generator voltage is maintained at a given level if the reactive power generation is within $Q_{\min} \le Q_{\text{G}} \le Q_{\max}$. 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.

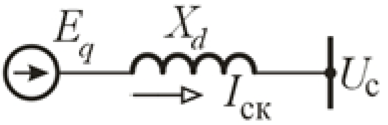


Fig. 5.1. The substitution scheme of the SC

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

$$Q = (E_q - U_{ph})U_{ph} / X_d. \tag{5.1}$$

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:

$$Q_{CB} = 3\omega C_{CB} U_{ph}^2. \tag{5.2}$$

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

$$Q^{/} = Q - Q_{CB}. \qquad (5.3)$$

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

$$P_{CB} = Q_{CB} \cdot tg\delta, \qquad (5.4)$$

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. 5.2 shows a stepwise increase in the generated power with a decrease in the voltage of the CB from three sections.

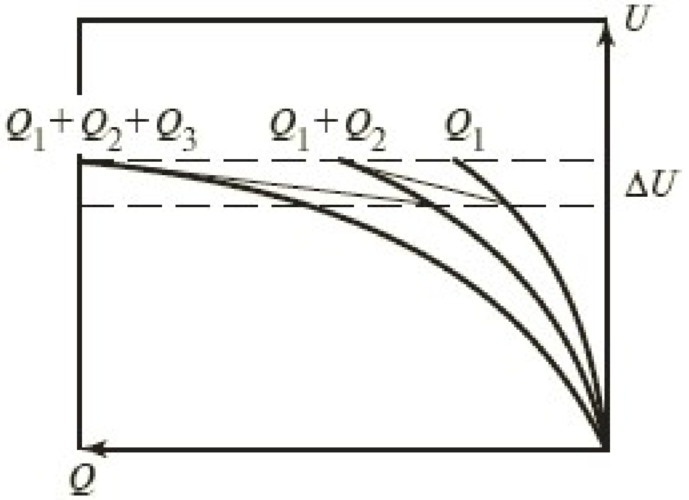


Fig. 5.2. Stepwise increase of the generated power of CB from three sections

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.

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.

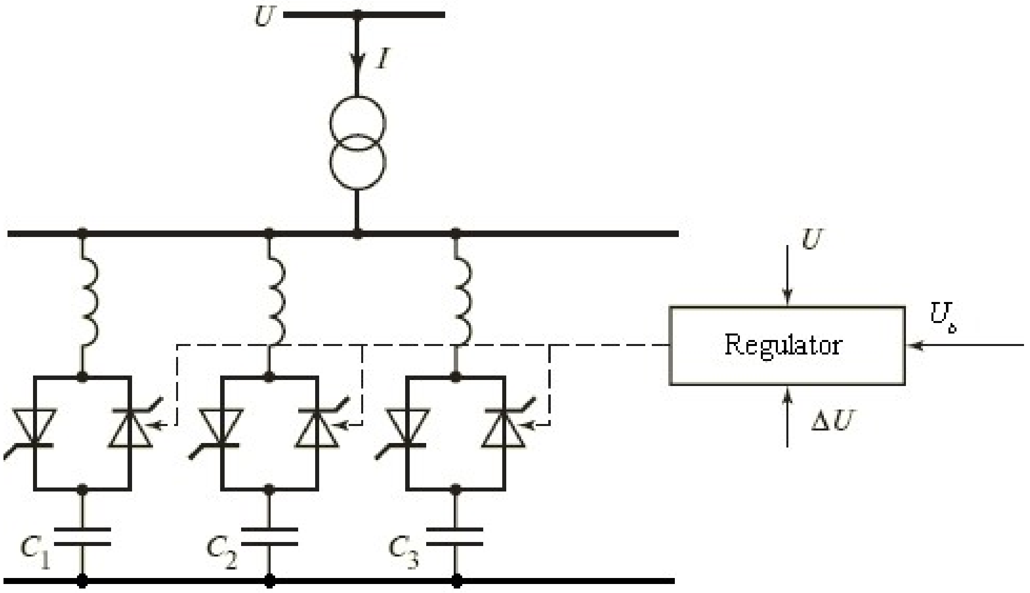
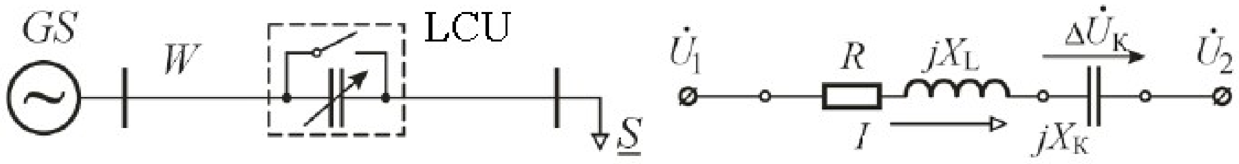


Fig. 5.3. Scheme of static thyristor compensator

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. 5.4.



a) switching scheme; b) substitution scheme

Fig. 5.4. 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

Capacity 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:

$$X_{LCU} < X_L, \tag{5.5}$$

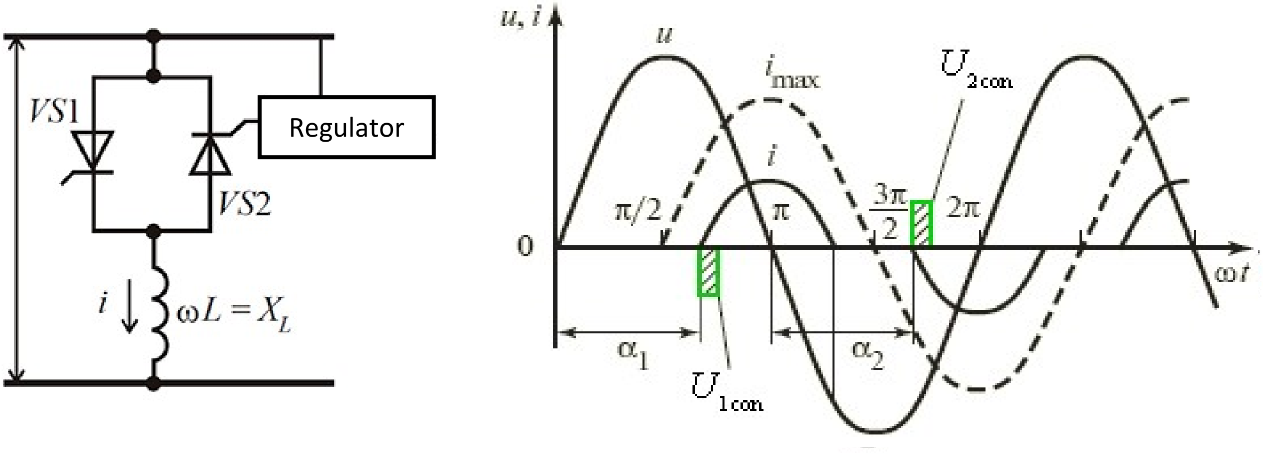
where X_L is the inductive resistance of the line.

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

The reactors operate in a linear mode, so do not create higher current harmonics. Reactor losses are 0.2-0.4% of rated capacity.

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 α = π / 2 only reactive power is consumed from the network, the current through the reactor has a sinusoidal shape, if α > π / 2 the reactive power consumed decreases, the current loses its sinusoidal shape, Fig. 5.5.



a) b)

Fig. 5.5. Reactive power compensator based on reactor:
a) electric scheme; b) timing diagrams

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

$$I_{(1)} \Big/ I_L = \frac{1}{\pi}\left(2(\pi-\alpha)+\sin 2\alpha\right). \qquad (5.6)$$

The static characteristic of the reactor depending on the value of the first harmonic $I_{(1)}$ is shown in Fig. 5.6.

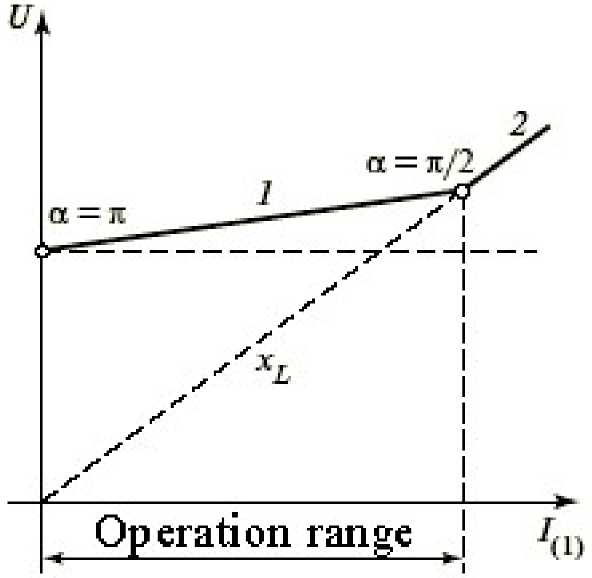


Рис. 5.6. Static characteristics of the STC reactor

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 STATCOM 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 STATCOM is shown in fig. 5.7.

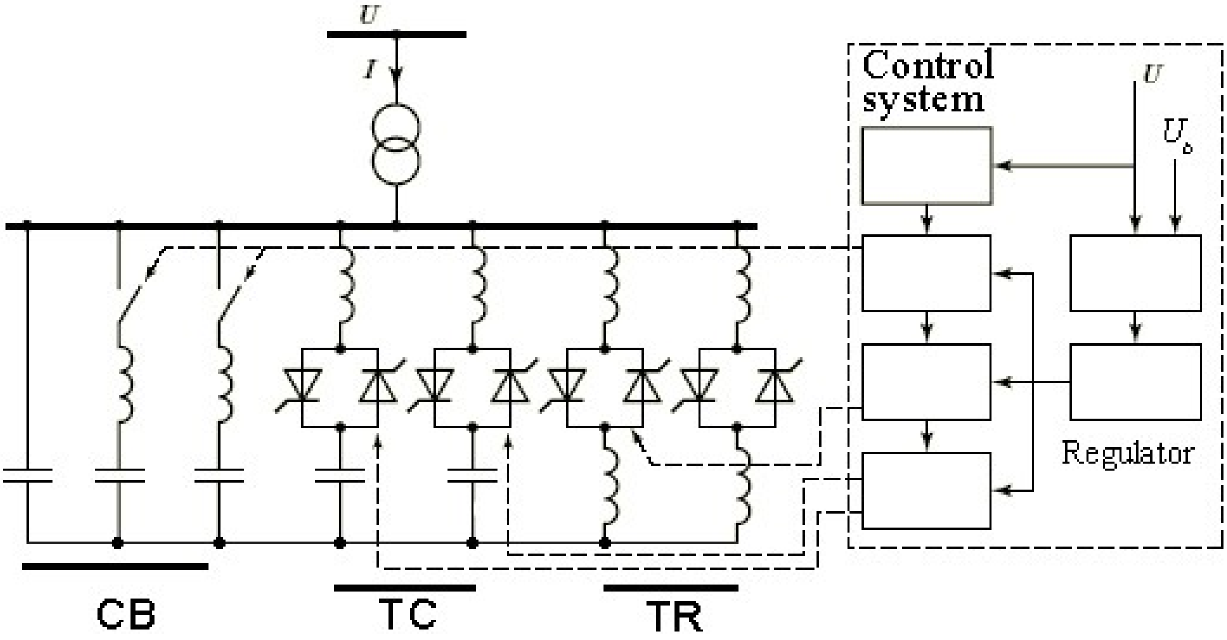


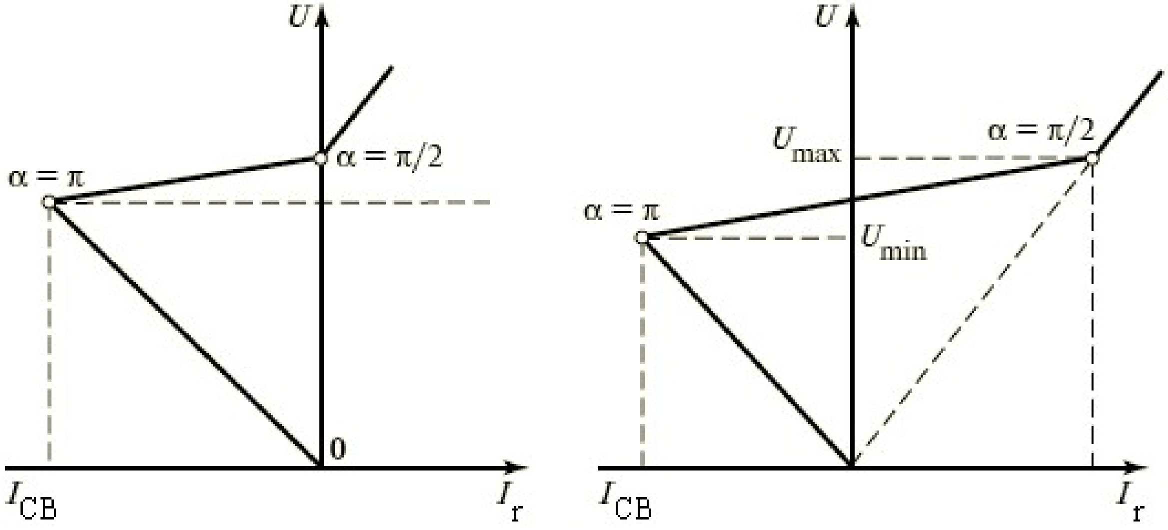
Fig. 5.7. The structure of the compensator STATKOM

As can be seen from Fig. 5.7, 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. 5.8 a).

2. $Q_{CB} = Q_P$. 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 shown in fig. 5.8 b).



a) b)

Fig. 5.8. Static characteristics of STATCOM

In practice, the STATCOM compensator contains a multi-section capacitor battery CB and thyristor-reactor section TR or thyristor-capacitor TC and thyristor-reactor section TR, Fig. 5.7.

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 principle of voltage formation of the converter with PWM is shown in Fig. 5.9.

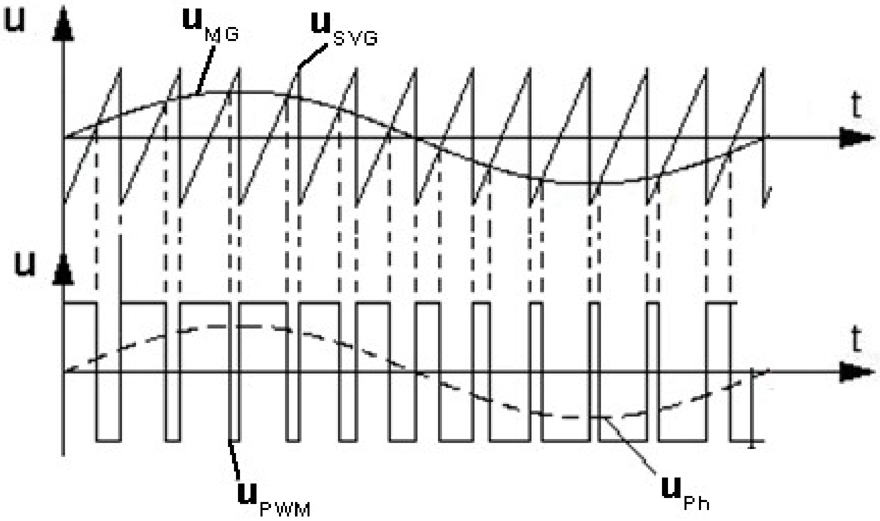


Fig. 5.9. The principle of voltage generation of the converter with PWM

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}.

Task solution examples

Task № 1

Three consumers are connected to the network: P_1= 8 kW, cos(φ_1) = 0.33, P_2 = 4 kW, cos(φ_2)= 0.65, P_3 = 15 kW, cos(φ_3) = 0.4. All loads are inductive. The voltage at the point of connection of consumers is U = 220 V. Determine the voltage of the generator, if the resistance of the line is Z = 0.1 + j0.02 Ohm. Assuming that the resistance of the generator is constant, calculate the power consumed by the generator after reactive power compensation.

Solution:

Set the voltage phase at the point of connection of consumers to zero:

$$U = 220e^{j0^\circ}\ V;$$

Find the current values of the currents of all 3 parallel loads:

$$I_1 = \frac{S_1}{U} = \frac{P_1}{\cos(\varphi_1)U} = \frac{8000}{0.33 * 220} = 109.08\text{ A};$$

$$I_2 = \frac{S_2}{U} = \frac{P_2}{\cos(\varphi_2)U} = \frac{4000}{0.65 * 220} = 27.97\text{ A};$$

$$I_3 = \frac{S_3}{U} = \frac{P_3}{\cos(\varphi_3)U} = \frac{15000}{0.4 * 220} = 170.45\text{ A}.$$

Now, starting from the initial phase U, you can find the phase currents through all loads. Assume that all loads are inductive (eg electric motors). Therefore, the current will lag behind the voltage:

$$\varphi_1 = 0 - \arccos(0.33) = -70.7°;$$

$$\varphi_2 = 0 - \arccos(0.65) = -49.5°;$$

$$\varphi_3 = 0 - \arccos(0.4) = -66.4°.$$

Hence,

$$\dot{I}_1 = 109.08e^{-j70.7°} = 36.06 - j102.96\text{ A};$$

$$\dot{I}_2 = 27.97e^{-j49.5°} = 18.17 - j21.26\text{ A};$$

$$\dot{I}_3 = 170.45e^{-j66.4°} = 68.25 - j156.2 \text{ A.}$$

Total power network current:

$$\dot{I}_z = \dot{I}_1 + \dot{I}_2 + \dot{I}_3 = 36.06 - j102.96 + 18.17 - j21.26 + 68.25 - j156.2 =$$

$$= 122.48 - j280.42 \text{ A.}$$

Then find the voltage drop across the resistance Z of the line:

$$\dot{U}_z = \dot{I}_z Z = (122.48 - j280.42)(0.1 + j0.02) = 17.86 - j25.6\, V.$$

Generator voltage:

$$\dot{U}_g = \dot{U}_z + \dot{U} = 17.86 - j25.6 + 220 = 237.86 - j25.6 \text{ V.}$$

Generator power:

$$\dot{S} = \dot{U}_g I_z^* = (237.86 - j25.6)(122.48 - j280.42) = 21.95 + j69.84 \text{ kVA.}$$

After reactive power compensation, the generator will give only active power:

$$P_g = Re(\dot{S}) = 21.95 \text{ kW.}$$

Answer: Generator voltage $\dot{U}_g = 237.86 - j25.6$ V**,** generator power after compensation $P_g = 21.95$ kW.

Tasks for themselves solving

Task № 1

Three consumers are connected to the network: S_1= 8 kVA, cos(φ_1) = 0.3 (capacitive load), S_2 = 4 kVA, cos(φ_2) = 0.65 (inductive load), S_3 = 10 kVA, cos(φ_3) = 0.4 (inductive load). All loads are inductive. The voltage at the point of connection of consumers is U = 220 V. Determine the voltage of the generator, if the resistance of the line is Z = 0.1 + j0.02 Ohm. Assuming that the resistance of the generator is constant, calculate the power consumed by the generator after reactive power compensation.

Task № 2

Calculate the parameters of the reactive power compensator STATCOM (capacitor capacity and reactor inductance), which operates at a voltage of 220 V ± 10%, 50 Hz and must ensure the generation of reactive power in the range of -1 MVAR..1 MVAR.

Task № 3

It is known that the AC mains 220 V ± 10%, 50 Hz can be connected in any order to consumers whose equivalent resistance varies in the range R = 1..10 Ohm, capacitance C = 10 μF .. 1 mF, inductance L = 1..100 μH. Calculate the parameters of the reactive power compensator, which completely eliminates the reactive power for any combination of values of R, C, L.

Task № 4

Calculate the number of sections of the capacitor bank and the capacity of each of them, designed to compensate for reactive power, the volume of which is Q = 1 kVAR ± 10%, if the current value of the mains voltage U varies in the range U = 200..300 V.

Task № 5

Calculate the inductance of the reactor connected to the network via a thyristor regulator, Fig.5.5 a), and the range of the control angle of the thyristors according to formula (5.6), if the amount of reactive power generated by the reactor varies in the range Q = 0.5… 2 kVAR ± 10%, and the effective value of the mains voltage is U = 380 V.

Practice lesson № 6. Passive and active filters of higher harmonics

Theory

Impact of power converters on power quality parameters of the power 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.

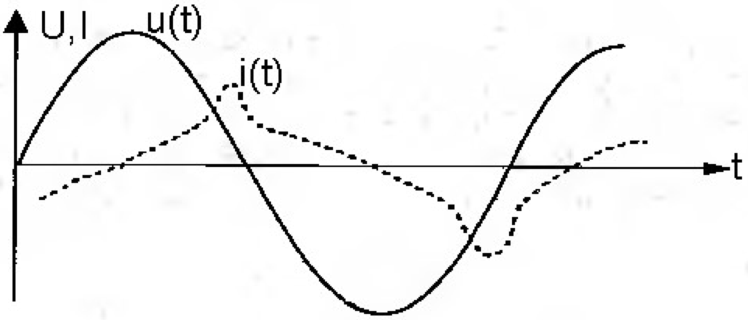


Fig. 6.1. The shape of the current at saturation of the transformer

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

Пасивні фільтри

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. 6.2.

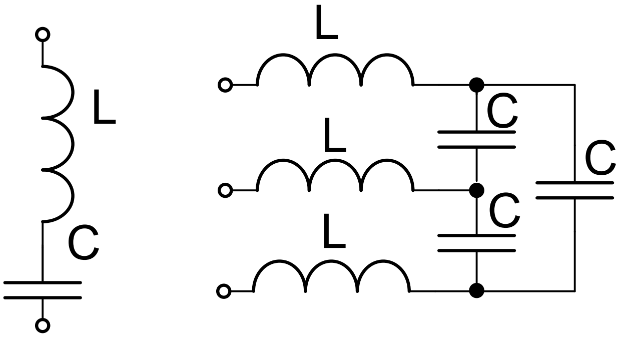


Fig. 6.2. Passive filters of higher harmonics

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. 6.3.

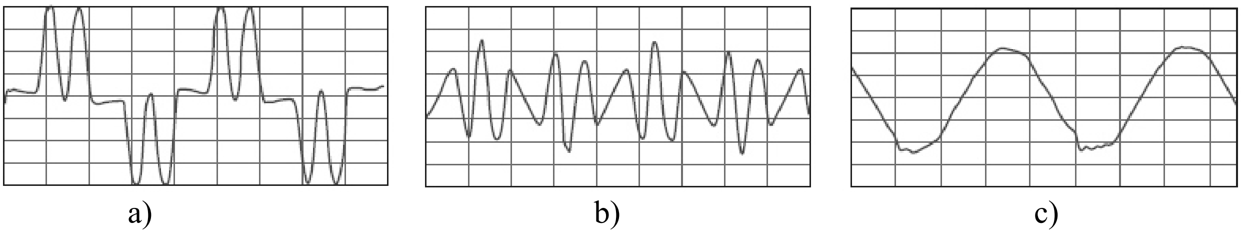
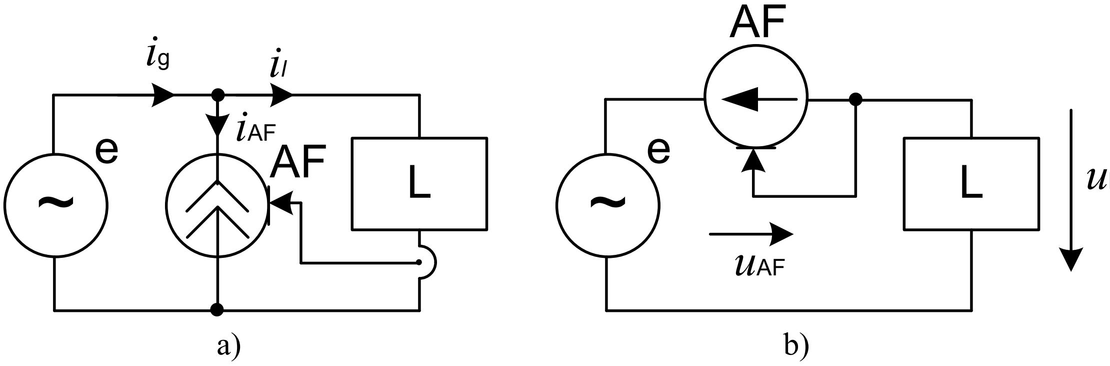

a) b) c)

Fig. 6.3. Diagrams of the active filter

In fig. 6.3 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. 6.4.



a) b)

Fig. 6.4. Functional connection diagrams of a) shunt AF and b) serial AF

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:

$$f_{PWM} = 2n_{\mathbf{max}} \cdot f_M, \tag{6.1}$$

where f_M is power network frequency.

Schemes of connection of AF to a network based on inverters are shown in Fig. 6.5 and 6.6.

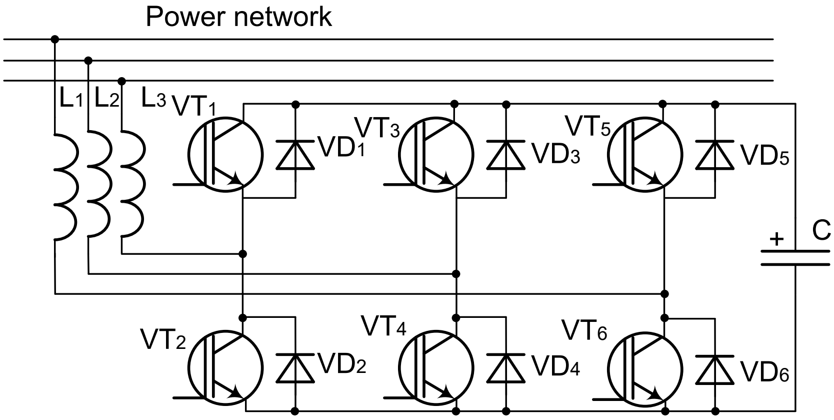


Fig. 6.5. Connection scheme of the parallel AF to power network

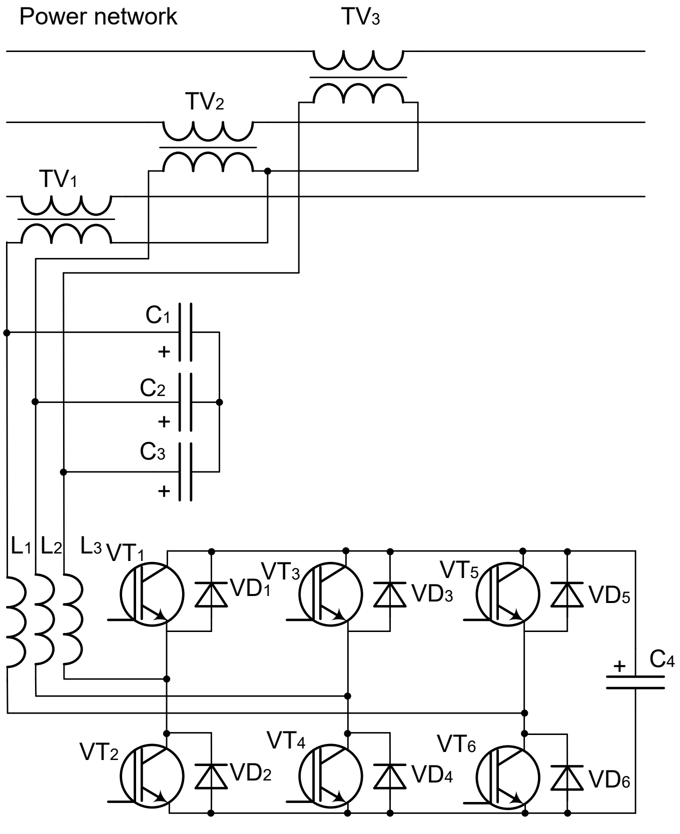


Fig. 6.6. The scheme of connection of serial AF to a network

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.

Task solution examples

Task № 1

From a single-phase AC network of 220 V, 50 Hz, a rectangular current with phase shift $\varphi_{sh} = 15°$ and amplitude $I_m = 5$ A is consumed. Calculate the shape of the current that should be generated by the parallel active filter to completely eliminate the reactive power and provide a sinusoidal shape of the power network current.

Solution:

The principle of operation of the active filter is the formation of current containing all the higher harmonics of the load current in antiphase, as well as the correction of the reactive power generated by the first harmonic current (in this case, complete elimination of reactive power).

First you need to get the current form of the active filter, which eliminates all the higher harmonics of the load current. To do this, find the first harmonic of the current signal, which is shown in Fig. 6.7.

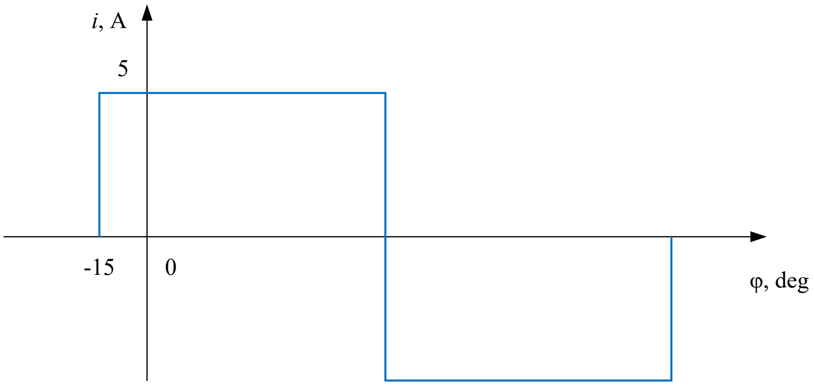


Fig. 6.7. Load current shape

To simplify, we find the amplitude of the first harmonic of the current without phase shift A_1. In this case, only the sine component will be in the row:

$$A_1 = \frac{2}{\pi}\int_0^{\pi} I_m \mathbf{sin}(\varphi)d\varphi = \frac{4I_m}{\pi}. \tag{6.2}$$

Therefore, the first harmonic of the current signal in the time domain i_1 is described by the formula:

$$i_1 = \frac{4I_m}{\pi}\mathbf{sin}\left(\varphi + \frac{\pi}{12}\right). \tag{6.3}$$

The current of the active filter i_{AF1}, which eliminates the higher harmonics of the load current i_L is described by the formula and shown in Fig. 6.8:

$$i_{AF1} = i_1 - i_L. \tag{6.4}$$

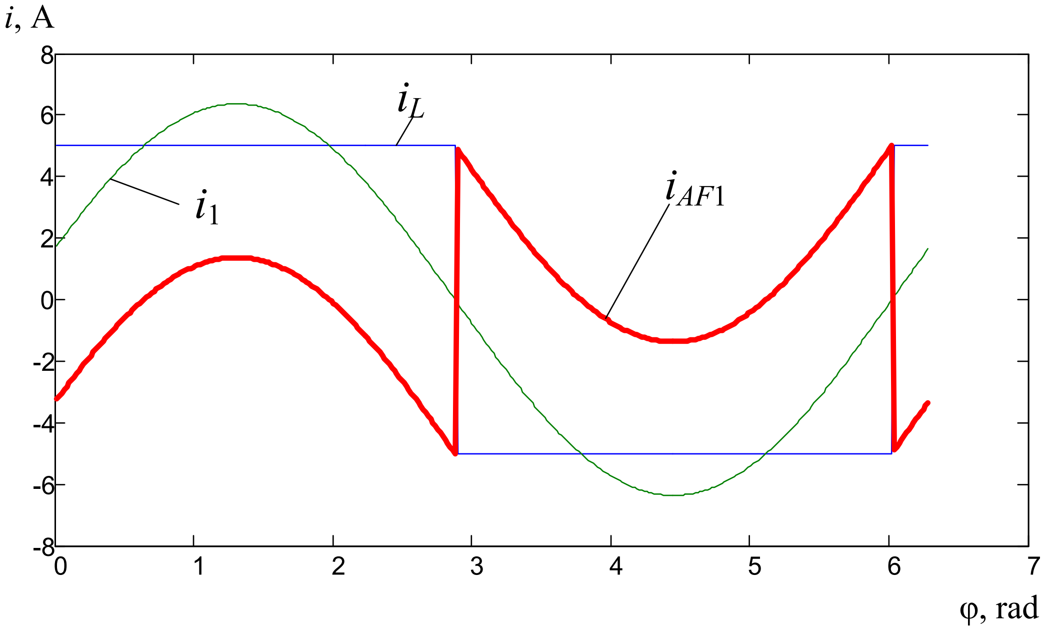


Fig. 6.8. The current shape of the active filter, designed to eliminate higher harmonics

To eliminate the reactive power of the first harmonic i_1, formula (6.3), it must contain only the sine component. To determine the cosine component, use the sine formula of the sum:

$$i_1 = i_{1\sin} + i_{1\cos} = \frac{4I_m}{\pi}\left(\mathbf{sin}(\varphi)\mathbf{cos}\left(\frac{\pi}{12}\right) + \mathbf{cos}(\varphi)\mathbf{sin}\left(\frac{\pi}{12}\right)\right). \tag{6.5}$$

Therefore, to eliminate the reactive power to the current of the active filter you need to add the second term of formula (6.5) with the sign "-", see Fig. 6.9:

$$i_{AF}=i_{AF1}+i_{AF2}=i_1-i_L-\frac{4I_m}{\pi}\mathbf{cos}(\varphi)\mathbf{sin}\left(\frac{\pi}{12}\right). \tag{6.6}$$

Then the in-phase current of sinusoidal form i_G will be consumed from the network, as shown in Fig. 6.9.

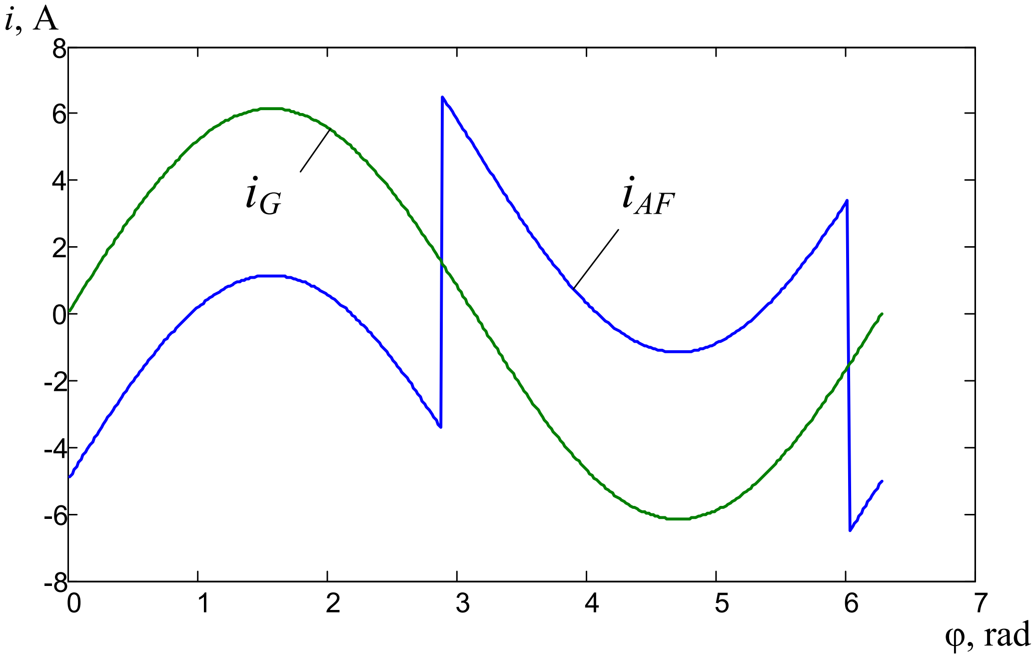


Fig. 6.9. Currents shape of active filter and power network

Answer: active filter current is defined by formula

$$i_{AF}=i_1-i_L-\frac{4I_m}{\pi}\mathbf{cos}(\varphi)\mathbf{sin}\left(\frac{\pi}{12}\right).$$

Task № 2

From a single-phase AC network of 220 V, 50 Hz is consumed a triangular current without phase shift and amplitude I_m = 10 A. Calculate the inductance L of the active filter, sufficient to generate current that compensates for distortion with current ripple δ_I, which is δ_I = 10% of amplitude value. The operating frequency of the active filter f = 50 kHz, the DC voltage source E connected to the input of the active filter has a value of E = 400 V.

Solution:

The shape of the load current is shown in Fig. 6.10.

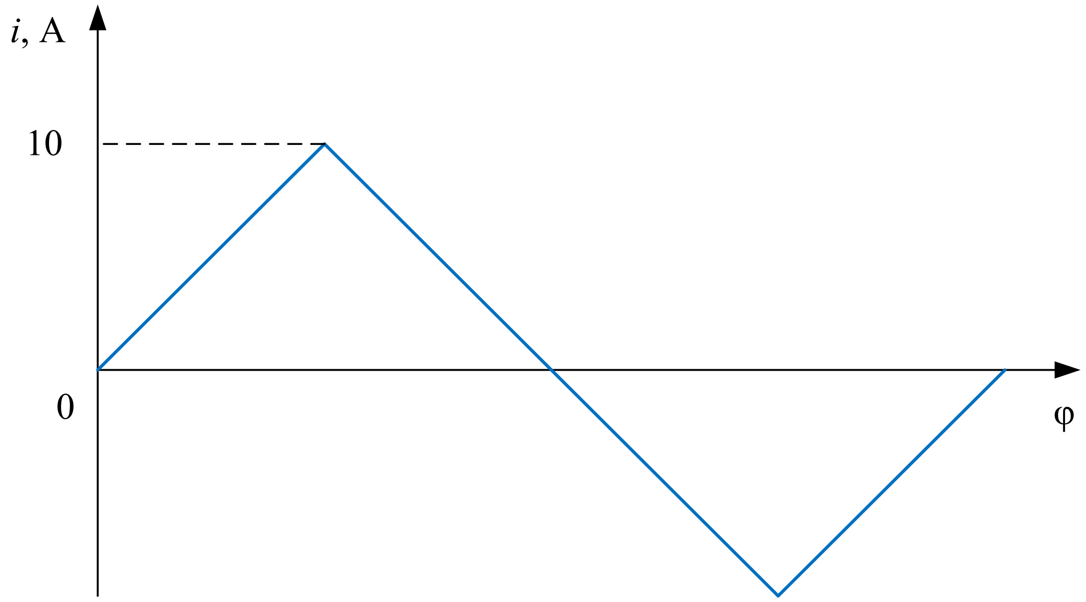


Fig. 6.10. The shape of the load current

Find the amplitude of the first harmonic of the current:

$$A_1 = \frac{4}{\pi}\int_0^{\frac{\pi}{2}} \frac{2\varphi I_m}{\pi}\mathbf{sin}(\varphi)d\varphi = \frac{8I_m}{\pi^2}. \tag{6.7}$$

The current form of the active filter is shown in Fig. 6.11.

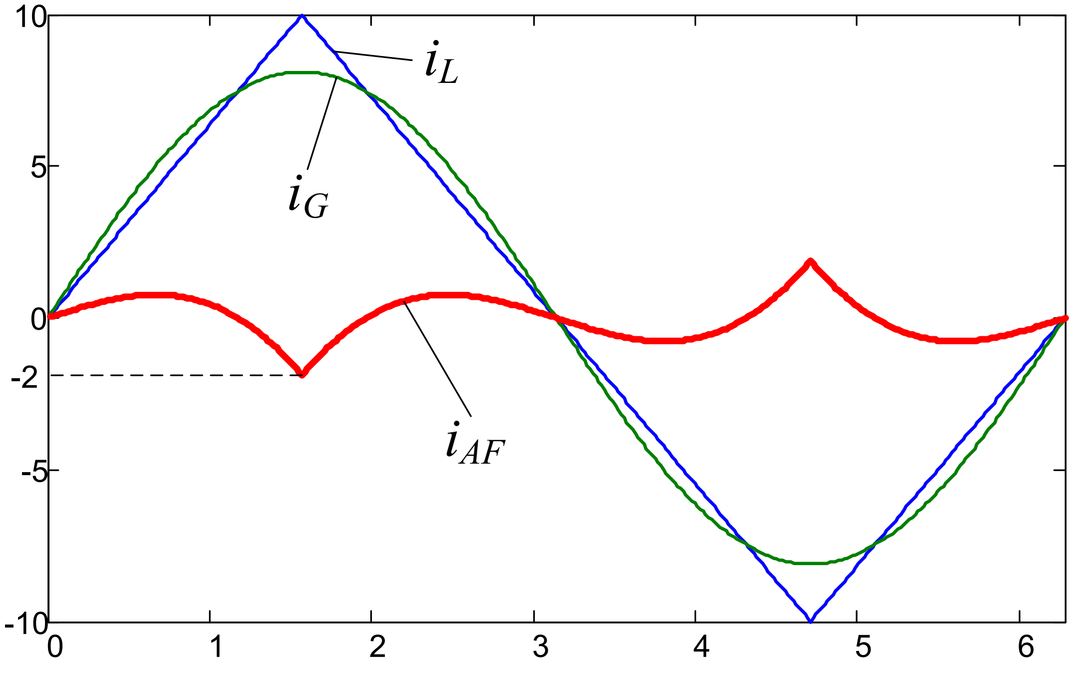


Fig. 6.11. The shape of the load current i_L, the active filter i_{AF} and the network i_G

According to Fig. 6.11 the maximum value of the current of the active filter is approximately 2 A, so the current ripple of the active filter is $\Delta I = 0.2$ A. The maximum current coincides with the maximum mains voltage $U_m = 311$ V. The active filter acts as a buck converter. Therefore, the pulse filling factor γ is calculated by the formula:

$$\gamma = \frac{U_m}{E} = 0.78. \tag{6.8}$$

The inductance L is calculated by the formula:

$$L = \frac{E - U_m}{\Delta I f}\gamma = \frac{89}{0.2 \cdot 50 \cdot 10^3} 0.78 \approx 6.9 \text{ mH}. \tag{6.9}$$

Answer: inductance of the active filter is equal to $L = 6.9$ mH.

Tasks for themselves solving

Task № 1

From a single-phase AC network of 220 V, 50 Hz, a triangular current with a phase shift $\varphi_{sh} = 30$ ° and an amplitude $I_m = 10$ A is consumed. Calculate the shape of the current that should be generated by the parallel active filter to completely eliminate the reactive power and provide a sinusoidal shape of the mains current.

Task № 2

From a single-phase network of alternating current of 220 V, 50 Hz rectangular current with phase shift $\varphi_{sh} = 30$ ° and amplitude $I_m = 20$ A is consumed. Calculate the inductance L of the active filter sufficient to generate a current that compensates for distortion with a current ripple $\delta_I = 10\%$ of the amplitude value. The operating frequency of the active filter $f = 50$ kHz, the DC voltage source E connected to the input of the active filter has a value of $E = 400$ V.

Task № 3

From a single-phase AC network of 220 V, 50 Hz consumes triangular current without phase shift and amplitude $I_m = 15$ A. Calculate the minimum operating frequency of the active filter $f_{\min}$, which can compensate for 95% of the distortion power of the network current.

Task № 4

Single-phase passive filter of higher harmonics, consists of a number of separate resonant filters, which are configured to suppress the higher odd harmonics: the third, fifth, seventh, etc. Other higher harmonics are suppressed by a single LC low pass filter. Determine the required number of resonant filters M, sufficient for the transmission factor of the first harmonic through the filter was $k_1 = 0.95$, and the first higher harmonic, which is suppressed by the low-pass filter, with the number 2M + 3 - k_{2M+3} 3 = 0.05.

Task № 5

Single-phase passive filter of higher harmonics, consists of 10 separate resonant filters, which are configured to suppress the first higher odd harmonics: the third, fifth, seventh, etc. Other higher harmonics are suppressed by a single LC low pass filter. The transfer coefficient of the first harmonic k1 through the filter is $k_1 = 0.95$. The load consumes a rectangular current without phase shift. Determine the THD of the mains current after connecting the passive filter of the higher harmonics.

Practice lesson № 7. Balancing devices of three-phase power supply systems

Theory

A symmetric three-phase voltage system is characterized by the same amplitudes and the same phase shift of the voltages of a three-phase system. Violation of one of the conditions indicates an asymmetric mode of operation of the network. Asymmetric modes in networks occur due to the following factors:

1) different phase loads;
2) incomplete operation of lines or other network elements;
3) non-equivalent parameters of the phases of power lines.

Most often, load asymmetry occurs due to the different nature of the load phases. In 0.38 kV low-voltage networks, the asymmetry is due to uneven connection of lighting and household appliances. In high-voltage networks, the asymmetry is caused by the connection of powerful loads: steel furnaces, heating systems, welding machines, traction substations of railway transport.

Voltage asymmetry causes the occurrence of currents of zero (phase currents have the same phase) and reverse (phase currents have inverse phase alternation) sequence, which leads to energy loss, reducing the effective value of forward sequence voltages, which worsens the operation of connected equipment, especially electric motors. The current of a direct sequence of motors creates a rotating magnetic field that rotates in the same direction as the rotor. Reverse sequence currents create a field that rotates in the opposite direction, which creates a braking electromagnetic moment and leads to an increase in rotor temperature, the appearance of motor vibrations, which reduces the service life of the motor.

To calculate the level of voltage asymmetry use special methods, the most common of which is the method of symmetric components. It is used to describe an arbitrary three-phase EMF system, voltages or currents by the sum of three symmetric systems - forward, reverse and zero sequences, Fig. 7.1.

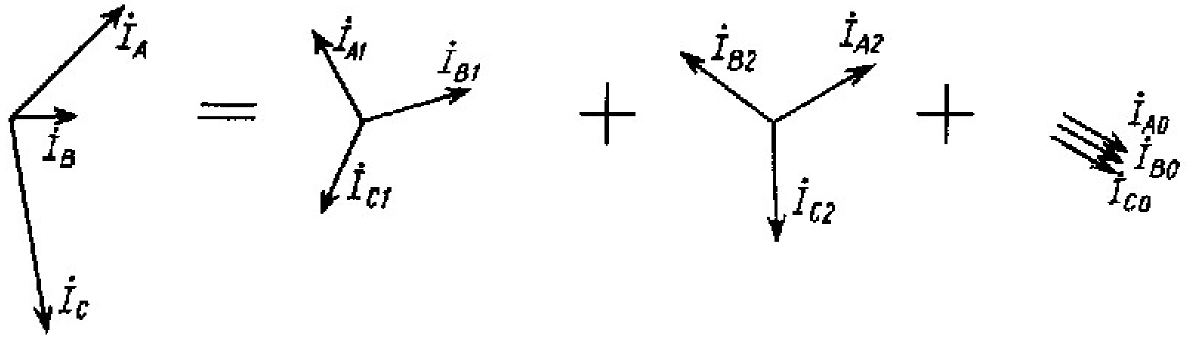


Рис. 7.1. Direct, inverse and zero sequences

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}:

$$\begin{cases} \dot{I}_A = \dot{I}_{A1} + \dot{I}_{A2} + \dot{I}_{A0}; \\ \dot{I}_B = \dot{I}_{B1} + \dot{I}_{B2} + \dot{I}_{B0}; \\ \dot{I}_C = \dot{I}_{C1} + \dot{I}_{C2} + \dot{I}_{C0}. \end{cases} \tag{7.1}$$

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:

$$\begin{aligned} & a^2 = e^{j4\pi/3} = e^{-j2\pi/3} = a^{-1} = -\frac{1}{2} - j\frac{\sqrt{3}}{2}; \\ & a^3 = e^{j2\pi} = 1; \\ & a + a^2 + 1 = 0. \end{aligned} \tag{7.2}$$

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

$$\dot{I}_{B1} = a^2 \cdot \dot{I}_{A1}; \dot{I}_{C1} = a \cdot \dot{I}_{A1}, \tag{7.3}$$

reverse

$$\dot{I}_{B2} = a \cdot \dot{I}_{A2}; \dot{I}_{C2} = a^2 \cdot \dot{I}_{A2}, \tag{7.4}$$

and zero sequences

$$\dot{I}_{A0} = \dot{I}_{B0} = \dot{I}_{C0}. \tag{7.5}$$

Substitution of (7.3) - (7.5) in the (7.1) for calculation of the resulting currents allows to receive the following relations:

$$\begin{cases} \dot{I}_A = \dot{I}_{A1} + \dot{I}_{A2} + \dot{I}_{A0}; \\ \dot{I}_B = a^2 \cdot \dot{I}_{A1} + a \cdot \dot{I}_{A2} + \dot{I}_{A0}; \\ \dot{I}_C = a \cdot \dot{I}_{A1} + a^2 \cdot \dot{I}_{A2} + \dot{I}_{A0}, \end{cases} \tag{7.6}$$

or in matrix form:

$$\begin{bmatrix} \dot{I}_A \\ \dot{I}_B \\ \dot{I}_C \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{bmatrix} \begin{bmatrix} \dot{I}_{A1} \\ \dot{I}_{A2} \\ \dot{I}_{A0} \end{bmatrix}, \tag{7.7}$$

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

$$\begin{cases} \dot{I}_{A1} = \left(\dot{I}_A + a \cdot \dot{I}_B + a^2 \cdot \dot{I}_C \right) / 3; \\ \dot{I}_{A2} = \left(\dot{I}_A + a^2 \cdot \dot{I}_B + a \cdot \dot{I}_C \right) / 3; \\ \dot{I}_{A0} = \left(\dot{I}_A + \dot{I}_B + \dot{I}_C \right) / 3. \end{cases} \tag{7.8}$$

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:

$$\begin{bmatrix} \dot{I}_A \\ \dot{I}_B \\ \dot{I}_C \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{bmatrix} \begin{bmatrix} \dot{I}_{A1} e^{-j\varphi 1} \\ \dot{I}_{A2} e^{-j\varphi 2} \\ \dot{I}_{A0} e^{-j\varphi 0} \end{bmatrix}, \tag{7.9}$$

where φ is the phase shift between voltage and current of the forward, reverse and zero sequences.

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:

$$\dot{I}_{AM}+\dot{I}_{BM}+\dot{I}_{CM}=0. \tag{7.10}$$

In scalar form, (7.10) will be rewritten as:

$$\begin{cases} \operatorname{Re}\left(\dot{I}_{AM}+\dot{I}_{BM}+\dot{I}_{CM}\right)=\operatorname{Re}\left(\dot{U}_{A}(jY_{A}+\dot{Y}_{AH})+\dot{U}_{B}(jY_{B}+\dot{Y}_{BH})+\dot{U}_{C}(jY_{C}+\dot{Y}_{CH})\right)=0; \\ \operatorname{Im}\left(\dot{I}_{AM}+\dot{I}_{BM}+\dot{I}_{CM}\right)=\operatorname{Im}\left(\dot{U}_{A}(jY_{A}+\dot{Y}_{AH})+\dot{U}_{B}(jY_{B}+\dot{Y}_{BH})+\dot{U}_{C}(jY_{C}+\dot{Y}_{CH})\right)=0. \end{cases} \tag{7.11}$$

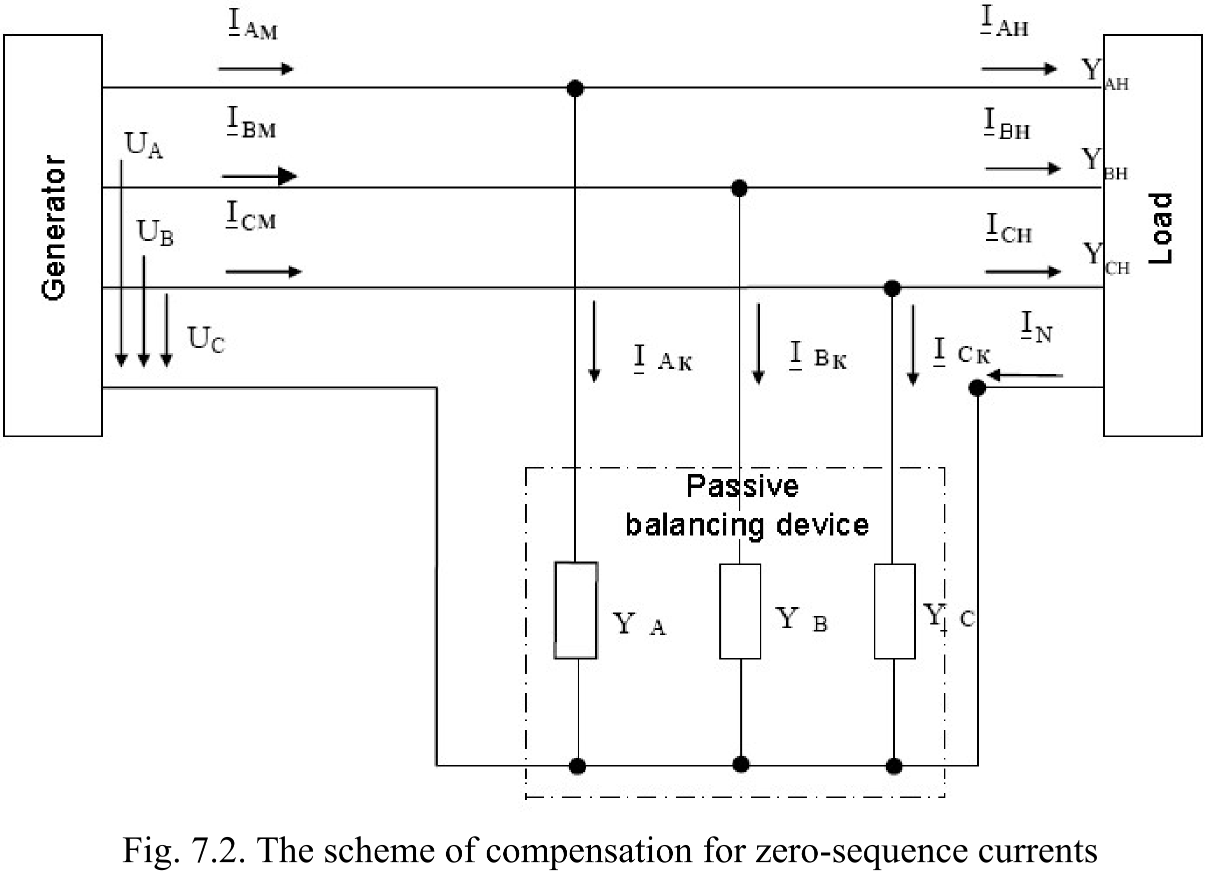


Fig. 7.2. The scheme of compensation for zero-sequence currents

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

$$\chi = \frac{\operatorname{Re}\left(\dot{U}_A \overset{*}{I}_{AM}\right) + \operatorname{Re}\left(\dot{U}_B \overset{*}{I}_{BM}\right) + \operatorname{Re}\left(\dot{U}_C \overset{*}{I}_{CM}\right)}{\left|\dot{U}_A \overset{*}{I}_{AM} + \dot{U}_B \overset{*}{I}_{BM} + \dot{U}_C \overset{*}{I}_{CM}\right|}. \qquad (7.12)$$

To compensate for the reverse sequence currents, the BD is connected according to a three-wire circuit, Fig. 7.3.

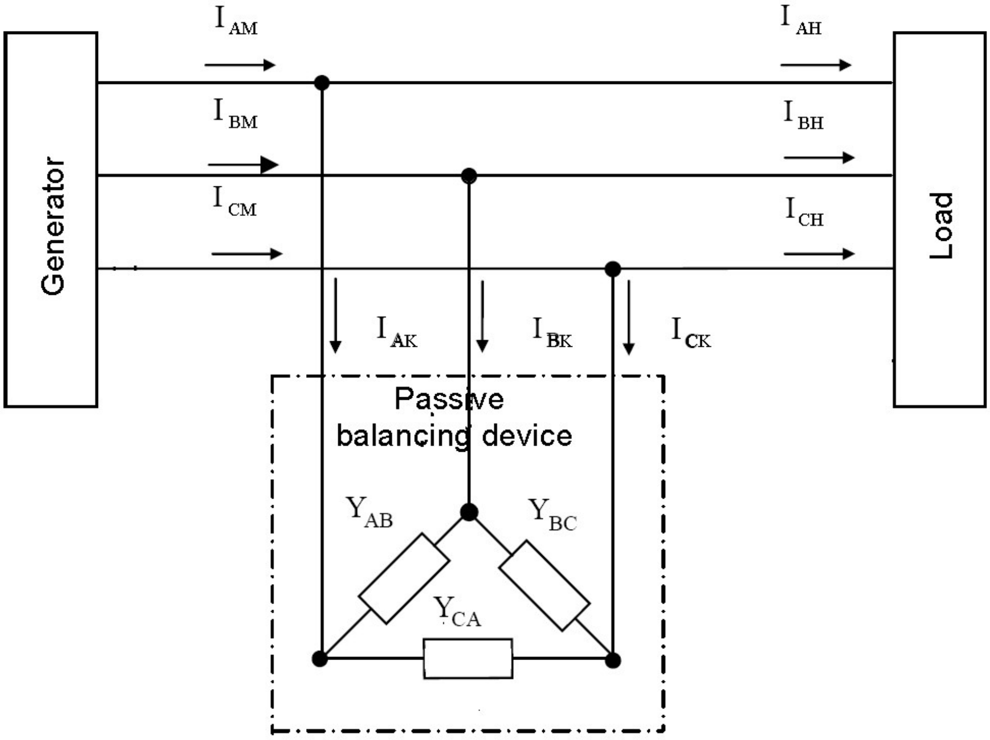


Fig. 7.3. Scheme of compensation for reverse sequence currents

Under the condition of a three-wire network, the balancing scheme shown in Fig. 7.3, 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:

$$Y_{ABH} = \frac{Y_{AH} Y_{BH}}{Y_{AH} + Y_{BH} + Y_{CH}}; Y_{BCH} = \frac{Y_{BH} Y_{CH}}{Y_{AH} + Y_{BH} + Y_{CH}}; Y_{ACH} = \frac{Y_{AH} Y_{CH}}{Y_{AH} + Y_{BH} + Y_{CH}}. \qquad (7.13)$$

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

$$\begin{cases} \operatorname{Im}\left(\dot{Y}_{AB}\right) = -\operatorname{Im}\left(\dot{Y}_{AB\,H}\right) - \dfrac{\operatorname{Re}\left(\dot{Y}_{AC\,H} - \dot{Y}_{BC\,H}\right)}{\sqrt{3}}; \\ \operatorname{Im}\left(\dot{Y}_{BC}\right) = -\operatorname{Im}\left(\dot{Y}_{BC\,H}\right) - \dfrac{\operatorname{Re}\left(\dot{Y}_{AB\,H} - \dot{Y}_{AC\,H}\right)}{\sqrt{3}}; \\ \operatorname{Im}\left(\dot{Y}_{AC}\right) = -\operatorname{Im}\left(\dot{Y}_{AC\,H}\right) - \dfrac{\operatorname{Re}\left(\dot{Y}_{BC\,H} - \dot{Y}_{AB\,H}\right)}{\sqrt{3}}. \end{cases} \qquad (7.14)$$

The power factor is calculated as follows:

$$\chi = \frac{U_{AB}\operatorname{Re}\left(\dot{Y}_{AB\,H}\right) + U_{BC}\operatorname{Re}\left(\dot{Y}_{BC\,H}\right) + U_{BC}\operatorname{Re}\left(\dot{Y}_{BC\,H}\right)}{\left|U_{AB}\left(\dot{Y}_{AB\,H} + \dot{Y}_{AB}\right) + U_{BC}\left(\dot{Y}_{BC\,H} + \dot{Y}_{BC}\right) + U_{BC}\left(\dot{Y}_{AC\,H} + \dot{Y}_{AC}\right)\right|} \qquad (7.15)$$

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:

$$\operatorname{Im}\left(\dot{Y}_0\right) = \frac{\sqrt{\left(\dfrac{1}{\chi_з^2} - 1\right)\operatorname{Re}\left(\dot{Y}_{AB\,H} + \dot{Y}_{BC\,H} + \dot{Y}_{AC\,H}\right) - \operatorname{Im}\left(\dot{Y}_{AB\,H} + \dot{Y}_{BC\,H} + \dot{Y}_{AC\,H} + \dot{Y}_{AB} + \dot{Y}_{BC} + \dot{Y}_{AC}\right)}}{3}. \qquad (7.16)$$

Task solution examples

Task № 1

There is 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. Calculate zero and reverse currents.

Solution:

1. Calculation of the conductivity of each phase:

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

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

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

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

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

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

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

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

$$\dot{I}_{A1} = \frac{\left(\dot{I}_{A} + a\cdot\dot{I}_{B} + a^{2}\cdot\dot{I}_{C}\right)}{3} = 5.815 - 15.136j \text{ A;}$$

$$\dot{I}_{A2} = \frac{\left(\dot{I}_{A} + a^{2}\cdot\dot{I}_{B} + a\cdot\dot{I}_{C}\right)}{3} = 18.455 + 5.288j \text{ A;}$$

$$\dot{I}_{A0} = \frac{\left(\dot{I}_{A} + \dot{I}_{B} + \dot{I}_{C}\right)}{3} = 5.185 - 13.561j \text{ A.}$$

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:

$$\chi = \frac{\operatorname{Re}\left(\dot{U}_{A}\overset{*}{I}_{AH}\right) + \operatorname{Re}\left(\dot{U}_{B}\overset{*}{I}_{BH}\right) + \operatorname{Re}\left(\dot{U}_{C}\overset{*}{I}_{CH}\right)}{\left|\dot{U}_{A}\overset{*}{I}_{AH} + \dot{U}_{B}\overset{*}{I}_{BH} + \dot{U}_{C}\overset{*}{I}_{CH}\right|} = 0.96.$$

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:

$$\begin{cases} U_{A}\operatorname{Re}\left(\dot{Y}_{AH}\right) - \frac{\sqrt{3}}{2}U_{B}Y_{B} - \frac{1}{2}U_{B}\operatorname{Re}\left(\dot{Y}_{BH}\right) - \\ -\frac{\sqrt{3}}{2}U_{B}\operatorname{Im}\left(\dot{Y}_{BH}\right) - \frac{1}{2}U_{C}\operatorname{Re}\left(\dot{Y}_{CH}\right) + \frac{\sqrt{3}}{2}U_{C}\operatorname{Im}\left(\dot{Y}_{CH}\right) = 0; \\ U_{A}Y_{A} + U_{A}\operatorname{Im}\left(\dot{Y}_{AH}\right) - \frac{1}{2}U_{B}Y_{B} + \frac{\sqrt{3}}{2}U_{B}\operatorname{Re}\left(\dot{Y}_{BH}\right) - \\ -\frac{1}{2}U_{B}\operatorname{Im}\left(\dot{Y}_{BH}\right) - \frac{\sqrt{3}}{2}U_{c}\operatorname{Re}\left(\dot{Y}_{CH}\right) - \frac{1}{2}U_{C}\operatorname{Im}\left(\dot{Y}_{CH}\right) = 0. \end{cases}$$

Where to get:

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

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:

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

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

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

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

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

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

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

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

Answer: $Y_A = 0.2257$ Sm (capacity), $Y_B = 0.08164$ Sm (capacity), $Y_c = 0$.

Task № 2

Eliminate the reverse sequence currents for the circuit of **Task № 1** and provide a power factor $\chi = 0.8$.

Solution:

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

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

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

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

2. Calculation of the parameters of the balancing device according to (7.14):

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

3. Calculation of the parameters of additional conductivity to ensure the required power factor χ for (7.15):

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

Answer: $\dot{Y}_{AB} = -\,0.06865j$ Sm; $\dot{Y}_{BC} = -\,0.04694j$ Sm;

$\dot{Y}_{AC} = -0.01091j$ Sm; $\mathrm{Im}\left(\dot{Y}_0\right) = 0.02097$ Sm.

Task № 3

Calculate currents and voltages in the load phases with a short-circuited phase A, Fig. 7.4. Assume that the currents of phases B and C are much smaller than the current of phase A ($I_B = I_C = 0$). The resistance of the forward, reverse and zero voltage sequences is Z_1, Z_2, Z_0.

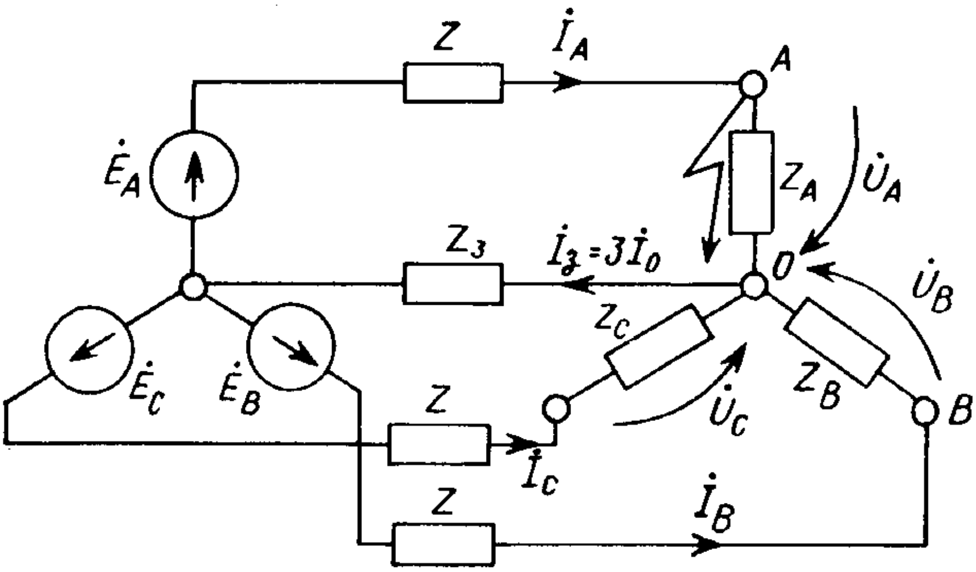


Fig. 7.4. The system under study

Solution

1. Express the currents of phases B and C, the voltage of phase A through symmetric components:

$$U_A = U_1 + U_2 + U_0,\ I_B = a^2 I_1 + a I_2 + I_0,\ I_C = a I_1 + a^2 I_2 + I_0.$$

2. Because $I_B = I_C = 0$, then $I_1 = I_2 = I_0$.

3. We write the forward, reverse and zero sequences for phase A of a three-phase source:

$E_1 = U_1 + I_1 Z_1;$

$0 = U_2 + I_2 Z_2;$

$0 = U_0 + I_0 Z_0.$

4. The system for calculating load currents and voltages is as follows:

$$\begin{cases} E_1 = I_1 Z_1 + U_1; \\ 0 = I_2 Z_2 + U_2; \\ 0 = I_0 Z_0 + U_0; \\ 0 = U_1 + U_2 + U_0; \\ I_1 = I_2 = I_0. \end{cases}$$

5. The system solution:

$$I_1 = I_2 = I_0 = \frac{3E_1}{Z_1 + Z_2 + Z_0};$$

$$U_1 = \frac{E_1(Z_2 + Z_0)}{Z_1 + Z_2 + Z_0};\ U_2 = -\frac{E_1 Z_2}{Z_1 + Z_2 + Z_0}; U_0 = -\frac{E_1 Z_0}{Z_1 + Z_2 + Z_0}.$$

6. Express the phase currents and voltages through the currents and voltages of the forward, reverse and zero sequences:

$$I_A = I_1 + I_2 + I_0 = \frac{3E_1}{Z_1 + Z_2 + Z_0};\ I_B = 0; I_C = 0.$$

$$U_A = 0; U_B = E_1 \frac{Z_2(a^2 - a) + Z_0(a^2 - 1)}{Z_1 + Z_2 + Z_0}; U_C = E_1 \frac{Z_2(a^2 - a) + Z_0(a - 1)}{Z_1 + Z_2 + Z_0}$$

Answer: $I_A = I_1 + I_2 + I_0 = \frac{3E_1}{Z_1 + Z_2 + Z_0};\ I_B = 0; I_C = 0.$

$$U_A = 0; U_B = E_1 \frac{Z_2(a^2 - a) + Z_0(a^2 - 1)}{Z_1 + Z_2 + Z_0}; U_C = E_1 \frac{Z_2(a^2 - a) + Z_0(a - 1)}{Z_1 + Z_2 + Z_0}$$

Task № 4

An asymmetric load connected by a star is connected to a three-phase generator with phase voltage Uf = 100V, fig. 7.5: Z_A = - j100 Ohm, Z_B = Z_C = 100 Ohm.

Determine currents in consumer phases and active power. Build a topographic diagram.

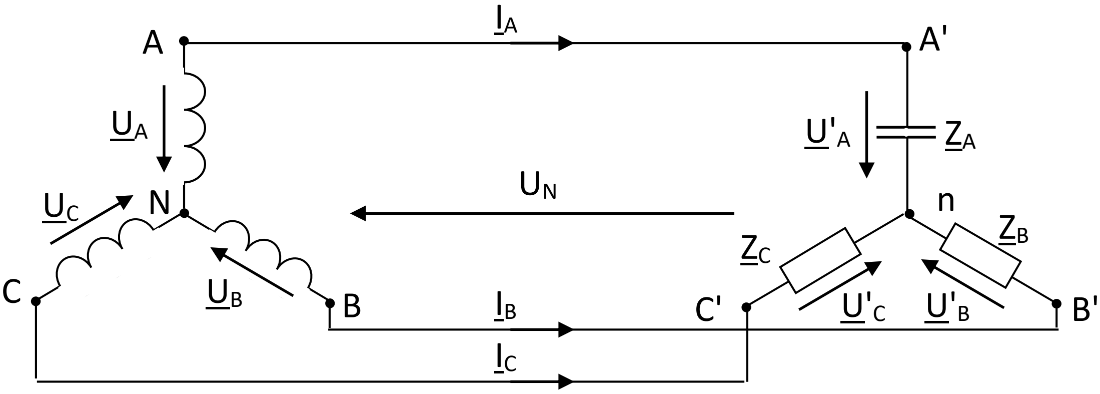


Fig. 7.5. Scheme of the system

Solution:

1. Determine the U_N voltage between the neutral points of the consumer and the generator:

$$\underline{U}_N = \frac{\underline{U}_A \underline{Y}_A + \underline{U}_B \underline{Y}_B + \underline{U}_C \underline{Y}_C}{\underline{Y}_A + \underline{Y}_B + \underline{Y}_C}.$$

Define $\underline{U}_A = 100$ *V.*

Then $\underline{U}_B = 100\, e^{-j120°}$ *V, де* $e^{-j120°} = -0.5 - j\,0.87,$

$\underline{U}_C = 100\, e^{j120°}$ *V, де* $e^{j120°} = -0.5 + j\,0.87.$

$$\underline{Y}_A = \frac{1}{\underline{Z}_A} = \frac{1}{-j100} = j0.01\ Sm; \quad \underline{Y}_B = \underline{Y}_C = \frac{1}{\underline{Z}_B} = 0.01\ Sm;$$

$$\underline{U}_N = \frac{100\cdot j0.01+100e^{-j120^\circ}\cdot 0.01+100e^{j120^\circ}\cdot 0.01}{j0.01+0.01+0.01} =$$

$$= \frac{100}{2+j}(j-0.5-j0.87-0.9+j0.87) = \frac{100(j-1)(2-j)}{(2+j)(2-j)} = 20(j2-2+1+j) = -20+j60V.$$

2. Determine the voltage on the load:

$\underline{U}'_A = \underline{U}_A - \underline{U}_N = 100 - (-20+j60) = 120 - j60 = 134\ e^{-j26^\circ 34'}$ V;

$\underline{U}'_B = \underline{U}_B - \underline{U}_N = 100\ e^{-j120^\circ} - (-20+j60) = -50 - j87 + 20 - j60 =$
$= -30 - j147 = -150\ e^{+j78^\circ 28'}$ V;

$\underline{U}'_C = \underline{U}_C - \underline{U}_N = 100e^{j120^\circ} - (-20+j60) = -50+j87+20-j60 = -30+j27 = -40e^{-j42^\circ}$ V;

3. Phase currents:

$$\underline{I}_A = \frac{\underline{U}'_A}{\underline{Z}_A} = \frac{134e^{-j26^\circ 34'}}{-j100} = 1.24e^{j63^\circ 26'}A;$$
$$\underline{I}_B = \frac{\underline{U}'_B}{\underline{Z}_B} = \frac{-150e^{j78^\circ 28'}}{100} = 1.5e^{j78^\circ 28'}A;$$
$$\underline{I}_C = \frac{\underline{U}'_C}{\underline{Z}_C} = \frac{-40e^{-j42^\circ}}{100} = -0.4e^{-j42^\circ}A.$$

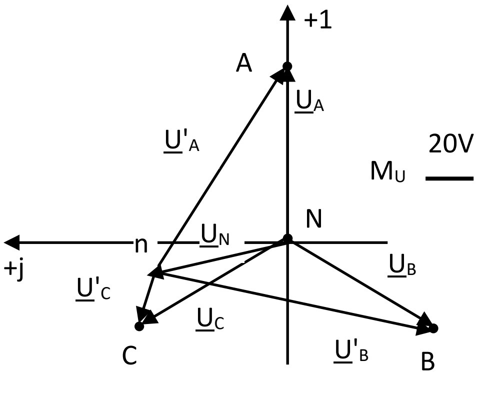


Fig. 7.6

4. Calculate active power:

$P_A = 0$,
$P_B = R_B I^2_B = 100\ (1{,}5)^2 = 225$ W,
$P_C = R_C I^2_C = 100\ (0{,}4)^2 = 16$ W,
$P = P_B + P_C = 225 + 16 = 241$ W.

5. Let's build a topographic diagram, Fig. 7.6.

We see that the voltages in phases B and C of the consumer are very different, although the resistances of these phases are the same.

Answer: $\underline{I}_A = 1.24e^{j63^\circ} A; \underline{I}_B = 1.5e\ A; \underline{I}_C = -0.4e\ A$; P_A = 0; P_B =225 W; P_C=16 W.

Tasks for themselves solving

Task № 1

Given a system of three phase loads with power: P_A = 7 kW, Q_A = -6 kVA; P_B = 3.5 kW, Q_B = 4 kVA; P_C = 5 kW, Q_C = 4.2 kVA. Loads are connected according to the scheme "star", fig. 7.2, and are powered by a three-phase network with a phase voltage U = 220 V. It is necessary to eliminate zero-sequence currents and provide a power factor χ = 0.9.

Task № 2

Given a system of three phase loads with power: P_A = 6.5 kW, Q_A = -3 kVA; P_B = 4 kW, Q_B = 6 kVA; P_C = 10 kW, Q_C = 4 kVA. Loads are connected according to the scheme "triangle", Fig. 7.3, and are powered by a three-phase network with a phase voltage U = 220 V. It is necessary to eliminate the reverse sequence currents and provide a power factor χ = 0.8.

Task № 3

Symmetrical three-phase load with complex phase resistance Z = 40 + j30 Ohm, connected by a triangle, works from a symmetrical generator, Fig. 7.7. Determine the phase and line currents, as well as the active, reactive and full power of the load, if U_A = 200 V. Construct a vector diagram of currents.

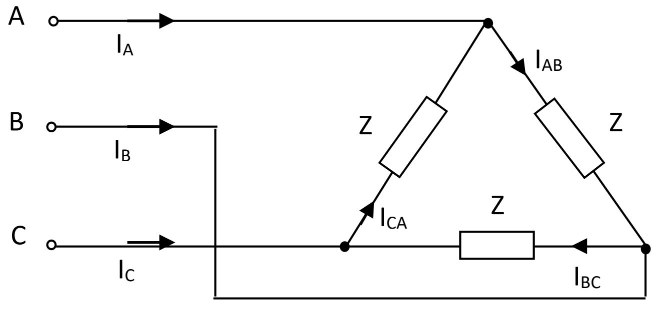


Fig. 7.7. Scheme of symmetrical three-phase load

Task № 4

Loads are connected to the three-phase symmetric generator, Fig. 7.8. Determine the currents in the linear and neutral wires, if U_P = 100V, $\underline{Z}_A$ = 10 Ohm, $\underline{Z}_B=10e^{-j30°}$ Ohm, $\underline{Z}_C=10e^{j30°}$ Ohm, $\underline{Z}_{AB}=17{,}3e^{j30°}$ Ohm, $\underline{Z}_{BC}=17{,}3e^{-j90°}$ Ohm, $\underline{Z}_{CA}=17{,}3e^{j60°}$ Ohm.

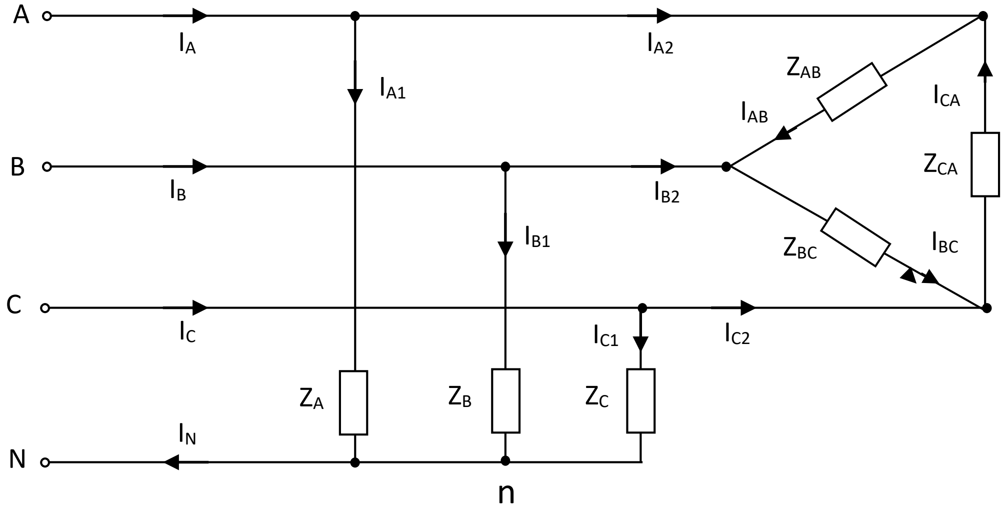


Fig. 7.8. Scheme of the system

Task № 5

In a three-phase electric circuit with a symmetrical energy source and two asymmetric consumers connected by a star and a triangle, Fig. 7.9, determine the phase and line currents and voltages on the elements of consumers, provided: E_P = 380 V; E_n = 180 V; Ψ_n = 60°; R_A = 90 Ohm; R_B = 0; R_C = 40 Ohm; X_A = 80 Ohm; X_B = - 80 Ohm; X_C = 70 Ohm; R_{AB} = 200 Ohm; R_{BC} = 0; R_{CA} = 150 Ohm; X_{AB} = 280 Ohm; X_{BC} = 150 Ohm; X_{CA} = - 150 Ohm; *n* is the index of the linear wire (in this case, *n* corresponds to the wire of phase *B* of the circuit). In a convenient scale to build a radial vector diagram of circuit currents and topographic vector diagrams of voltages for each of the consumers..

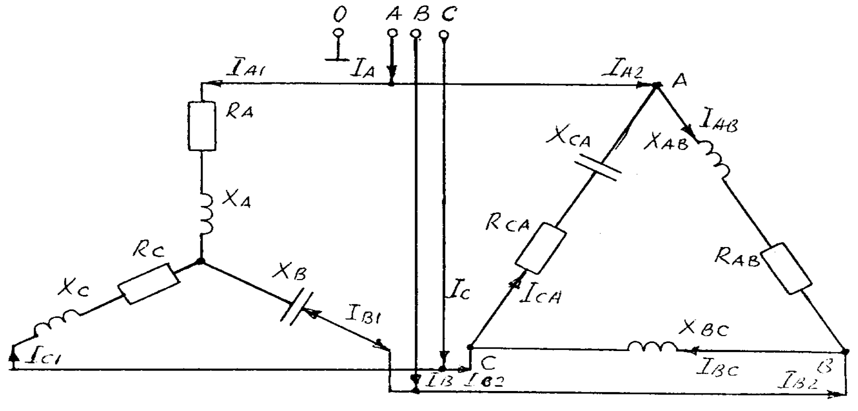


Fig. 7.9. Scheme of the system

Task № 6

Decompose the asymmetric system of phase EMF vectors $E_A = 380$ V, $E_B = 180\, e^{j60^0}$ V, $E_C = 380\, e^{j120^0}$ V into symmetric components. Construct vector of voltage diagram of an asymmetric three-phase power source and their symmetric components.

Practice lesson № 8. DC power supply systems

Theory

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):

$$S_{\max} = \frac{U_m^2}{\omega L}, \tag{8.1}$$

therefore, as the length of the line increases, its maximum power decreases. Ємність повітряної лінії практично не впливає на процес передачі енергії 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.

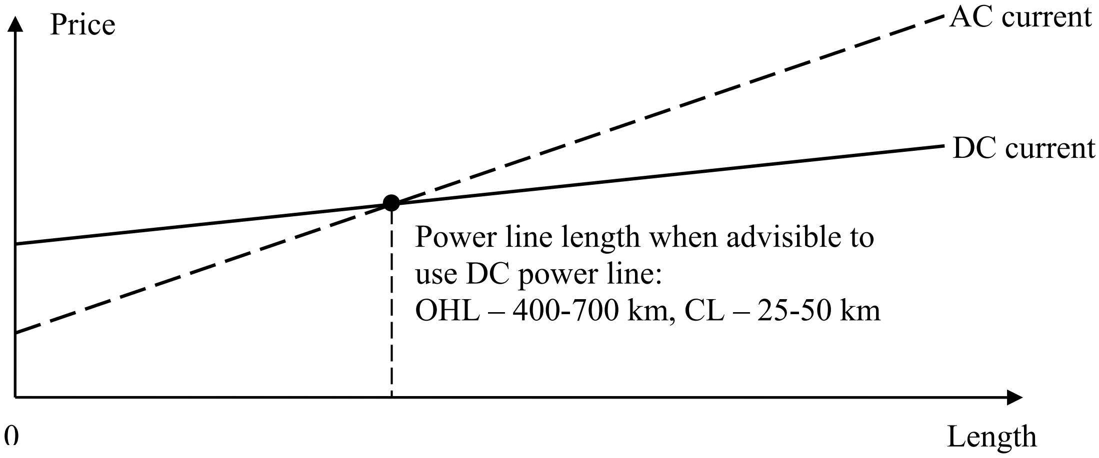


Fig. 8.1. Graph the cost of DC and AC lines depending on their length

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. 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. 8.2.

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.

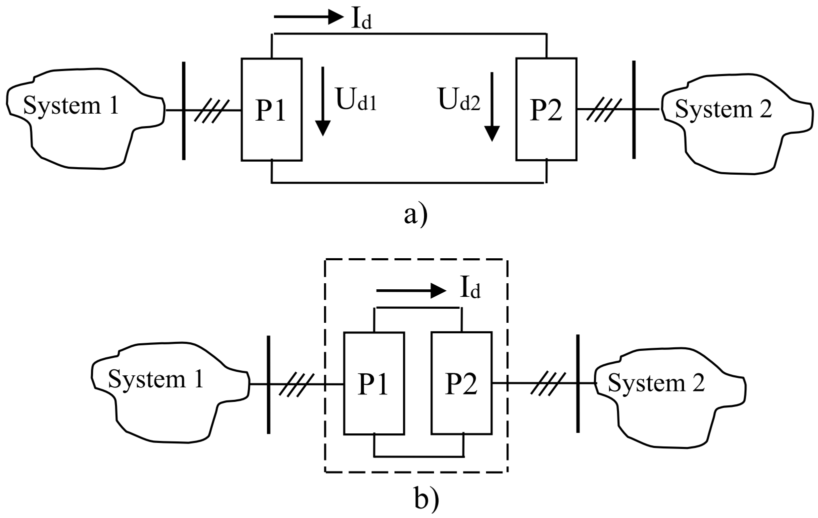
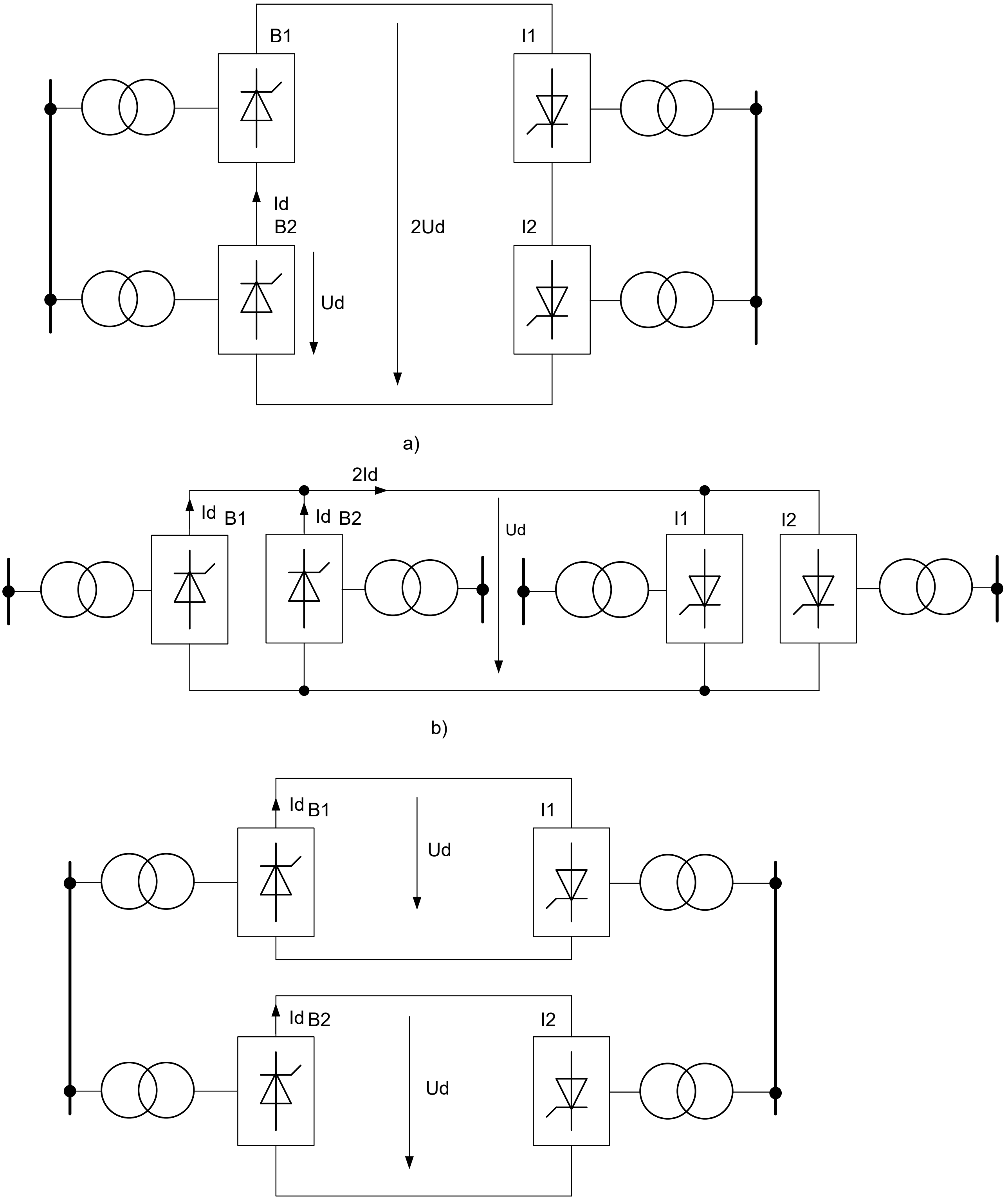


Fig. 8.2. Block diagrams of DCT (a) and IDC (b)

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. 8.3 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. 8.3 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. 8.3 c).



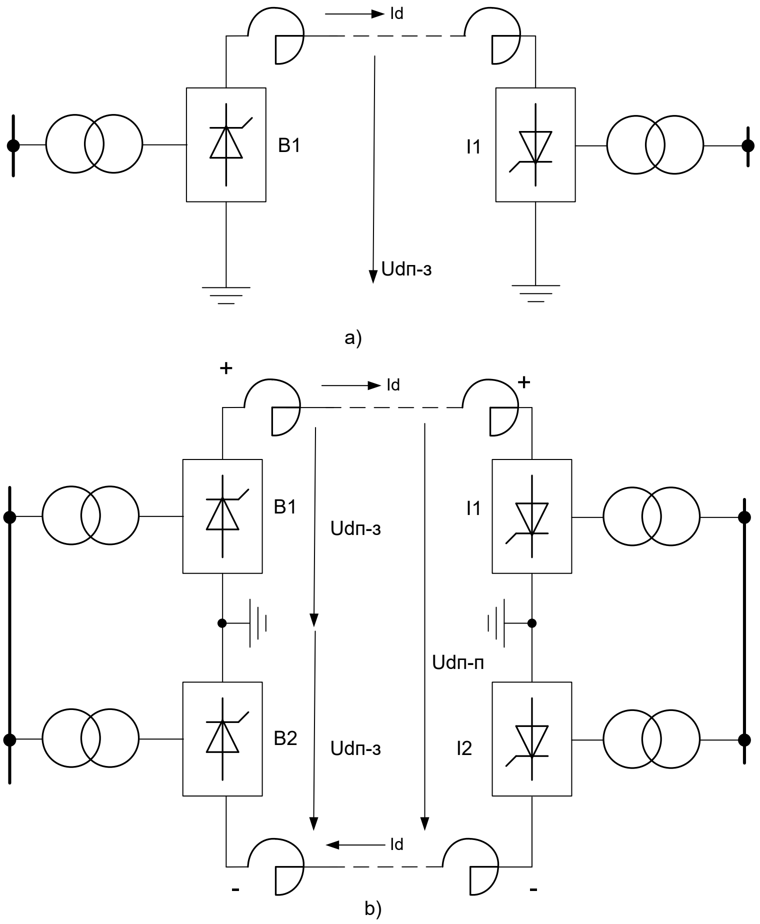
a)

b)

c)

a) increase in line voltage; b) increase the pole current; c) creation of a double-chain line
Fig. 8.3. 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. 8.4.

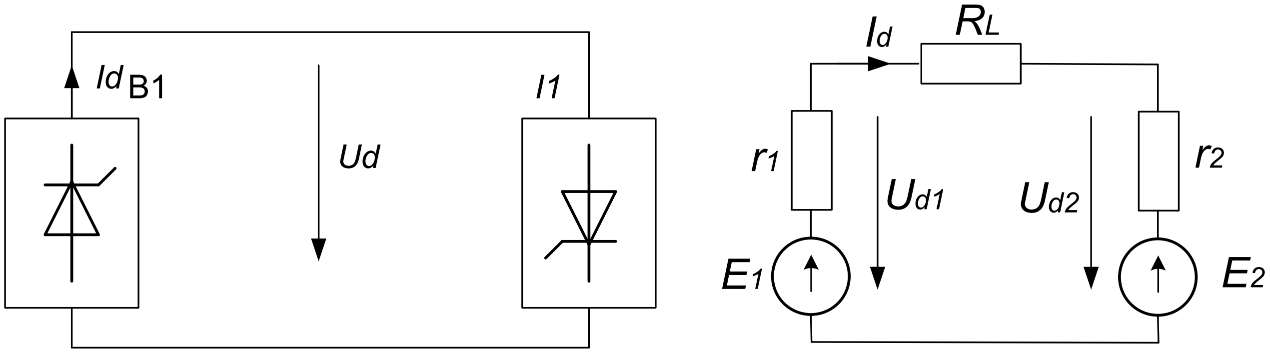


a) unipolar DCT; b) bipolar DCT
Fig. 8.4. Schemes of DCT transmissions

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.

The DCT scheme with two substations on incompletely controlled valves and their substitution scheme is shown in Fig. 8.5.



a) functional diagram of a two-substation DCT; b) two-substation replacement scheme DCT

Fig. 8.5. Two-substation DCT

In this circuit, the rectifier is represented by EMF E_1 and output resistance r_1, and the inverter - EMF E_2 and output resistance r_2. The rectifier and inverter are connected by a power line from the R_L poles. The EMF values E_1 and E_2 are regulated in a wide range independently of each other, which makes it possible to control the process of electricity transmission. The line current is calculated by the formula:

$$I_d = \frac{E_1 - E_2}{r_1 + r_2 + R_L}. \tag{8.2}$$

Power transmitted by DCT:

$$P_{d1} = I_d \cdot E_1. \tag{8.3}$$

Power at the end of DCT:

$$P_{d2} = I_d \cdot E_2. \tag{8.4}$$

The rectifier in the DCT circuit is a generator of electricity, and the inverter is a consumer. The following conditions are valid in the DCT:

$$E_1 > U_{d1},\ U_{d2} > E_2. \tag{8.5}$$

To adjust the line power from zero to the nominal value, it is enough to change the values of E_1 and E_2 to a value not exceeding 8-10% of their nominal value. In the case of using a rectifier and inverter based on thyristors, their control characteristics are described by the following formulas:

$$E_1 = U_{d0B} \mathbf{cos}(\alpha); \tag{8.6}$$

$$E_2 = U_{d0I} \mathbf{cos}(\beta); \tag{8.7}$$

$$U_{d1} = U_{d0B} \mathbf{cos}(\alpha) - I_d r_1; \tag{8.8}$$

$$U_{d2} = U_{d0I} \mathbf{cos}(\beta) + I_d r_2, \tag{8.9}$$

where U_{d0B} is the average value of the voltage at the output of the rectifier in the uncontrolled mode, α is the opening angle of the rectifier, U_{d0B} is the voltage at the input of the inverter in the uncontrolled mode, β is the advance angle of the inverter β = π – α.

Substituting expressions (8.6) and (8.7) into formula (8.2), we obtain:

$$I_d = \frac{U_{d0B}\cos(\alpha) - U_{d0I}\cos(\beta)}{r_1 + r_2 + R_L}. \tag{8.10}$$

The choice of the method of regulating the energy transmitted by the DCT is chosen from the conditions of speed and stability of the system with minimal generation of higher harmonics and reactive power.

Consider one possible way to control power by regulating current. Operating modes for a given method of control is calculated by the control characteristics of the rectifier and inverter, shown in Fig. 8.6.

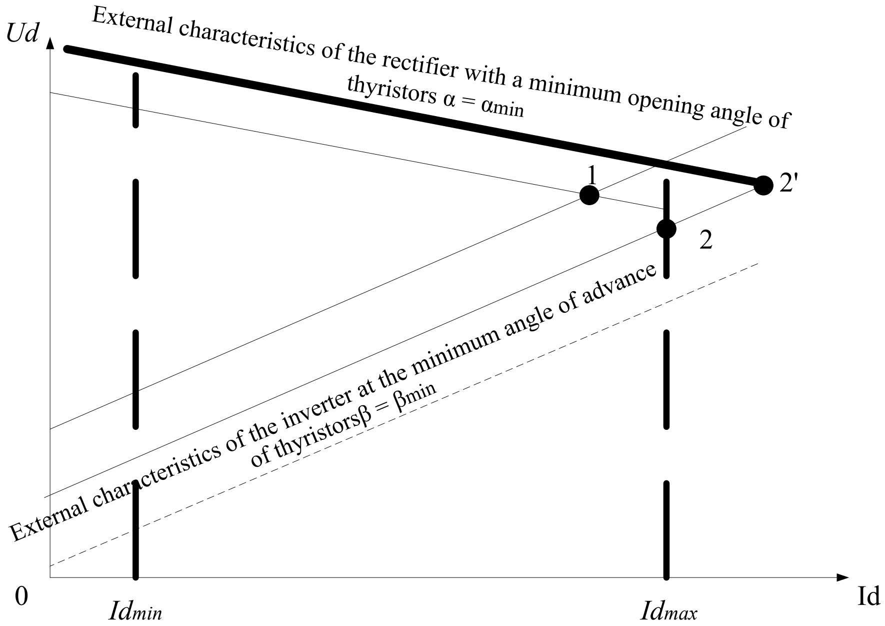


Fig. 8.6. Adjusting characteristics of the rectifier and inverter

In fig. 8.6 segment AB describes the external characteristics of the rectifier, the analytical expression of which is calculated by formula (8.8). The slope of the characteristic depends on the value of the output resistance r1 of the rectifier. The order of power of the transmitting power system is estimated by the value of resistance r_1: $P_1 \sim U_d^2/r_1$. In the case of rated operating modes, the output resistance of the rectifier must be much lower than the load resistance $r_1 \ll U_d/I_d$. The maximum value of the rectified voltage is obtained under the condition that the thyristors operate in the uncontrolled mode α = 0. In practice, to ensure the minimum positive voltage on the valves, the minimum value of the opening angle of the thyristors is chosen in the range α = (2-5)°. If the control angle is larger, the external characteristics are lower than the specified external characteristic. The external characteristic of the rectifier has a maximum Idmax and a minimum Idmin current limit. The minimum current limit ensures the flow of continuous current through the rectifier, and the maximum - protection against overloads.

The external characteristics of the inverter are described by formula (8.9). The input resistance of the inverter r_2 is more important due to the lower power of the receiving system. The external characteristic of the inverter is growing. The minimum advance angle of the inverter thyristors is set in the range β = (100-110) °, which ensures the minimum voltage at the inverter input when the DCT is turned on.

The amount of energy transferred from one power system to another is regulated by the opening angles of the thyristors of the rectifier and inverter α and β, respectively. The operating point of the system is at the intersection of the characteristics of the rectifier and inverter, if the condition of current limitation is not met, point 1 in Fig. 8.6. If the current of the operating point $I_{d\max}$ of the system exceeds the maximum value of the current Idmax, point $2^{/}$ in Fig. 8.6, the DCT current is limited with the transition to operating point 2. The DCT operating modes may also be limited to a certain range of thyristor opening angles.

In practice, the mode of operation of the inverter is significantly affected by the switching angle of thyristors γ, which occurs due to the accumulation of energy in the scattering inductances of the transformer. In such systems, the mode of operation of the inverter is set by the attenuation angle of the thyristors δ, which is calculated by the formula:

$$\delta = \beta - \gamma. \tag{8.11}$$

In this mode, under the condition of increasing the load current, to maintain a constant voltage value increase the advance angle β by the regulator of the attenuation angle (RAA). The control characteristic of the inverter taking into account the switching angle of the thyristors is described by the following formula:

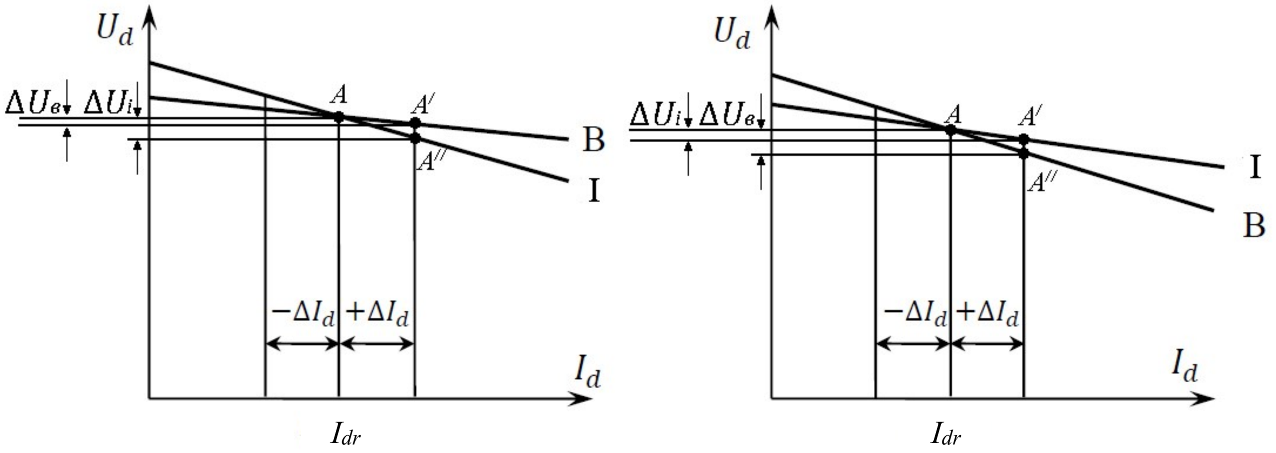
$$U_d = U_{d0} cos\delta - \frac{3}{\pi} I_d X_{K.I.}, \tag{8.12}$$

where $X_{K.I.}$ is reactance of leakage inductances of transformer windings connected to inverter.

The decreasing external characteristic of the inverter, formula (8.12), can lead to unstable modes of operation of the DCT. This situation occurs when the slope of the rectifier characteristic is less than that of the inverter, Fig. 8.6, ie, when the power of the system from which energy is taken is greater than the power of the system that consumes energy, Fig. 8.7 a). From fig. 8.7 a) it is seen that in steady state the rectifier system operates at operating point A. Offset of the operating point by the value $+\Delta I_d$ will reduce the output voltage of the rectifier and the input voltage of the inverter. Under this condition, the mode of operation of the rectifier is described by the operating point $A^{/}$, the inverter - $A^{//}$. Since the voltage gain of the rectifier ΔU_B is less than the voltage gain of the inverter ΔU_i, an unbalanced EMF will appear in the system, which will lead to an additional increase in transmission current. Therefore, this mode of operation is unstable. Similarly, it can be shown that if the current is reduced, the rectifier-inverter system is also unstable.

In the case where the rectifier characteristic is steeper than that of the inverter, any oscillation relative to equilibrium point A will result in a current in the system with the opposite sign.

To further increase the stability of the system, the rectifier-inverter also uses current control. The current regulator (CR) changes the opening angle of the rectifier thyristors to maintain a constant current value. The characteristics of the rectifier are similar to those shown in Fig. 8.7. If the voltage in the transmission system decreases, the controller reduces the value of the angle α. The CR provides stable operation at any ratio of transmitting and receiving systems.

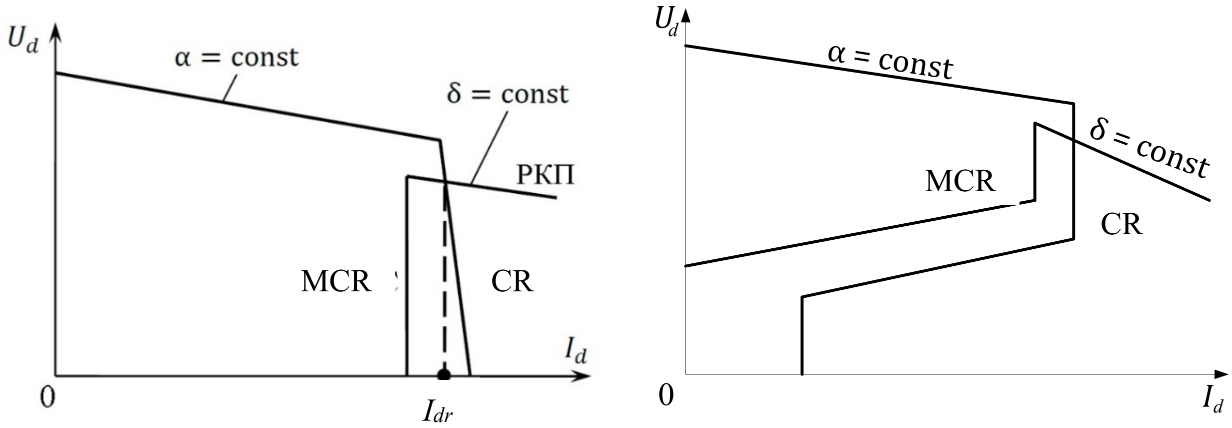


a) unstable mode b) stable mode

Fig. 8.7. Operation modes of the rectifier-inverter system

With a significant reduction in voltage, the control range of the CR is not enough. In this case, use a voltage regulator (VR). The main disadvantage of the device is its high inertia.

If the output voltage of the rectifier at zero value of the opening angle of the thyristors α = 0 becomes less than the anti-EMF of the inverter, the system becomes unstable and the current in the line drops to zero. To avoid this mode, at the same time as reducing the voltage of the rectifier, it is necessary to reduce the anti-EMF of the inverter. To do this, install a minimum current regulator (MCR) in the inverter. It increases the advance angle β of the thyristor opening as the line current decreases, reducing its anti-EMF if the transmission current becomes less than the minimum value set by the MCR. Usually the minimum value of the MCR current of the inverter is 90% of the maximum value of the PC rectifier. If one of the specified values changes, the other is automatically changed. Therefore, the line current is limited on two sides and its value does not exceed the specified limits, even in the event of a short circuit. Only the output voltage of the rectifier and the EMF of the inverter change. The corresponding characteristics of the rectifier-inverter system are shown in Fig. 8.8 a). DCT current regulation is provided by changing the maximum value of the CR current. At the same time the minimum value of MCR current changes, Fig. 8.8 b).



a) rectifier and inverter current limiting system б) coordinated regulation of maximum and minimum line current

Fig. 8.8. Characteristics of the rectifier-inverter system

This method of regulating the operating modes provides a stable mode of operation of the DCT in a wide range of transported energy. The main task of regulation is to maintain a constant value of DCT power, which can be done by regulating both the voltage and current of the line. DCT power is regulated by changing the line current, which ensures minimal losses in converter substations. Additional benefits of current regulation are protection against short circuits in the line and reduction of system inertia.

DCT voltage regulation is used to further reduce DCT losses caused by higher current harmonics generated by the rectifier and inverter as nonlinear consumers. It is obvious that the agreed reduction of the opening angle of the thyristors of the rectifier α and the inverter β will not change the value of DCT current, formula (8.2), (8.8), (8.9), but at the same time improve the harmonic composition of DCT current consumed.

Task solution examples

Task № 1

Two-wire direct power line with a diameter of wires $d = 20$ mm, made of copper (resistivity of copper $\rho = 0.01673$ Ohm·mm^2 / m), has a length of $l = 1000$ km and feeds a load capacity of $P_L = 50$ MW. What should be the voltage at the beginning of the line so that the efficiency of energy transfer was $\eta = 0.9$?

Solution:

The total resistance of the transmission line R is:

$$R = \frac{8\rho \cdot l}{\pi \cdot d^2} = \frac{8 \cdot 0.01673 \cdot 10^6}{3.14 \cdot 400} = 106.5 \text{ Ohm.}$$

Energy losses in the P_{loss} transmission line are:

$$P_{loss} = \frac{P_L}{\eta} - P_L = 5.56 \text{ MW.}$$

The current of the I_L line is calculated by the formula:

$$I_L = \sqrt{\frac{P_{loss}}{R}} = 228.4 \text{ A.}$$

Voltage at the beginning of the line U_1:

$$U_1 = \frac{P_{loss} + P_L}{I_L} = 243.24 \text{ kV.}$$

Answer: Voltage at the beginning of the line U_1 =234.24 kV.

Tasks for themselves solving

Task № 1

Two-wire DC power line 100 kV with wires with a diameter of $d = 40$ mm, made of copper (resistivity of copper $\rho = 0.01673$ Ohm·mm^2 / m), has a length of $l = 2000$ km. What is the load capacity of the P_L should be fed to the line, so that the efficiency of energy transport was $\eta = 0.8$.

Task № 2

DC and AC power lines 10 kV with a frequency of 50 Hz were designed using the same type of conductors with the following parameters: $R_0 = 0.5$ Ohm / km, $L_0 = 0.1$ H / km, $G_0 \approx 0$, $C_0 = 1$ mF / km. Compare the maximum length of lines l_1 and l_2 of direct and alternating current power lines, respectively, at which the efficiency of the system is $\eta = 0.8$, if the load power $P_\mathrm{L} = 1$ MW.

Task № 3

Between two 380 V, 50 Hz AC networks there is a DC insert that transports energy from network 1 to network 2. A rectifier at the input of the DC insert connecting it to network 1 and an inverter driven by a network at the output of the insert connecting it to network 2 is designed on the basis of three-phase bridge controlled thyristor rectifiers. The inverter operates with a constant angle β, which provides a value of DC voltage at the output of the DC insert $U_{out} = 250$ V. Calculate the range of control angle of the insert rectifier $\alpha_{\min}..\alpha_{\max}$ to adjust the power of the insert in the range $P_{INS} = 10..20$ kW, if the resistance of the insert $R_{INS} = 0.3$ Ohm.

Task № 4

Between two 380 V, 50 Hz AC networks there is a DC insert that transports energy from network 1 to network 2. A rectifier at the input of the DC insert connecting it to network 1 and an inverter driven by a network at the output of the insert connecting it to network 2 is designed on the basis of three-phase bridge controlled thyristor rectifiers. The inverter operates with a constant angle β, which provides a value of DC voltage at the output of the DC insert $U_{out} = 250$ V. It is known that to regulate the input power of the insert in the range $P_{INS} = 10..20$ kW voltage at the input input varies in the range $U_{INS} = 300. .320.7$ V. Calculate the values of the capacity, reactor and ranges of its control angles of the reactive power compensator STATCOM, which provides compensation for the reactive power generated by the input controlled rectifier rectifier insert DC.

Task № 5

Between two 380 V, 50 Hz AC networks there is a DC insert that transports energy from network 1 to network 2. A rectifier at the input of the DC insert connecting it to network 1 and an inverter driven by a network at the output of the insert connecting it to network 2 is designed on the basis of three-phase bridge controlled thyristor rectifiers. The insertion resistance $R_{INS} = 0.5$ Ohm, the rectifier system 1 has an output resistance $r_1 = 0.3$ Ohm, and the inverter system 2 output resistance $r_2 = 0.7$ Ohm. Determine at which control angles α and β from system 1 to system 2 the power of 10 kW with the minimum amount of reactive power generation is transmitted.

Task № 6

Direct and alternating current power lines $U_{in} = 10$ kV with frequency $f = 50$ Hz are designed using the same type of conductors with parameters: $R_0 = 0.5$ Ohm / km, $L_0 = 0.1$ H / km, $G_0 \approx 0$, $C_0 = 1$ mF / km. Compare the maximum length of lines l_1 and l_2 of DC and AC power, respectively, at which the total power of the generator S_G will be at least twice the active power released at a load of $P_L = 1$ MW (active load).

Practice lesson № 9. Basics of operation of the electricity market of Ukraine

Theory

According to the Law on Electricity Market, the market participants are: electricity producers, electricity supplier, market operator, trader, consumer, guaranteed buyer (currently SE Energorynok), transmission system operator (currently NEK Ukrenergo ") and the distribution system operator (currently electricity transmission companies).

Components of the New Electricity Market:

- balancing market;
- market of ancillary services;
- day-ahead market;
- intraday market;
- bilateral agreement.

The main functions provided by the New Electricity Market

Balancing market - ensuring real-time balancing of production / imports and consumption / exports, settlement of systemic constraints in the UES of Ukraine, as well as financial settlement of electricity imbalances.

Ancillary services market - acquisition by the Operator of the system of transfer of ancillary services from ancillary service providers.

Day-ahead market - purchase and sale of electricity on the day following the day of the auction.

Intraday market - purchase and sale of electricity after the end of trading on the market "for the day ahead" and during the day of physical supply of electricity.

Bilateral agreements - purchase and sale of electricity between two market participants outside organized market segments, except for the contract for the supply of electricity to consumers. The scheme of interaction of market participants is shown in Fig. 9.1.

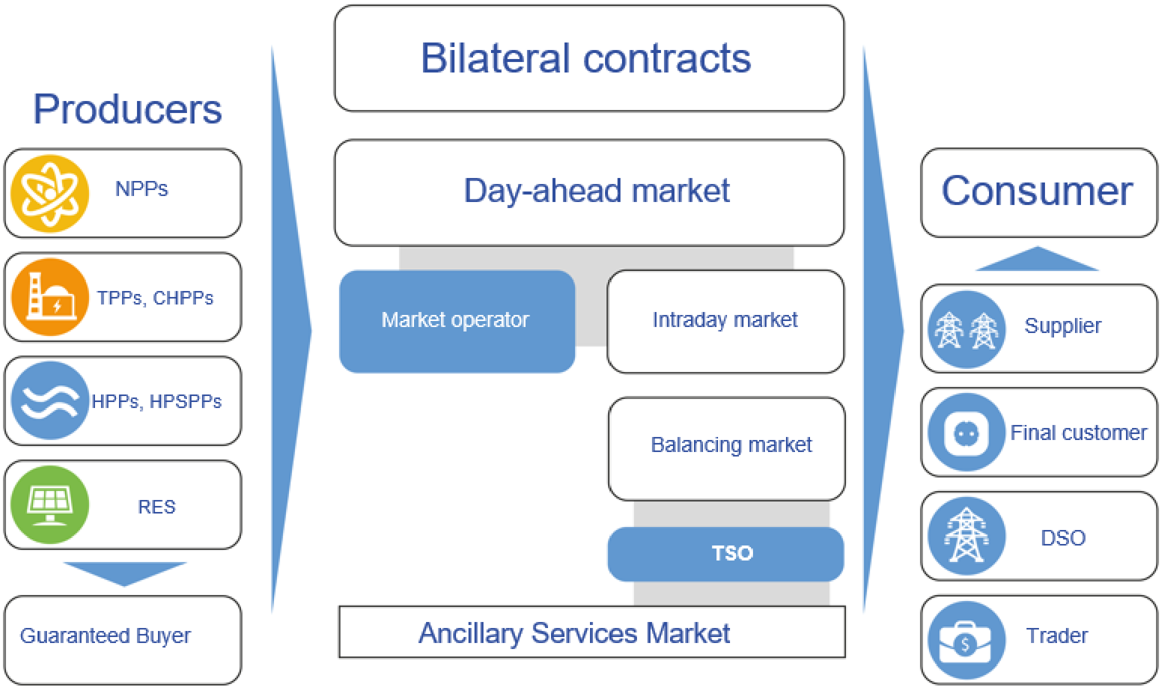


Fig. 9.1. Scheme of interaction of electricity market participants

An important condition for the stable operation of the electricity market is to maintain a balance between production and consumption of electricity. The difference between the actual volume of supply or consumption, import, export of electricity is called imbalance. Depending on the difference between supply and consumption, imbalances can be positive or negative.

A positive imbalance is an excess of electricity produced and not consumed, and a negative imbalance is the amount of unproduced electricity or electricity that needs to be purchased for consumption.

Based on these features of positive and negative imbalances, the issues of their payment are resolved by the transmission system operator (TSO) of NEC Ukrenergo as follows:

- in case of a positive imbalance, TSO buys up excess electricity, but at a much lower price than in other market segments;
- in case of a negative imbalance, it is necessary to buy additional electricity at higher prices, and these costs will be borne by the party responsible for the balance.

In Ukraine, the party responsible for the balance is the market participant, which is obliged to report and comply with its hourly schedules of electricity supply in accordance with the volume of purchased and / or sold electricity, and is financially responsible to the TSO for its imbalances. All participants in the electricity market are responsible for imbalances, except for consumers who buy it under a supply contract. But RES producers also have certain characteristics regarding liability for imbalances.

From 2021, RES producers in Ukraine are responsible for imbalances within the balancing group of the guaranteed buyer. In particular, they reimburse the guaranteed buyer for the cost of settling imbalances according to the following rules:

- for RES facilities with an installed capacity of more than 1 MW:

- from January 1, 2021 - 50%;
- from January 1, 2022 - 100%;

• for RES facilities with an installed capacity of less than 1 MW:

- from January 1, 2021
- 10% with a further increase of 10% annually to 100% in 2030.

At the same time, when reimbursing the cost of settling imbalances for RES producers until December 31, 2029, the permissible deviations in the actual hourly volumes of electricity supply were set at 10% for wind generation and 5% for solar generation.

Therefore, all participants in the electricity market in Ukraine, except for the exceptions for RES producers and consumers, are obliged to bear financial responsibility for electricity imbalances before the TSO. But this responsibility depends on the results of settling imbalances.

Features of settlement of imbalances

Settlement of electricity imbalances is the sale of surplus electricity or the purchase of its insufficient volumes on the balancing market.

To resolve imbalances, market participants must:

• become a party responsible for the balance sheet or a member of a balancing group to transfer its financial responsibility to another party responsible for the balance sheet;

• enter into an agreement on the settlement of imbalances with the TSO;

• provide guarantees of fulfillment of financial obligations under agreements on settlement of imbalances in accordance with the Market Rules.

At the same time, in accordance with the rules of the market, the guaranteed buyer is released from the obligation to provide the operator of the transmission system with financial guarantees of fulfillment of obligations under contracts for the settlement of electricity imbalances.

In the balancing group of a guaranteed buyer, the party responsible for the balance is the guaranteed buyer. According to the Register of Guaranteed Buyers, as of February 8, 2021, the balancing group includes 838 RES producers. According to the Market Rules, the guaranteed buyer is financially liable to the TSO for electricity imbalances of all members of the balancing group. The value of imbalances of the guaranteed buyer is calculated by the TSO for each settlement period of the day depending on the amount of imbalances and their prices determined by the Market Rules.

It should be noted that according to the Market Rules, the members of the balancing group are financially liable for imbalances to the party responsible for the balance within their electricity imbalances. Therefore, RES producers as members of the balancing group of the guaranteed buyer are responsible for imbalances to the guaranteed buyer.

Responsibility for imbalances

According to the Procedure for Purchase of Electricity Produced from Alternative Energy Sources by the Guaranteed Buyer, approved by the Resolution of the National Commission for Energy Regulation of Ukraine No. 641 of April 26, 2019 (hereinafter - the Procedure), RES producers reimburse the guaranteed buyer. The amount of compensation is calculated by formulas and depends on:

1. *The results of forecasting the supply of electricity*

On January 15, 2021, the National Commission for Regulation of Economic Competition amended the Procedure for forecasting the supply and consumption of electricity. Under the new rules, RES producers must provide the guaranteed buyer with forecast and updated schedules of supply and consumption:

- until 9:00 the day before the trading day;
- from 15:00 the day before the trade, but not later than 55 minutes before the "closing of the gates" of the Intraday market (IM).

In the previous provisions of the Procedure, the updated schedule of electricity supply could be provided no later than 2 hours and 45 minutes, ie almost 3 hours before the "closing of the gates" of the IM. Under such conditions, it is very difficult to forecast the release of electricity from solar and wind generation, so reducing the period for updating the holiday schedule to 55 minutes will have a positive impact on the quality of forecasting of RES producers.

2. Volumes of electricity not released by RES producers as a result of execution of TSO commands

Another important change is to take into account when calculating the share of the cost of settling the imbalances of volumes of electricity not released by the RES producer as a result of the execution of TSO commands to reduce the load. In previous editions of the Procedure, possible TSO commands to reduce the load in the calculation of imbalances were not taken into account.

Payment of imbalances in the balancing group of the guaranteed buyer is as follows:

- the guaranteed buyer signs the act of purchase and sale of electricity to resolve imbalances with TSO for the billing month;
- after settlements with TSO, the guaranteed buyer calculates the share of reimbursement of the cost of settling the imbalance of electricity of the guaranteed buyer and sends to RES producers an act of acceptance-transfer of the share of reimbursement of the cost of settling the imbalance of electricity;
- the guaranteed buyer and the RES producer sign an act of acceptance-transfer of the share of reimbursement of the cost of settling the imbalance within the time limits set in the Procedure;
- RES producer pays the share of reimbursement of the cost of settlement of electricity imbalance to the guaranteed buyer within the first 3 working days from the date of receipt of the acceptance certificate.

It is important to keep in mind that RES producers lose their membership in the balancing group of the guaranteed buyer in the event of failure to pay a share of the reimbursement of the cost of settling the imbalance. The guaranteed buyer notifies TSO of this the day after the violation of the terms and conditions of payment. However, RES producers acquire the right to membership in the balancing group of the guaranteed buyer after:

- providing supporting documents on full payment of the share of reimbursement of the cost of settling the imbalance;

• obtaining from the guaranteed buyer within 3 working days consent to join the balancing group.

Thus, the rules for settling imbalances are set for all participants in the electricity market. However, since 2021, there have been significant changes in the liability for imbalances of RES producers, who were previously released from liability for the balance. And they concern not only the amount of liability for imbalances, but also the conditions for forecasting and operation of the balancing group of the guaranteed buyer.

Green auctions

Ukraine has an energy sector, which provides for an increase in the use of renewable energy sources in Ukraine by 2035 to 25%. However, with the development of the industry, the green tariff loses its effectiveness. The rapid development of renewable energy sources and high green tariffs, in addition to the positive effects, create certain problems. Technical problems with balancing and integration of RES into the unified energy system of Ukraine. In addition, there is a burden on the state budget and risks of significant price increases for electricity consumers.

Therefore, there is a need to review the existing model of industry support. To attract the first investors, countries are introducing a fixed tariff that allows them to learn, implement the first projects, assess their value. But when the industry is already formed - you need to work under market conditions, in particular in the framework of green auctions.

Support quota auctions are a way to identify green generation projects that will receive government support for electricity generation. They work on the reverse principle: the investor who offers the lowest price for electricity wins. The starting price is the size of the green tariff established by law, from which participants reduce rates. The winner gets the opportunity to build new capacity and sell electricity at the price determined at the auction for 20 years from the date of commissioning of the station.

The size of quotas determines how many new green capacities the state is ready to support. The total support quota is divided into three lots - sun, wind and other renewable energy sources. Competition in auctions takes place between projects in one category (although the law provides for the possibility of technology-neutral auctions). The share of quotas for each category may not be less than 15%.

The main advantage of auctions over the established green tariff is market mechanisms. Competition allows you to determine a fair price for electricity from alternative sources, which will be more profitable for the state and end consumers.

Green auctions now operate in many European countries, including Germany. After the introduction of this system in 2015, solar electricity prices fell from 9.17 eurocents / kWh to 4.91 in October 2017. Currently, the average price for solar electricity at the country's auctions is 5.68 eurocents.

In the UK, according to the results of the 2019 auction, new wind farms have agreed on a price that may not require additional subsidies for the first time - 3.96 pence / kWh. Back in 2012, the guaranteed price for such projects was 15 pence / kWh.

The fixed green tariff in Ukraine in 2020 for large solar stations is 11.26 eurocents / kWh, for wind - 9.05 eurocents / kWh.

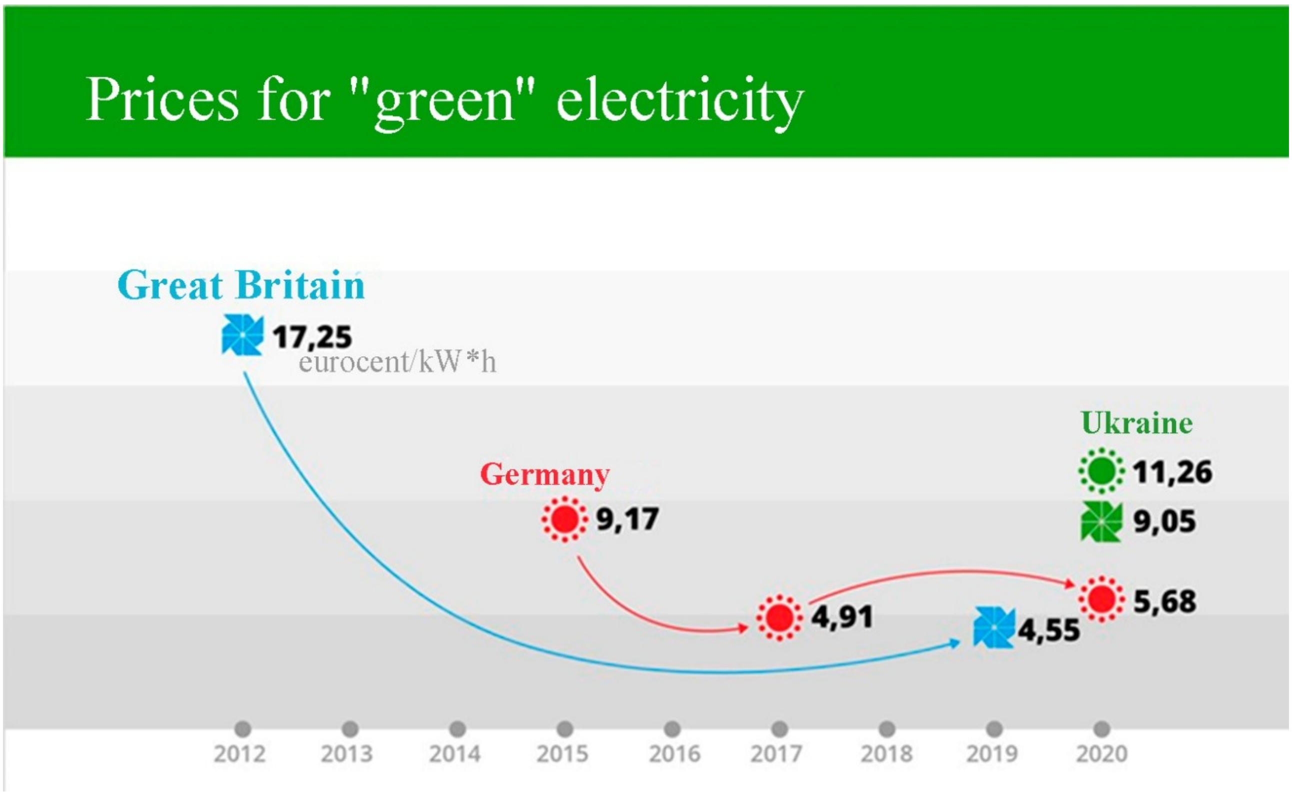


Fig. 9.2. Prices for electricity from RES in different countries

Another advantage of auctions is the fixing of the price for 20 years, while the green tariff is valid only until 2030. Long-term and transparent conditions for receiving support at the auction will guarantee investors the efficiency of investing, will form the investment attractiveness of the industry and increase the availability of cheap loans.

Investors also prefer auctions because of their reliability. When the price is determined in a competitive competition, there is no dispute about whether it is too high or too low. If public authorities do not set a tariff, they are less tempted to revise it later.

The shares are designed primarily for new large wind (over 5 MW) and solar power plants (over 1 MW). Investors in lower-capacity power plants and those running on other renewable energy sources, such as biomass and biogas, can participate in auctions voluntarily or receive a green tariff until 2030 under a pre-existing procedure. In addition, all stations that have already been commissioned by 2020 continue to sell electricity at the established tariff.

Task solution examples

Task № 1

The solar power plant, connected to the UES of Ukraine, generates energy with an average daily capacity of P_C = 5 MW. The station has a solar power forecasting system with a standard deviation of σ_1 = 1 MW. Calculate what profit will improve the forecast system, which will reduce the error to $\sigma_2 = 0.25$ MW. The cost of electricity is $B = 7$ UAH / kWh. The law of distribution of forecast error is considered normal.

Solution:

According to the conditions on the electricity market, producers of electricity based on solar power plants pay a penalty for imbalances if the forecast error does not exceed $\delta = 5\%$, which corresponds to the power range $P = 5 \pm 0.25$ MW. Having set the normal law of power distribution p_d:

$$p_d = \frac{1}{\sigma_1\sqrt{2\pi}} exp\left(\frac{\left(p - P_C\right)^2}{2\sigma_1{}^2}\right), \tag{9.1}$$

and integrating this value in the range of 4.75..5.25 we obtain the share of energy δ_{W1} generated without imbalances.

$$\delta_{W1} = \int\limits_{4.75}^{5.25} p_d dp = 20\ \%. \tag{9.2}$$

Hence, for 20 % of electricity, i.e.:

$$W_1 = P_C{\cdot}24{\cdot}\delta_{W1} = 24\ \text{MW·h}, \tag{9.3}$$

the solar power plant will make a profit Pr_1:

$$Pr_1 = W_1{\cdot}B = 168\,000\ \text{UAH}, \tag{9.4}$$

and for 80 % electricity

$$W_2 = P_C{\cdot}24{\cdot}(1\text{-}\delta_{W1}) = 96\ \text{MW·h}, \tag{9.5}$$

pay a penalty Pn_1:

$$Pn_1 = W_2{\cdot}B = 672\,000\ \text{UAH}, \tag{9.6}$$

that is, such a power plant is unprofitable and operating at a loss 504 000 UAH.

After improving the forecast system, the share of energy δ_{W2} generated without imbalances is:

$$\delta_{W2} = \int\limits_{4.75}^{5.25} p_d dp = 68\ \%. \tag{9.7}$$

Hence, for 68 % of electricity, i.e.:

$$W_3 = P_C{\cdot}24{\cdot}\delta_{W2} = 81.6\ \text{MW·h}, \tag{9.8}$$

the solar power plant will make a profit Pr_2:

$$Pr_2 = W_3 \cdot B = 571\ 200 \text{ UAH}, \qquad (9.9)$$

and for 32 % electricity

$$W_4 = P_C \cdot 24 \cdot (1 - \delta_{W2}) = 38.4 \text{ MW} \cdot \text{h}, \qquad (9.10)$$

pay a penalty Pn_2:

$$Pn_2 = W_4 \cdot B = 268\ 800 \text{ UAH}, \qquad (9.11)$$

which allows you to make a profit $Pr = 302\ 400$ UAH.

Answer: profit $Pr = 302\ 400$ UAH.

Tasks for themselves solving

Task № 1

The wind power plant, connected to the UES of Ukraine, generates energy with an average daily capacity of $P_C = 10$ MW. What is the value of the standard deviation of the forecast system is sufficient to obtain 90% of the profit from the maximum value. The law of distribution of forecast error is considered uniform.

Task № 2

The power of a wind farm varies according to the law $P(t) = 100 + 15 \cdot \sin(2\pi t/60)$ W, where time t is measured in minutes. Power forecasting is carried out with a certain error according to the law $P_f(t) = 100 + 15 \cdot \sin(2\pi t/60)$ W. Determine the capacity of the battery, which will eliminate penalties for imbalances in the sale of electricity to the integrated power grid. Assume that the charge and discharge of the battery is performed without loss.

Task № 3

The power of a wind farm varies according to the law $P(t) = 100 + 15 \cdot \sin(2\pi t/60)$ W, where time t is measured in minutes. Power forecasting is carried out with a certain error according to the law $P_f(t) = 100 + 15 \cdot \sin(2\pi t/60)$ W. Determine the capacity of the battery that will provide maximum profit. The cost of 1 kWh of the battery is Ba = 10 UAH, the cost of electricity Be = 7 UAH / kWh, the efficiency of charging and discharging the battery is $\eta = 0.8$.

References

1. IEC 6100-4-7 Electromagnetic compatibility (EMC) Part 4-7: Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto.
2. IEC 61000-4-30 Electromagnetic compatibility. Testing and measurement techniques – Current quality measurement methods.
3. EN 50160:1999. Voltage characteristics of electricity supplied by public distribution systems. CENELEC. 1999, 44 p.
4. Мережі постійного і змінного струму з альтернативними джерелами енергії – 2: Конспект лекцій [Електронний ресурс]: навч. посіб. для студ. спеціальності 171 «Електроніка» / КПІ ім. Ігоря Сікорського; уклад.: Є.В. Вербицький– Електронні текстові дані (1 файл: 4,3 Мбайт). – Київ: КПІ ім. Ігоря Сікорського, 2021. – 96 с. – Назва з екрана.
5. Мережі постійного і змінного струму з альтернативними джерелами енергії – 1. Конспект лекцій [Електронний ресурс] : навчальний посібник для студентів спеціальності 171 «Електроніка» / КПІ ім. Ігоря Сікорського ; уклад.: Є. В. Вербицький, Л. М. Батрак. – Електронні текстові дані (1 файл: 3,9 Мбайт). – Київ : КПІ ім. Ігоря Сікорського, 2021. – 140 с. – Назва з екрана.
6. ДСТУ IEC 60050-604:2004. Словник електротехнічних термінів. Частина 604. Вироблляння, передавання та розподіляння електричної енергії. Експлуатація електротехнічних установок.
7. Закон "Про ринок електричної енергії" від 21 липня 2020 року № 810-IX.
8. Передача электроэнергии на большие расстояния: Учебное пособие/ С. С. Ананичева, П. И. Бартоломей, А. Л. Мызин; изд. 3-е, исправл. Екатеринбург: УрФУ, 2012. 85 с.
9. Электрические сети сверх- и ультравысокого напряжения ЕЭС России. Теоретические и практические основы: в 3 т. Том 1. Электропередачи переменного тока. / под общей редакцией чл. корр. А.Ф. Дьякова. М.: НТФ «Энергопрогресс», 2012 – 696 с.
10. Электрические сети сверх- и ультравысокого напряжения ЕЭС России. Теоретические и практические основы: в 3 т. Том 2. Электрические подстанции переменного тока. Средства и интеллектуальные системы управления / под общей редакцией чл. корр. А.Ф. Дьякова. М.: НТФ «Энергопрогресс», 2012 – 668 с.
11. Электрические сети сверх- и ультравысокого напряжения ЕЭС России. Теоретические и практические основы: в 3 т. Том 3. Электропередачи переменного тока специального исполнения. Электропередачи и вставки постоянного тока. / под общей редакцией чл. корр. А.Ф. Дьякова. М.: НТФ «Энергопрогресс», 2012 – 368 с.
12. Електричні процеси в електричних колах з ключовими елементами/ Жуйков В.Я., Денисюк С.П. – К.: ТЕКСТ, 2010. – 264 с.

13. Баланс энергий в электрических цепях / Тонкаль В.Е., Новосельцев А.В., Денисюк С.П. и др.; Отв. ред. Волков И.В.; АН Украины. Ин-т пробл. Энергосбережения. – Киев: Наук. Думка, 1992. – 312 с.

14. Нормативно-правовое регулирование качества электрической энергии. Анализ украинских и европейских законодательных актов и нормативно-технических документов/ Жаркин А.Ф., Новский В.А., Палачев С.А. – Киев: Ин-т электродинамики НАН Украины, 2010. – 167 с.

15. Герасименко, А. А. Электроэнергетические системы и сети. Версия 1.0 [Электронный ресурс] :конспект лекций / А. А. Герасименко, Е. С. Кинев, Т. М. Чупак. – Электрон. – Красноярск : ИПК СФУ, 2008.

16. Енергетичний аудит: Навчальний посібник / О.І. Соловей, В.П. Розен, Ю.Г. Лега, О.О. Ситник А.В. Чернявський, Г.В. Курбаса. – Черкаси, 2005. – 299 с.

17. Куско А. Качество электроэнергии в электрических сетях. / Куско А., Томпсон М.: пер. с англ. Рабодзея А.Н. – М.: Додека XXI – 2008, 336 с.

18. Виджей. К. Суд. HVDC and FACTS controllers: применение статических преобразователей в энергетических системах: Пер. с англ.: НП «НИИА», 2009. – 344 с.

19. В.И. Мелешин. Транзисторная преобразовательная техника. М.: Техносфера, 2005, 632 с.