Ministry of Education and Science of the Russian Federation
State Educational Institution of Higher Professional Education
«TOMSK POLYTECHNIC UNIVERSITY»

A.V. KABYSHEV, G.A. NIZKODUBOV

ELECTRICAL SUPPLY OF INDUSTRIAL ENTERPRISES

Recommended as a study guide by Editorial Board of
Tomsk Polytechnic University

Publishing house of
Tomsk polytechnic university

2012

Library Bibliographic Classification (LBC) 658.26:621.31 (075.8)
Universal Decimal Classification (UDC) 31.29–5я7
К12
Kabyshev A.V.

Electrical supply of industrial enterprises: study guide/A.V. Kabyshev, G.A. Nizkodubov - Tomsk: Publishing house of Tomsk Polytechnic University, 2012. – 234 p.

A concept of reactive power of simple electrical circuits is given in the study guide, actions for its compensation have been revealed. The main factors that influence a decrease in power factor in power supply systems have been analyzed. Specific consequences that entail its lowest value have been studied. Recommendations on capacitor banks installation areas in the existing networks have been provided. Some issues of exploitation of capacitor units at industrial facilities and their impact on stability of load nodes have been briefly discussed. Numerical examples have been provided in the study guide.

The study guide is designed for students of 140400 - "Power and Electrical Engineering" (Master's program "Optimization of developing power systems"), a specialty 140211 - "Power Supply"

LBC **658.26:621.31 (075.8)**
UDC **31.29–5я73**

Reviewers
Engineering manager of JSC “Tomsk Electric-Bulb Plant”
A.I. Prudnikov
Deputy Director of Future Policy Staff Department LLC "Gorseti", Tomsk
T.N. Kirilova

CONTENTS

INTRODUCTION

An increase in production capacity in industry leads to an overload of electrical equipment installed and requires a conversion of power supply system. Traditional solution - laying additional cables or replacing cables by larger cross section conductors, also installation of additional transformers will be of great help. This approach requires significant capital investment and ultimately reflects on the price of products. In addition, capacity of medium-voltage networks is limited. This entails a rejection of electricity supplying organization in bending of additional capacity or a fee for technological connection cost of mains reconstruction above balance sheet attribution.

Feasibility of implementation of reactive power compensation installations at an enterprise is already evident at the stage of technical and economic comparison. As a rule, implementation of capacitor units is cheaper than reconstruction of the electricity network. In addition, by the order №49 of the Ministry of Energy dated February 22, 2007 a procedure of calculating ratio values of the of consumption of active and reactive power has been introduced. According to the procedure a consumer of installed capacity of 150 kW limit allowable values of power factor are 0.4 for networks 6-35 kV and 0.35 for 0.4 kV networks.

Reactive power compensation can improve efficiency of energy use in three main areas: increase in lines and transformers capacity, reduction of active energy losses, voltage normalization. Installation of compensating devices can reduce active losses by reduction of total current. Thus, reactive power compensation can be fully identified as one of energy saving technologies. Even at enterprises where there are no problems with overloading of power grid equipment by reducing the loss of active measures for reactive power compensation recovered over a relatively short period of time.

According to a coefficient of reactive power one can judge how much of the energy consumed is used to perform useful work. A possible approximation of the power factor receptors to the unit and is mainly technical and economic problem of reactive power compensation.

The proposed study guide contains six sections and encompasses theoretical aspects of reactive power compensation at different levels of power supply system of the plant for treatment-sequence fundamental frequency of the alternating current. Asymmetric and non-sinusoidal modes, as well as the modes of the network with very variable reactive loads in the manual are not considered. Availability of the manual does not relieve students from having to use different teaching methods in the literature detailed design of individual questions, designing of distribution networks and electrical power systems, optimization of their work.

The first section summarizes physical principles and basic laws of electrical engineering as applied to the issues of reactive power compensation, components of the full power of the electric networks are considered, using a simple electrical circuits, a concept of reactive power compensation principle and reactive loads is given.

The second section contains materials on the reactive power sources which are used in electrical systems and power systems projects. A principle of their action was summarized, fundamental electrical circuits and static characteristics of the device application were introduced.

The third section deals with issues of reactive power consumption of industrial power consumers. The main factors that influence the decline in the power supply systems were analyzed, businesses and the specific consequences that entails a low power factor.

The fourth section deals with compensation of reactive loads in the presence of consumer companies with synchronous electric motors, and without them, comparative analysis of the characteristics of longitudinal and transverse capacitive reactive power compensation was given, their areas of application wereintroduced as well. Reasons for appropriateness of the compensation of reactive power close to where its consumption were introduced. Distribution of power capacitor banks at load nodes craft networks with voltage up to 1000V includes material management of reactive power in networks of power systems were given in details.

A handbook is illustrated with calculations and examples that encourage students learning.

1. A CONCEPT OF REACTIVE POWER AND ITS COMPENSATION

1.1. Physical foundations and basic laws of electrical engineering as applied to reactive power compensation

1.1.1. AC

Electrical energy is produced, distributed and consumed mostly in the form of an alternating current. Current that changes in time is considered to be an alternating one. At any time point the current is called the instantaneous value of current i. Currents, which values are repeated at regular intervals in the same sequence, are periodic currents. The smallest time interval, over which there are repetitions of the current, is called period T and the reciprocal of the period - the frequency f. Numerically it is equal to the number of periods per unit time.

Alternating current, used in electric power, varies according to the sine law. Instantaneous value of the sinusoidal current is given by: $i = I_m \sin\left(\frac{2\pi}{T}t + \varphi\right)$

(1.1)

– where $\left(\frac{2\pi}{T}t + \varphi\right)$ is an argument of the sine which determines the phase of the harmonic current change; I_m - peak current value; φ – phase angle value at the initial time (t = 0).

The value $2\pi/T = \omega$ is the rate of a phase angle change – it is called the angular frequency that is measured by the number of radians ω by which the phase angle can increase in one second, that is $\omega = 2\pi f$.

The arithmetic average for the whole period of the sinusoid is zero, since the curve is symmetrical about the horizontal axis. The average value of sine wave for a half period of φ up to $\omega\frac{T}{2}+\varphi$ is equal to a half-wave area divided by its base $T/2$ (Fig. 1.1), i.e.:

$$I_{cp} = \frac{1}{T/2}\int_{\varphi}^{\omega\frac{T}{2}+\varphi} i\,\mathrm{d}t = \frac{2\cdot I_m}{T}\int_{\varphi}^{\omega\frac{T}{2}+\varphi}\sin\omega t\,\mathrm{d}t = \frac{2\cdot I_m}{\pi}$$

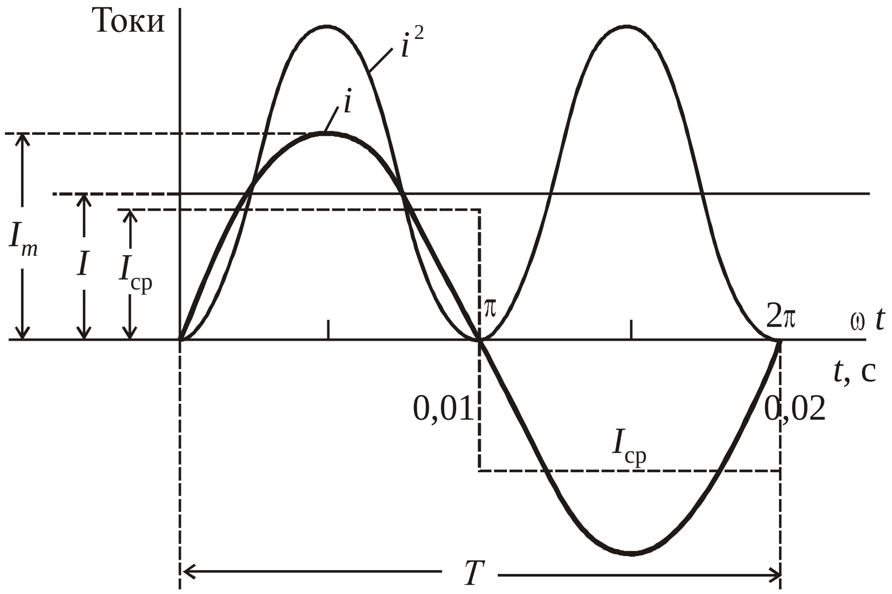


Figure 1.1. The sine value in the rectangular coordinates

Mechanical strength of interaction of two conductors, both have the same current, is proportional to the instantaneous current. The thermal effect of the current is also proportional to the current square. In order to consider the magnitude of harmonic current the concept of mean square or effective current has been introduced: it is necessary to build a quadratic curve of current i^2 over the period (or half-period) and to determine the square root of its mean value:

$$I=\sqrt{\frac{1}{T/2}\int_0^{T/2} i^2 \mathrm{d}t}=I_m\sqrt{\frac{1}{T/2}\int_0^{T/2} \sin^2 \omega t \mathrm{d}t}=\frac{I_m}{\sqrt{2}} \quad . \qquad (1.3)$$

The current value is numerically equal to the direct current which while resistance emits the same amount of heat as the current variable over one time period.
The ratio of rms current to its average value for the positive half-wave is called the current waveform:

$$\kappa_i=\frac{I}{I_{cp}} \; . \; (1.4)$$

When a sinusoidal current changes:

$$\kappa_i=\frac{I}{I_{cp}}=\frac{\pi}{2\sqrt{2}}=1{,}11 \quad .$$

In electrical engineering alternating current consists of active and reactive components.
Active current component is called a component that aimed at creating the work used at current-using equipment. This component is in phase with the voltage. Current component perpendicular to the stress vector is called reactance. The presence of this component in electrical networks is due to the fact that the main types of current-using equipment for their operation need an alternating magnetic field. In addition, in electrical equipment is widely used electrical insulation which forms with the live parts and ground a wide range of capacitors. Reactance of current or power is also required to create an electric field of the capacitors.

1.1.2. A law of electromagnetic induction

In a conductor, located in a magnetic field and moving relative to the magnetic lines, originates an electromotive force, the magnitude and direction of which can be determined based on the law of electromagnetic induction (Faraday's law). In electrical machines, conductors, in which EMF is induced, generally move perpendicular to the magnetic field lines, for such conductors Faraday's law can be written as:

$$e_x = B_x \cdot l \cdot v \quad (1.5)$$

here e_x - the instantaneous voltage in one conductor, B – intensity of the magnetic field or magnetic induction (the number of magnetic lines per unit area at the location of the conductor), l - the active subject to the action of the magnetic flux conductor length, v - velocity relative to the conductor of magnetic lines. Thus, the EMF is directly proportional to the speed of the magnetic lines of the conductor intersection. In most electrical products, a conductor, in which EMF is induced, is an unchanged, closed loop. In this case it is convenient to use the formulation of Faraday's law, proposed by Maxwell:

$$\dot{e} = -\frac{d\dot{\Phi}}{dt} \quad (1.6)$$

here $\dot{\Phi}$ - the total magnetic flux that mates with the contour, $\frac{d\dot{\Phi}}{dt}$ - the rate of the flow change. The minus sign indicates that the EMF originating in the circuit has a direction in which the current generated by it tends to prevent the change produced, mating with the contour. The direction of the EMF is determined by the mnemonic rules (section 1.1.3).

Generator operation of electrical machines is based on the Faraday's law.

1.1.3. A Right-thumb rule

To determine the direction of induced EMF it is convenient to use the right-hand rule. If you position your right hand so that the magnetic field lines enter a palm of the hand (their direction from north N to south pole S), the deflected thumb will indicate the direction of the conductor movement, the rest of the straightened fingers will show the direction of induced EMF (current direction in a closed loop).

In synchronous machines a conductor is usually in a fixed position and the magnetic flux moves with the poles. In other words, the flow is stationary and the conductor moves in a direction opposite to the actual flow. Accordingly, it is necessary to apply the right-hand rule, placing the thumb in the direction of relative motion of the conductor, i.e. in a direction opposite to the actual movement of the poles.

The following rule can be applied to synchronous machines: EMF, induced in a conductor and if the poles rotate clockwise, has the direction from the observer. In the drawings the direction of EMF is marked: the cross - the direction from the observer (the rear end of the arrow), point - to the observer (the front end of the arrow).

1.1.4. The Biot-Savart law

In the magnetic field a conductor carrying an electric current experiences mechanical (electromagnetic) force F, which value can be determined by the Biot-Savart law. In electrical machines, the angle between a conductor and direction of magnetic field lines is 90 °, so the Biot-Savart law:

$$\dot{F} = B \cdot l \cdot i . \quad (1.7)$$

Motor effect of electric cars is based on this law.

1.1.5. Direction of electromagnetic force

Direction of electromagnetic force can be determined by a left thumb rule. If you position your left hand so that the magnetic lines of force enter the palm of your hand and four straightened fingers coincide with direction of current, a deflected thumb will indicate a direction of the force. The rule is of little help applied to electrical products. Figure 1.2 depicts the mechanism of induction. When current passes through a wire it is surrounded by closed circular magnetic lines. Their direction is determined by the right-hand thumb rule: if the gimlet is screwed with the right thread in the current direction, direction of rotation provides the direction for magnetic lines that surround the conductor. These magnetic lines interact with the main magnetic field lines: on one side of the conductor the field will weaken as a result of blending opposite directions of magnetic lines, on the other side of the conductor equally directed magnetic lines will increase the magnetic field (Fig. 1.2). Magnetic lines always tend to reduce its length (as stretched elastic threads), so the wire will experience a force coming from the magnetic lines. The force is directed from the condensation of magnetic field lines towards vacuum. Thus, in Fig. 1.2 a conductor will be pushed to the left. According to Newton's law “To every action there is always an equal and opposite reaction”, then the same strength coming from the conductor, but aimed at the opposite direction, will be experienced by the magnetic lines.

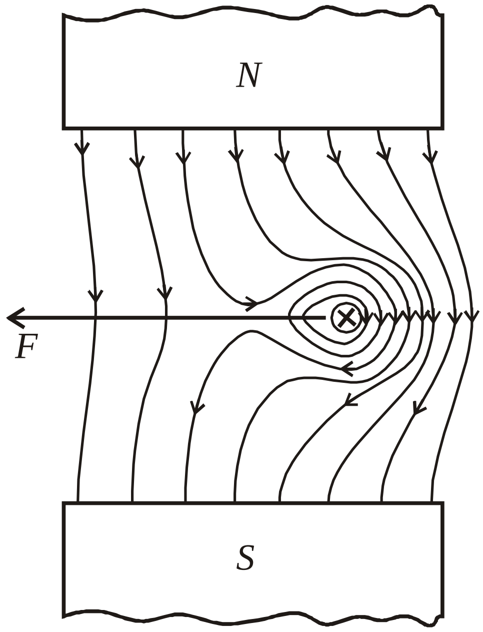


Fig. 1.2. Direction of electromagnetic force

1.1.6. Lenz’s Law

In accordance with the law of Lenz any electromagnetic system tries to keep unchanged the magnetic flux. When the external magnetic flux, connected to a conducting circuit, is changed, forces of electrical and mechanical type appear and try to preserve the value of the magnetic flux. The forces of electrical type (electromotive forces) cause currents that generate their own magnetic fluxes directed in such a way that the resulting stream remains unchanged. Mechanical forces (electromagnetic forces) cause movement of the circuit so that a new magnetic flux remains equal to its previous value. Using Lenz's law, we can determine the direction of the EMF as well as the electromagnetic force.
A reciprocity principle of electrical machines is based on Lenz's law, i.e. electrical machines can operate both as a generator or a motor.

1.1.7. Electromagnetic field

Electromagnetic field is formed around a conductor through which flows an electric current. Influence of this field on other conductors can be observed at a considerable distance. The electric and magnetic field components are always linked but in electrical engineering, depending on the task, they may be considered separately.
Magnetic field is associated with the movement of electrically charged particles or

bodies. It is represented by imaginary magnetic lines that are closed concentrically around a conductor and create a magnetic flux Φ. The intensity of the magnetic field B is proportional to the current and depends on the shape and size of a conductor, as well as the environment - magnetic permeability. Magnetic induction, referred to the absolute permeability μ, characterizes the magnetic field H (magnetizing force):

$$\dot{H} = \frac{\dot{B}}{\mu} \quad (1.8)$$

If a conductor is in the form of a coil and can pass current, magnetic fields of all *n* windings will be formed inside the coil therefore total magnetic flux is formed. The magnetic flux is equal to the algebraic sum of Φ_i fluxes connected (linked) with separate windings of the coil and is called the flux linkage:

$$\psi = \Phi_1 + \Phi_2 + ... + \Phi_n \ . \ (1.9)$$

In case of equality between magnetic fluxes:

$$\psi = w \cdot \Phi \ (1.10)$$

where Φ - the magnetic flux of one coil; w - number of windings in the coil.
If the closed loop (coil) is moved in an inhomogeneous magnetic field or a fixed closed loop is put in a time-varying magnetic field, EMF occurs (is induced) in the circuit. The induced EMF in the circuit is proportional to the rate of flux change in time and number of windings of the circuit and is opposed to the direction (sign) of the magnetic flux:

$$\dot{e} = -w \frac{d\dot{\Phi}}{dt} \ . \ (1.11)$$

In case of decrease in magnetic flux, EMF is positive, in case of increase - negative. Current direction, which arises in the circuit under the influence of the induced EMF, coincides with the voltage. Current is always directed in such a way that counteracts the change in magnetic flux inside the loop (Lenz's law). The coefficient of proportionality between the flux and coil current that generates a magnetic field with a constant magnetic permeability of the environment is called coil inductance:

$$L = \frac{\Psi}{I} = \frac{w \cdot \Phi}{I} \ . \ (1.12)$$

Coil inductance in the air is constant and determined by its structure (size, number of windings). Coil inductance in a ferromagnetic environment increases in proportion to μ. A ferromagnetic environment for a coil is often created by the closed steel core – a magnetic circuit. Magnetic permeability of steel depends on

the magnetic induction $\mu = f(B)$. Therefore, coil inductance with a steel core is not constant: it is determined by the power flowing through the coil current.
μ = f (B) dependence is not often used, magnetization curves establishing relationship between magnetic induction and magnetizing force are used instead (Figure 1.3). Magnetic induction *B* is increased almost proportionally to *H* in case when there is an increase in magnetic field. After that its growth slows down due to magnetic saturation.

General flow of a coil is changed when current in the coil changes. As a result EMF self-induction is induced in the coil. Electromotive

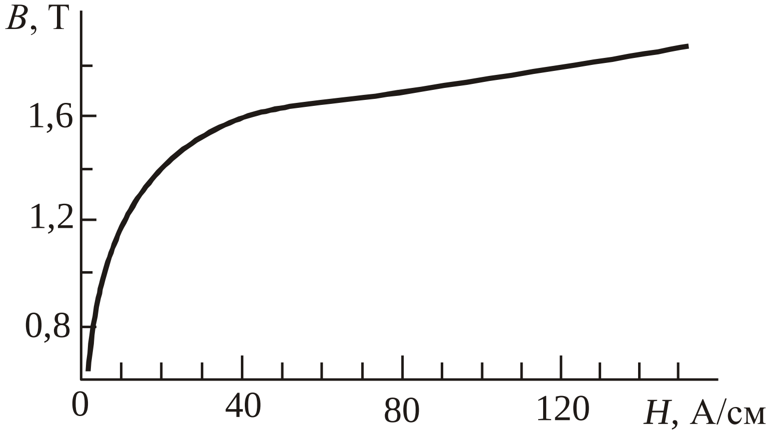


Fig. 1.3. A magnetization curve of electrical steel

self-induction force also depends on the rate of magnetic flux change associated with a change in current in the coil and the number of windings:

$$e_L = -\frac{wd\Phi}{dt} = -L\frac{di}{dt}\ . \quad (1.13)$$

In case of a sinusoidal current $i = I_m \sin\omega t$ self-induction EMF is:

$$e_L = -L\frac{di}{dt} = -\omega L \cdot I_m \cos\omega t = E_m \cos(\pi - \omega t) = E_m \cos\left(\frac{\pi}{2} + \left(\frac{\pi}{2} - \omega t\right)\right) =$$
$$= -E_m \sin\left(\frac{\pi}{2} - \omega t\right) = E_m \sin\left(-\left(\frac{\pi}{2} - \omega t\right)\right) = E_m \sin\left(\omega t - \frac{\pi}{2}\right), \quad (1.14)$$

that is lagging in phase by a quarter period of the current.
By Lenz's law the direction of self-induction EMF is as follows: when the current is increased, self-induction EMF reduces the current in the circuit, and when the current is decreased, EMF is added to the voltage applied to the coil (and causes a current in it). In order for an alternating current to pass through inductance, there must be voltage at inductance terminals which is equal and opposite to induced EMF:

$$u = -e_L = L\frac{di}{dt} = \omega L I_m \sin\left(\omega t + \frac{\pi}{2}\right) = U_m \sin\left(\omega t + \frac{\pi}{2}\right). \quad (1.15)$$

In AC circuits magnetic cores are periodically remagnetized. When demagnetized, magnetic induction core is not decreased to zero: there is a residual magnetism. The change of magnetic induction over a single period of the current shown in Fig. 1.4. Magnetic hysteresis causes steel heating and power losses in magnetic reversal. The area of the hysteresis loop is proportional to the energy used. For different ferromagnetic materials the area of hysteresis loops is different and characterizes properties of materials.

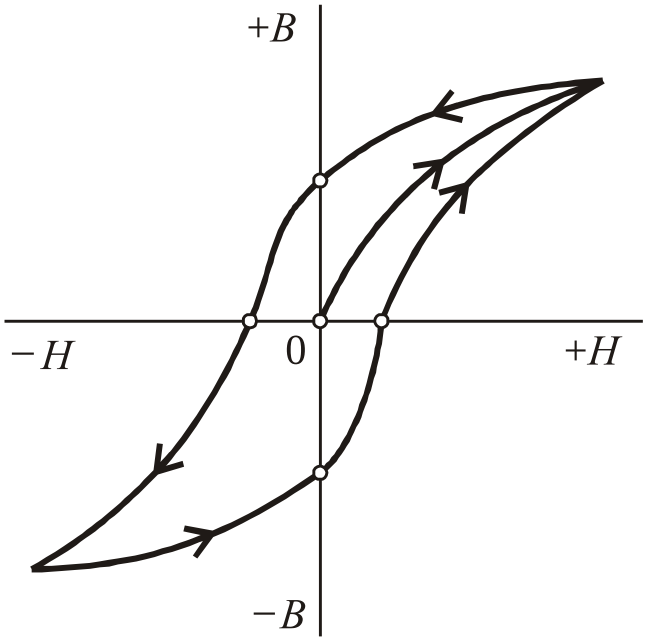


Fig. 1.4. Hysteresis loop

In a DC circuit a coil stores energy in a magnetic field only during the transition process, that is, during the current rise from zero (the moment of switching a coil) to a steady-state value. Later energy in the circuit, coming from the power supply, consumes only heat in the resistance of a coil. If power supply is switched off and a coil is made, the magnetic field, decreasing (disappearing), will induce in a coil EMF of self- inductance and arising damped current will allocate stored in the magnetic field energy in the form of heat on active resistance of the circuit. If a circuit of a current-carrying coil is broken, then the magnetic energy released in the form of an arc (spark) at a circuit break. Almost instantaneous change in current I to a zero value of induced EMF of self-induction will be great, it is determined by the almost instantaneous change in a flow $d\Phi/dt$.

The second component of the electromagnetic field - electric field. Electric charges are affected by a certain magnitude and direction of force. Field lines start on positive charges and end on the negative. They are always perpendicular to the surface of a conductor. Intensity of the electric field is characterized by its intensity *E,* which is defined as the ratio of force *F* to the magnitude of charge *q*, placed in an electric field of a conductor:

$$\dot{E} = \frac{\dot{F}}{q} \qquad (1.16)$$

Physical bodies and structures, with a property to accumulate and retain charges, have capacity. The capacitance C is determined by the ratio of electric charge *q* of the body to the applied voltage:

$$C = \frac{q}{u} \text{ . } (1.17)$$

Current in the circuit with a capacity is equal to the rate of change of its charge:

$$i = \frac{dq}{dt} = C\frac{du}{dt} \text{ } (1.18)$$

or

$$u = \frac{1}{C}\int idt \text{ . } (1.19)$$

In case of a sinusoidal voltage $u = U_m \sin \omega t$ current is

$$i = C\frac{du}{dt} = \omega C U_m \cos\omega t = I_m \sin\left(\omega t + \frac{\pi}{2}\right) \text{ } (1.20)$$

that is it is ahead in phase by a quarter period of the applied voltage to the terminals.

If a discharged capacitor is on for a constant voltage, then at the moment when *q* = 0 and thus the voltage at its terminals $U_c = {}^{q}\!/_{C} = 0$, which is an equivalent to a short circuit. Charge current will be determined by only power supply voltage and external circuit resistance *r*.

Later charging current will subside and will be zero when a capacitor is fully charged. The charging time is determined by a time constant of the circuit.

If the charged capacitor, when power supply is off, is made at resistance *r*, then it begins to discharge at the same time constant. Stored energy is converted into heat generated in this resistance. With a capacitor is made, electric field energy is released in a spark formed by making capacitor terminals.

Thus, in a DC circuit capacitor stores energy only at the time of the charge. A charged capacitor does not consume current from a power supply.

1.2. Components of total power of electrical networks

For a three-phase symmetrical power grid which has a sinusoidal voltage $u = U_m \sin \omega t$ and current $i = I_m \sin(\omega t - \varphi)$, shifted by an angle φ relative to voltage , is determined by:

$$p = u \cdot i = U_m \cdot I_m \cdot \sin \omega t \cdot \sin(\omega t - \varphi) = \frac{1}{2} U_m \cdot I_m [\cos(\omega t - (\omega t - \varphi)) -$$

$$- \cos(\omega t + (\omega t - \varphi))] = \frac{1}{2} U_m \cdot I_m [\cos\varphi - \cos(2\omega t - \varphi)] = \quad (1.21)$$

$$= \frac{1}{2} U_m \cdot I_m \cos\varphi - \frac{1}{2} U_m \cdot I_m \cos(2\omega t - \varphi)$$

Integration of (1.21) over a period of alternating current provides total amount of energy that is given to the power source to the network.
Consideration of simple electrical circuits can reveal the essence in the expression (1.21) terms.

1.2.1. An inductive element in a circuit of harmonic current

Connection circuit is shown in Fig. 1.5a. If an alternating current i_L varies sinusoidally (Fig. 1.5b), change of the magnetic flux Φ, inextricably connected with the current that causes it, will follow the change in current, that is current and magnetic flux are in a phase. If an instantaneous current is given by:

$$i_L = I_m \sin \omega t \quad (1.22)$$

an instantaneous value of magnetic flux is equal to:

$$\Phi = \Phi_m \sin \omega t \quad (1.23)$$

Change of magnetic flux gives rise to self-induction coil EMF which also varies sinusoidally (Fig. 1.5b). e_L value depends on the number of windings of the coil and frequency of the alternating current. Fig. 1.5b shows that an increase in current over the same period of time Δt is different $\frac{\Delta i'_L}{\Delta t} > \frac{\Delta i''_L}{\Delta t}$, and, hence, a rate of current change ${di}/{dt}$ (and flux ${d\Phi}/{dt}$) is maximum when passing through the sinusoids zero, that is, for the time when polarity of the current is zero.

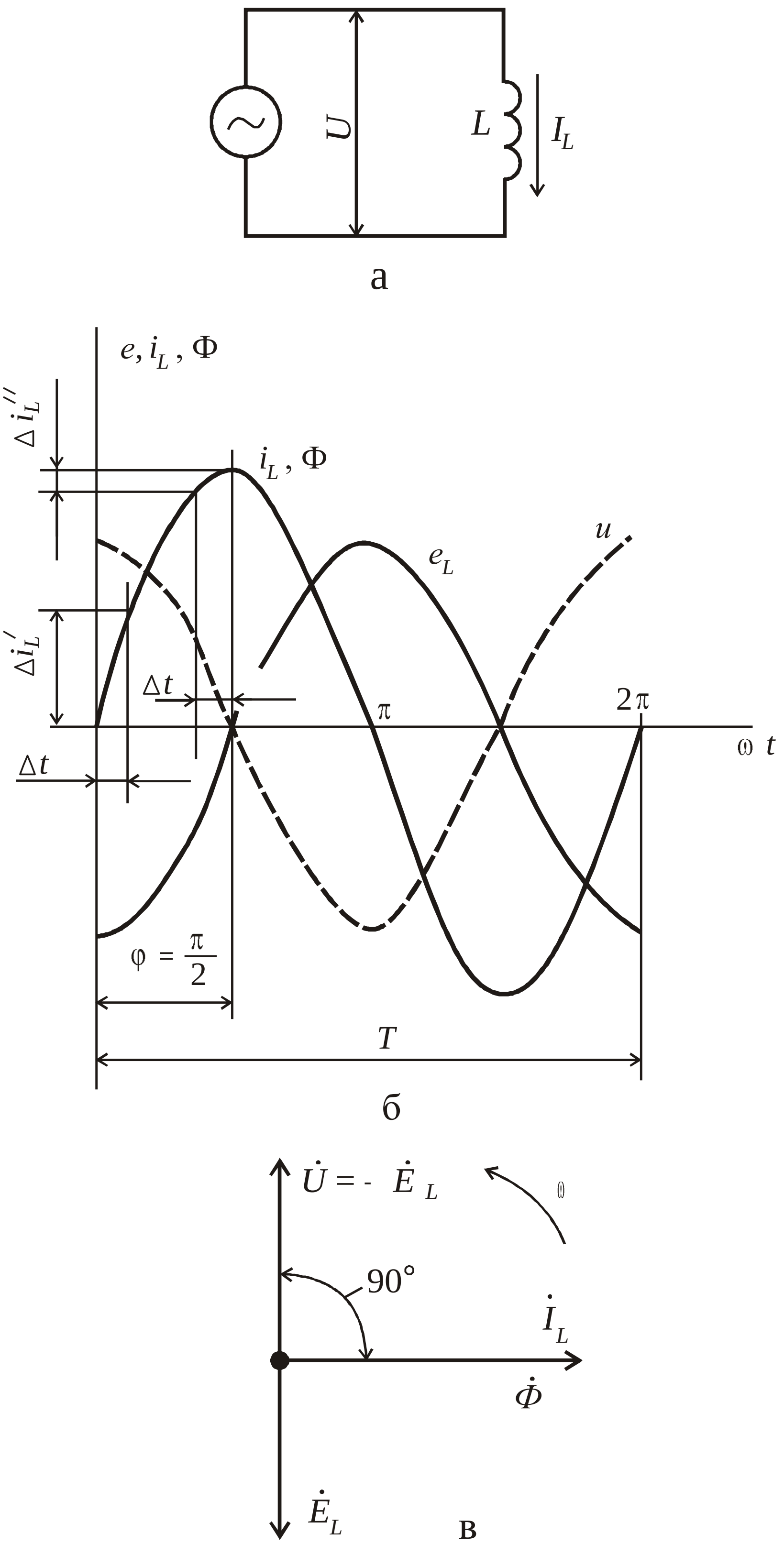


Fig. 1.5. Inductive circuit: a – a connection circuit, b – a curve of i, flux F, self-induction EMF e_L and the applied voltage, c - vector diagram

It means that e_L reaches the maximum if $i_L = 0$. When current reaches the maximum, its rate of change is zero, as the current increases; it reaches the maximum and then begins to decrease. At this point, self-induced EMF is zero. According to Fig. 1.5b in the first quarter of the period (with the current increases) self-induced EMF is negative, in the second quarter of the period (when the current decreases) - is positive, that is self-induced EMF lags in a phase by causing its current-quarter period. A similar result was obtained analytically in the derivation of (1.14). It is necessary to balance the voltage of a power supply, so that the current in the circuit with a coil can overcome EMF inductance. This balancing voltage is equal to EMF of self-induction at any given time, but is in the opposite direction (U = – E_L), and therefore faster than the current flowing in the coil, the angle $\pi/2$ (see (1.15) and Fig. 1.5в):

$$u = U_m \sin\left(\omega t + \frac{\pi}{2}\right) . \quad (1.24)$$

Instantaneous power circuit that contains only the coil inductance is the product of the instantaneous current i_L and the voltage u for any time:

$$p = u \cdot i_L = U_m \sin\left(\omega t + \frac{\pi}{2}\right) \cdot I_{mL} \sin \omega t = U_m \cdot I_{mL} \cos \omega t \cdot \sin \omega t = \\ = \frac{U_m \cdot I_{mL}}{2} \sin 2\omega t = U I_L \sin 2\omega t^*, \quad (1.25)$$

since $I_{mL} = \sqrt{2} \cdot I_L$ and $U_m = \sqrt{2} \cdot U$, where I_L and U – active values of voltage and current.

A curve of instantaneous power changes in a circuit with an ideal inductance coil is shown in Fig. 1.6. Period average value of instantaneous power or active power consumed is:

$$P_L = \frac{1}{T}\int_0^T p_L (t) dt = \frac{1}{T}\int_0^T U \cdot I_L \sin 2\omega t \, dt = 0 . \quad (1.26)$$

Zero equality of the average for the period of power P_L is shown in Fig. 1.6: a square of positive sine half-wave p_L is equal to a square of its negative half-wave, that is, the circuit does not consume active power from a power source.

From the expressions (1.25) and (1.26):

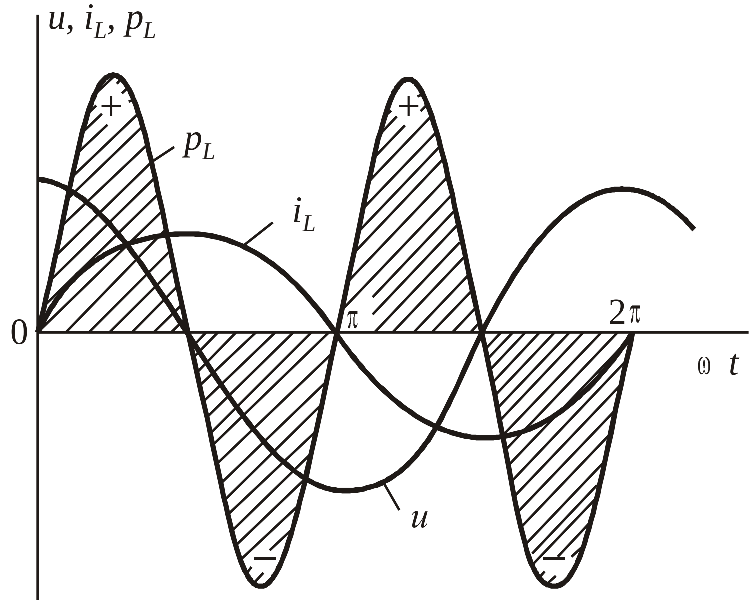


Fig. 1.6. Curves of instantaneous current, voltage and power in a circuit with an inductance, resistance is zero

• instantaneous power coil when r = 0 varies sinusoidally, but with a double frequency;
• average value, over the period of power (or active power) consumed by inductance, is zero.

Physically, it means that during the first positive half-cycle energy flows from a generator to a coil and is stored as magnetic energy:

$$W_L = \int_{t=0}^{t=T/4} u \cdot i \, dt = \int_{0}^{I_{mL}} L \frac{di_L}{dt} i_L \, dt = L \int_{0}^{I_{mL}} i_L \, di_L = L \frac{i_L^2}{2} \Bigg|_0^{I_{mL}} = \frac{L \cdot I_{mL}^2}{2} \quad (1.27)$$

and for the second - is returned to the generator. There is a periodic exchange of energy, without converting it into a different form, between a generator and a magnetic field of an inductance coil. Oscillating process of instantaneous power transfer $\pm p_L$ perceived by a generator turbine shaft as a uniform load with a double frequency that does not cause additional fuel consumption.

Interchange energy between a generator and an inductance is estimated by the maximum value of instantaneous exchange capacity (when $\sin 2\omega t = 1$). This power is called reactive power and is determined by:

$$Q = U \cdot I_L = I_L^2 \omega L \ . \ (1.28)$$

In power systems some parts of power transfer and power loads are always inductive components (transformers, transmission lines, asynchronous motors).

1.2.2. A capacitive element in a circuit of harmonic current

Connection circuit is shown in Fig. 1.7a. Current $i_c = I_{mc} \sin \omega t$ that passes through a capacitance which can be ignored, advances (see equation (1.20)) applied to its terminal voltage up to 90 ° (Fig. 1.7b), i.e.

$$u = U_m \sin\left(\omega t - \frac{\pi}{2}\right). \quad (1.29)$$

Instantaneous power circuit that contains only capacitance is:

$$p_c = u \cdot i_c = U_m \sin\left(\omega t - \frac{\pi}{2}\right) \cdot I_{mc} \sin \omega t = U_m \cdot I_{mc} \sin\left(\omega t - \frac{\pi}{2}\right) \cdot \sin \omega t =$$

$$= \frac{U_m \cdot I_{mc}}{2}\left[\cos\left(\omega t - \frac{\pi}{2} - \omega t\right) - \cos\left(\omega t - \frac{\pi}{2} + \omega t\right)\right] =$$

$$= \frac{U_m \cdot I_{mc}}{2}\left[\cos\left(-\frac{\pi}{2}\right) - \cos\left(2\omega t - \frac{\pi}{2}\right)\right] = -\frac{U_m \cdot I_{mc}}{2}\cos\left(2\omega t - \frac{\pi}{2}\right) = \quad (1.30)$$

$$= -\frac{U_m \cdot I_{mc}}{2}\cos\left(-\left(\frac{\pi}{2} - 2\omega t\right)\right) = -\frac{U_m \cdot I_{mc}}{2}\cos\left(\frac{\pi}{2} - 2\omega t\right) =$$

$$= -\frac{U_m \cdot I_{mc}}{2}\sin 2\omega t = -U \cdot I_c \sin 2\omega t,$$

since $I_{mc} = \sqrt{2} \cdot I_c$ and $U_m = \sqrt{2} \cdot U$, where I_c and U - active values of voltage and current.

A curve of instantaneous power change in a circuit with an ideal capacity is shown in Fig. 1.7в. Period average value of instantaneous power (or consumed active power) is:

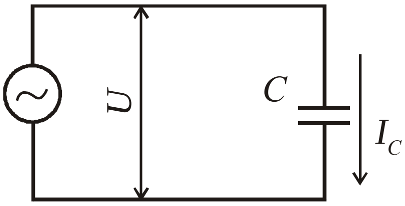
$$P_c = \frac{1}{T}\int_0^T p_c(t)dt = 0. \quad (1.31)$$

According to (1.30) and (1.31) :

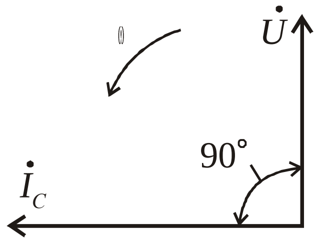
• instantaneous power of a capacitor when $r = 0$ varies sinusoidally with a double frequency;

• an average (i.e., active) power of a capacitor is zero;

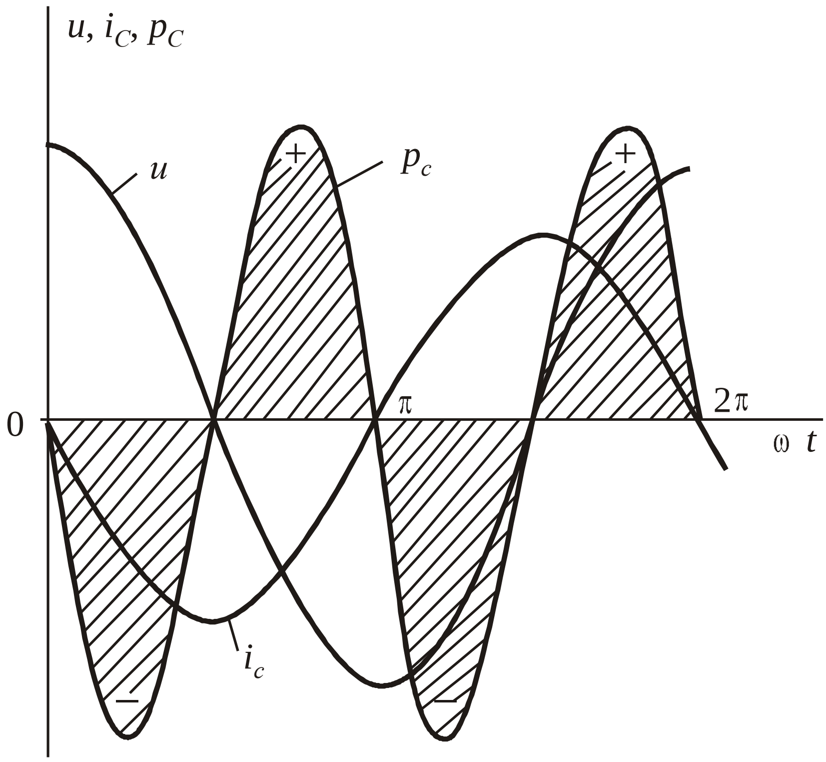
• instantaneous power circuit with a capacitance ratio is negative related to instantaneous power in a circuit with an inductance (compare Fig. 1.7d to Fig. 1.6).



а



б



в

Fig. 1.7. Circuit (а), a vector diagram of voltage and current (б) and a curve of instantaneous voltage values changes, current and power (в) single path circuit with a capacitive load, resistance of the circuit is zero

According to Fig. 1.7в for the first and third quarters of the period, capacitor terminal voltage decreases from the maximum value of U_m to zero (regardless of voltage) and a capacitor is discharged, and during the second and four-quarter period the voltage is increased from 0 to U_m and a capacitor is charged. This allows you to formally assume that AC current passes through a capacitor that value depends on capacitance and frequency.

While charged, a capacitor consumes energy from a generator that varies from zero to

$$W_c = \int_0^{T/4} u \cdot i \, dt = \int_0^{U_m} uC\frac{du}{dt}dt = C\int_0^{U_m} u \, du = C\frac{u^2}{2}\Bigg|_0^{U_m} = \frac{CU_m^2}{2}. \quad (1.32)$$

used to create an electric field of a capacitor, and during energy discharge energy stored in the electric field of a capacitor is reduced from $CU_m^2/2$ to zero. Thus, when a capacitor is switched on in the circuit of an alternator there is an oscillating periodic exchange of instantaneous power $\pm p_c$ between a generator and the electric field of a capacitor without conversion to another form of energy. The exchange of energy between a generator and condenser occurs during each half-cycle of an alternating current, so that the energy consumed by a capacitor is zero.

An instantaneous value of power in a circuit, with a capacity of up to maximum value for the time when $\sin 2\omega t = 1$, is a measure of energy exchange between a generator and load capacitance and is called reactive power capacitor and determined by:

$$Q = U \cdot I_c = C\omega U^2. \quad (1.33)$$

In power systems natural capacitors are overhead transmission lines relative to each other and the earth, cable strands- insulation of electrical equipment.

1.2.3. A resistive element in a circuit of harmonic current

Connection circuit is shown in Fig. 1.8a. An instantaneous value of the current in the circuit $i_R = I_{mR} \sin \omega t$. According to Ohm's law

$$u = Ri = RI_{mR} \sin \omega t = U_m \sin \omega t. \quad (1.34)$$

The current passing in resistive coincides in phase with the applied voltage to its terminals (Fig. 1.8б).

Instantaneous power circuit containing a resistive element is:

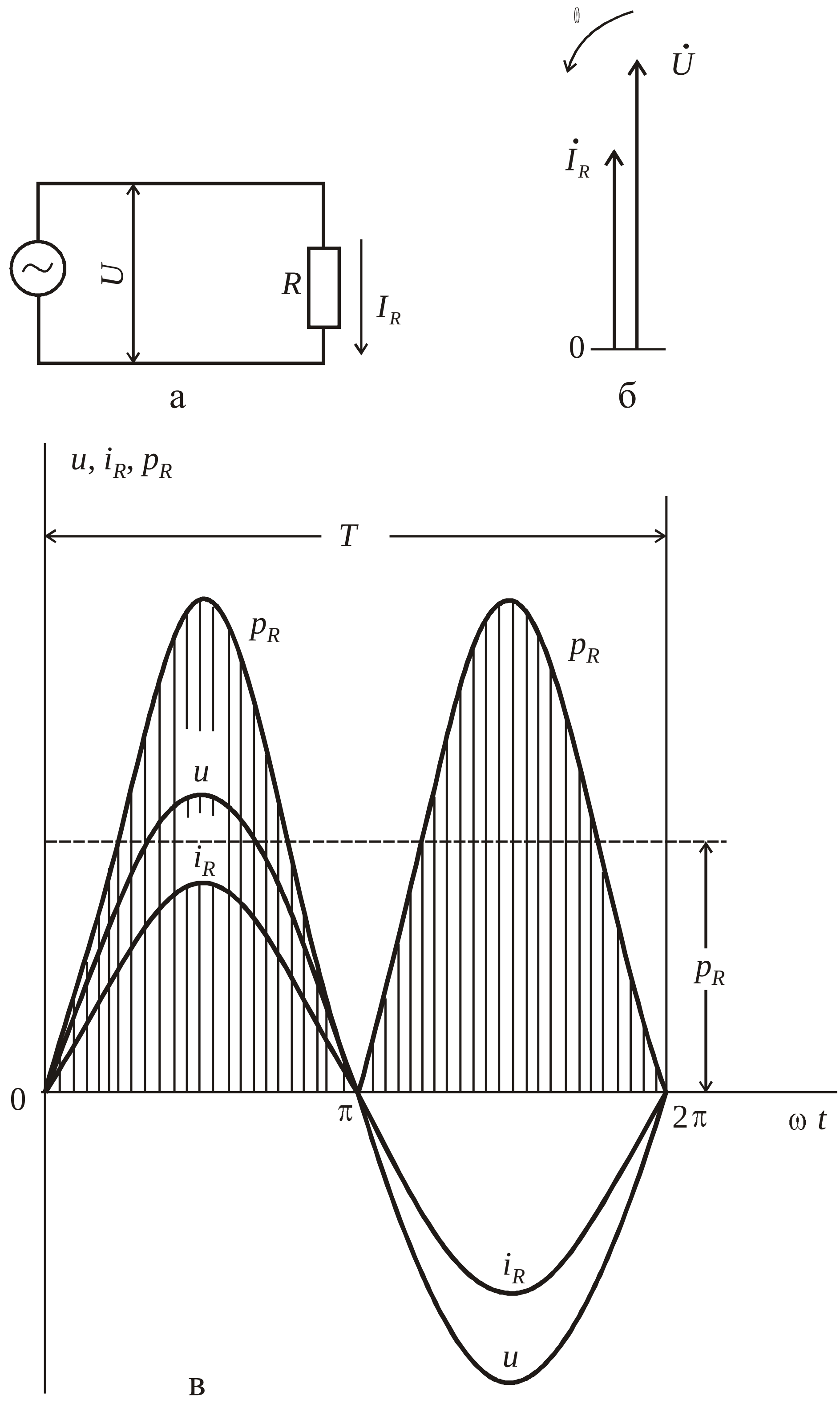


Fig. 1.8. Circuit (а), a vector diagram of voltage and current (б) and a curve of instantaneous values of voltage, current and power (в) single-path circuit with

resistive load

$$p_R = u \cdot i_R = U_m \sin \omega t \cdot I_{mR} \sin \omega t = U_m \cdot I_{mR} \cdot \sin^2 \omega t =$$
$$= \frac{U_m \cdot I_{mR}}{2}(1 - \cos 2\omega t) = \frac{\sqrt{2} \cdot U \cdot \sqrt{2} \cdot I_R}{2}(1 - \cos 2\omega t) = \quad (1.35)$$
$$= U \cdot I_R (1 - \cos 2\omega t),$$

where I_R and U - active values of voltage and current.

In Fig. 1.8в curves of instantaneous values of current, voltage and power are shown. Instantaneous power of p_R has a DC component $U{\cdot}I_R$, and $U{\cdot}I_R\cos2\omega t$ component varying with frequency 2ω (see (1.35)). dt energy consumed by a power source for a time period is equal to the energy $p_R\,dt$ and the average value over the period of power (or active) is:

$$P_R = \frac{1}{T}\int_0^T p_R(t)dt = \frac{1}{T}\int_0^T UI_R(1 - \cos 2\omega t)dt = U \cdot I_R > 0 \quad (1.36)$$

In electric power systems a huge part of the active power (energy) is spent on useful work but a small part of it is lost in networks and in electrical equipment.

1.2.4. A power factor

In real conditions of power supply, units of power transmission and customer load include, along with the resistance, components of inductive and capacitive type. As a rule, inductive load prevails, so that reactive power of inductive type must be transmitted along with active power. In general, the load in the AC circuit can be reduced to a circuit consisting of an active r_a, inductive reactive x_L which has resistance r and reactance x_C of capacitive impedance. In Fig. 1.9a an equivalent circuit diagram of one phase is shown. It contains all resistance components. In Fig. 1.9б a vector diagram is introduced for this circuit. Voltage $\dot{U}$ is applied to all three parallel connected branches. Current $\dot{I}_L$ in the branch with inductance lags the voltage $\dot{U}$ by an angle φ_L which can be determined from the triangle of resistances (Fig. 1.9в), created for the branch with inductance $\mathrm{tg}\varphi_L = x_L/r$. Current $\dot{I}_a$ in the circuit with active resistance coincides with a phase of voltage $\dot{U}$, current $\dot{I}_C$ in the circuit with a capacity leads the voltage of an angle φ = 90 °.

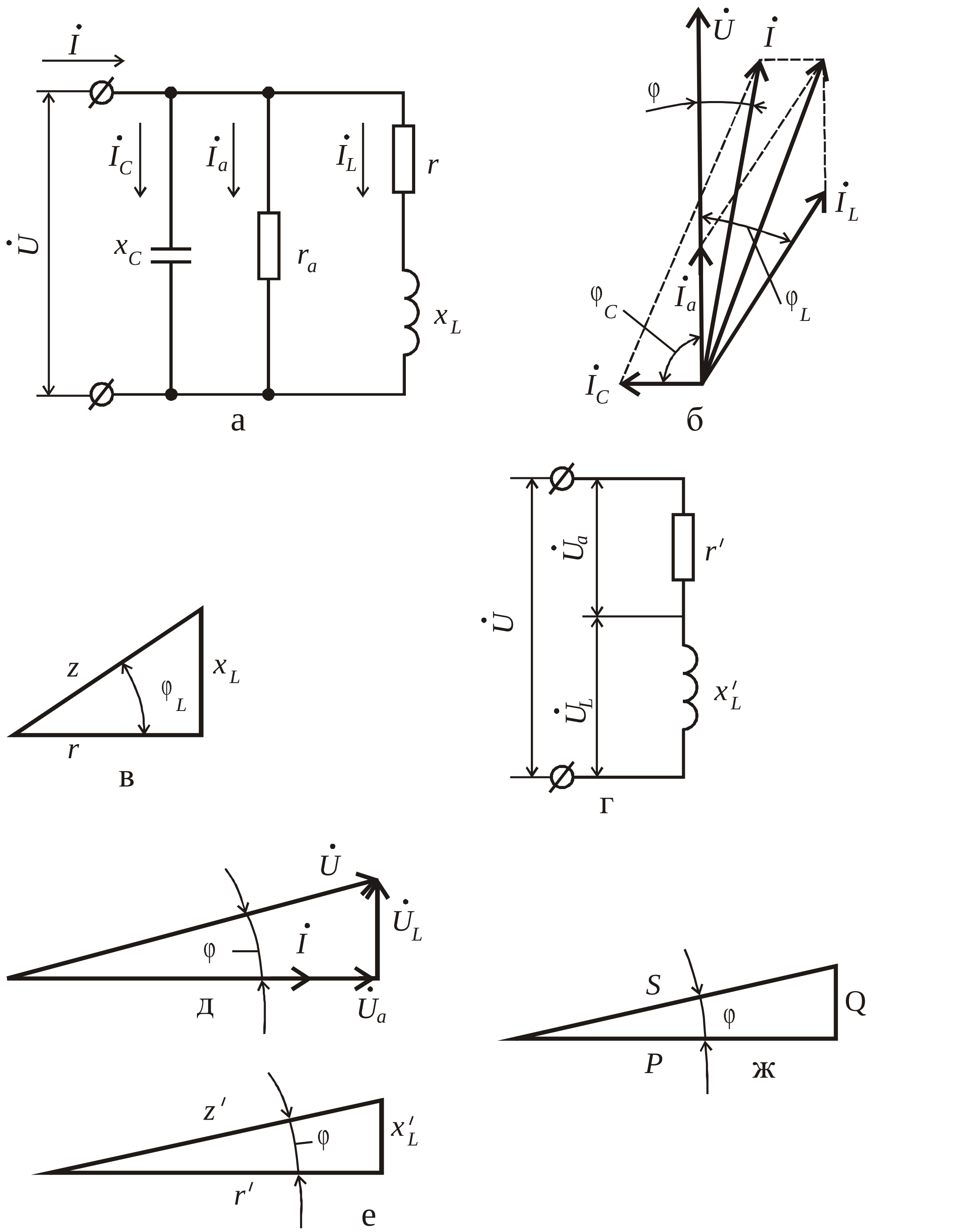


Fig. 1.9. Load in the AC circuit and vector diagram:
а - equivalent load circuit, б - a vector diagram, в – delta network for the branch with inductance, г - equivalent circuit load, д - a vector diagram of equivalent

circuit, e - delta network of equivalent circuit, ж - delta of power load

Depending on the ratio of reactances and x_C and x_L total current load $\dot{I}$ may lag behind or leads voltage $\dot{U}$. In this example, inductive reactance dominates and current $\dot{I}$ lags behind $\dot{U}$.

The vector diagram shows that an equivalent circuit for power consumers can be replaced by a more simple one consisting of r' and x'_L (Fig. 1.9g), for them a vector diagram and a delta network are shown in Fig. 1.9д and 1.9e, respectively. In Fig. 1.9g capacitance is not shown but it is opposite in its effect to inductance and so it is partially compensated. This is reflected in a vector diagram: x'_L in Fig. 1.9e is less than x_L in Fig. 1.9в.

Instantaneous power consumed by power consumers (Fig. 1.9г), is equal to:

$$p = u \cdot i = u_a i + u_L i = p_a + p_L . \quad (1.37)$$

A component of instantaneous power in active resistance, expressed in terms of actual values, is:

$$\begin{aligned} p_a &= u_a \cdot i = U_{m.a} \sin \omega t \cdot I_{m.a} \sin \omega t = U_{m.a} I_{m.a} \sin^2 \omega t = \\ &= \frac{U_{m.a} I_{m.a}}{2} - \frac{U_{m.a} I_{m.a}}{2} \cos 2\omega t = U_a I - U_a I \cos 2\omega t \end{aligned} \quad (1.38)$$

where $I_{m.a}$ and $U_{m.a}$. - maximum active values of current and voltage.

The average value of the second term for the period is zero (alternating load on a turbine shaft). A constant component $U_a I$ representing the average power used during the period of active resistance (see (1.36)) is called active power of the circuit:

$$P = U_a I = I^2 r' . \quad (1.39)$$

According to a vector diagram in Fig. 1.9д $U_a = U\cos\varphi$, therefore:

$$P = UI \cos\varphi . \quad (1.40)$$

A component of instantaneous power in inductive reactance (see section 1.2.1):

$$p_L = u_L \cdot i = U_L I \sin 2\omega t . \quad (1.41)$$

A maximum value of reactive power is reached at $\sin 2\omega t = 1$, according to Fig. 1.9д $U_L = U\sin\varphi$, then the reactive power of the circuit:

$$Q = U \cdot I \sin \varphi \quad (1.42)$$

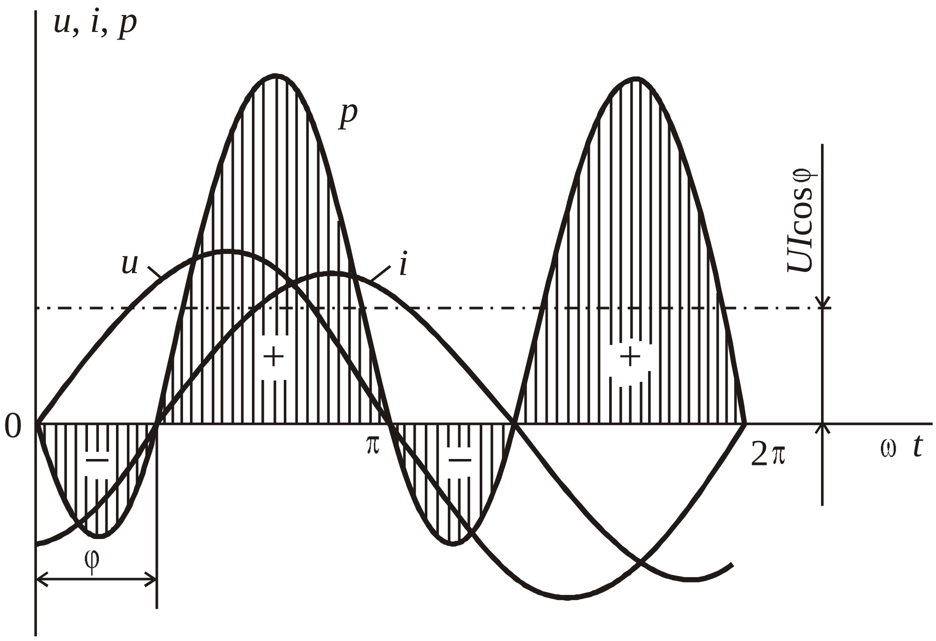


Fig. 1.10. Change in voltage, current and power over time in the circuit with mixed loads

In Fig. 1.10 curves *u*, *i* and *p* are shown in case if the circuit has a mixed active-inductive load $(x_L \;\; x_c) > 0$. In this case power *p* varies with a double frequency relative to the line raised over X-axis by the amount of active power $P = UI\cos\varphi$. Instantaneous values of power are taken as positive as well as negative but the energy, coming from a power source to the considered circuit, is higher than the energy that comes back. Energy process in this circuit (Fig. 1.9г) contains energy fluctuations between a power supply and circuit, resistance r' is heated not only due to active power through a resistive load $\Delta P_a = (\cos\varphi)^2 r'$, but also additionally through the exchange of energy between a power supply and electromagnetic load field $\Delta P_p = (\sin\varphi)^2 r'$. In other words, during the exchange of energy between a generator and magnetic field and vice versa, there are additional active power losses in the network due to reactive power transmission through the network.

Ratio of active to reactive power characterizes ratio of reactive power circuit

$$tg\varphi = \frac{Q}{P} \quad (1.43)$$

which expresses reactive power at fractions of the active. Here φ – a phase angle between voltage and current loads.

Power factor of the circuit is determined by a cosine of the phase angle between voltage and current loads and for a three-phase current is expressed as

$$\cos\varphi = \frac{P}{\sqrt{3}\cdot U\cdot I}. \quad (1.44)$$

Expression

$$\cos\varphi = \frac{1}{\sqrt{1+\mathrm{tg}^2\varphi}} \quad (1.45)$$

establishes a connection between these coefficients.
Power factor is less illustratory for assessing reactive power circuit.

1.2.5. Active, reactive and apparent power

According to (1.21) for a single-phase of a three-phase symmetrical network instantaneous power is:

$$p = u\cdot i = \frac{1}{2}U_m I_m\cos\varphi - \frac{1}{2}U_m I_m\cos(2\omega t-\varphi). \quad (1.46)$$

In this equation the first component is active power and it is constant since according to the definition active power P is an average value of instantaneous power p for the period:

$$P = \frac{1}{2\pi}\int_0^{2\pi} p\,dt = \frac{1}{2\pi}\int_0^{2\pi} u(t)\cdot i(t)\,dt = \frac{1}{2}U_m\cdot I_m\cdot\cos\varphi. \quad (1.47)$$

The second component is a harmonically varying quantity of a double frequency. By integration of (1.46) during the period of AC, we will determine total amount of energy produced by the power source and given to the network:

$$W = \frac{1}{f}P = T\cdot P \quad (1.48)$$

where f - frequency of 50 Hz.
It follows that power generation and its subsequent transfer to a consumer is associated with the first component of instantaneous power, i.e. the active power, which requires consumption of primary fuels at power plants.
The second component of instantaneous power at AC circuit specifies a periodic exchange of energy between a generator (voltage source) and a consumer with a dual frequency. The exchange is due to the presence of inductive and capacitive elements in the circuit. The energy of this oscillatory component is zero and does not require cost of primary energy.

Taking into account that $\cos(2\omega t-\varphi) = \cos 2\omega t\cdot\cos\varphi + \sin 2\omega t\cdot\sin\varphi$, we rewrite (1.46) as follows:

$$p = \frac{1}{2}U_m \cdot I_m \cdot \cos\varphi - \frac{1}{2}U_m \cdot I_m \cdot \cos(2\omega t - \varphi) = \frac{1}{2}U_m \cdot I_m \cdot \cos\varphi -$$
$$- \frac{1}{2}U_m \cdot I_m \cdot \cos 2\omega t \cdot \cos\varphi - \frac{1}{2}U_m \cdot I_m \cdot \sin 2\omega t \cdot \sin\varphi =$$
$$= \frac{1}{2}U_m \cdot I_m \cdot \cos\varphi \cdot (1 - \cos 2\omega t) - \frac{1}{2}U_m \cdot I_m \cdot \sin 2\omega t \cdot \sin\varphi =$$
$$= U \cdot I \cdot \cos\varphi \cdot (1 - \cos 2\omega t) - U \cdot I \cdot \sin 2\omega t \cdot \sin\varphi =$$
$$= P(1 - \cos 2\omega t) - Q \sin 2\omega t,$$

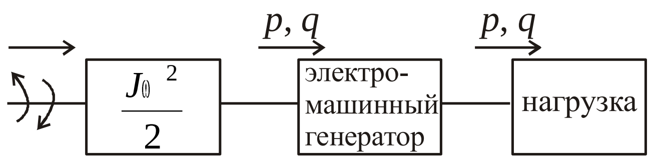
where $P = U \cdot I \cos\varphi$ - active power; $Q = U \cdot I \sin\varphi$ - reactive power.
Apparent power *S*=*UI* or $S^2 = (U \cdot I \cos\varphi)^2 + (U \cdot I \sin\varphi)^2 = (U \cdot I)^2$ is determined as $S = \sqrt{P^2 + Q^2}$. This expression corresponds to a power triangle (Fig. 1.9ж) which helps to define $\cos\varphi = P/S$, $\sin\varphi = Q/S$ and $\mathrm{tg}\varphi = Q/P$.
Lagging and leading current results in a change of sinφ sign and direction of reactive power flow that is conditional due to the periodic nature of the exchange.
Since for inductance and capacitance we have $\varphi = \pi/2$, for a capacitance $\varphi = -\pi/2$ we obtain from (1.49)

$$p = \pm Q \cdot \sin 2\omega t$$

with $P = 0$, and $S = Q = U \cdot I$.
Thus, inductance can be regarded as a consumer and a capacity as a generator of reactive power. However, a source of AC voltage power that supplies inductance-produce and a source that supplies capacity - consumes reactive power.
In terms of "generation" and "consumption" of reactive power there is a certain conventionality. It emphasizes that interaction of capacitive and inductive elements in the electric network has a compensating effect $Q_\Sigma = Q_L - Q_C$. This property of elements is widely used in practice to compensate for reactive capacity, thereby reducing voltage drop across the network, electricity losses.
As a whole electrical network requires equality of generation and consumption of active and reactive power. The main standard measure to maintain a balance of active power at any given time is AC frequency which is a system-wide criterion. The main standard measure to maintain a balance of reactive power at any given time is voltage level – a local criterion which is substantially different for each load node and rated voltage level. Therefore, in contrast to a balance of active power it is necessary to provide a balance and a reserve of reactive power not only in the power system as a whole but also at load nodes. In many cases, unacceptable voltage levels at load nodes are largely due to a local shortage of reactive power.

1.2.6. Power flow in a power converter

Currently, the main transmitter of some kind of energy into electricity is an electric machine, for example, synchronous generator, capable of operating as a generator and a motor. Assuming a three-phase system as a balanced one, for a single-phase circuit you can use relations mentioned above. In the steady state of operation, points created by a turbine or other mechanical drive and a generator are equal and oppositely directed, balancing each other. In this regime power, selected from a turbine by a generator, is active and corresponds to an average value of instantaneous power (relation (1.47)), transmitted by a loaded generator.
Energy flow coming from a turbine to a generator has a unidirectional flow which is true for the majority of current sources including alternative, for example, solar and other DC sources. In these cases, to supply AC load solid-state inverters with capacitive or inductive-effective storage on the DC side are used [1]. Thus, a storage ring is a prerequisite device for load supply that has reactive elements.



a

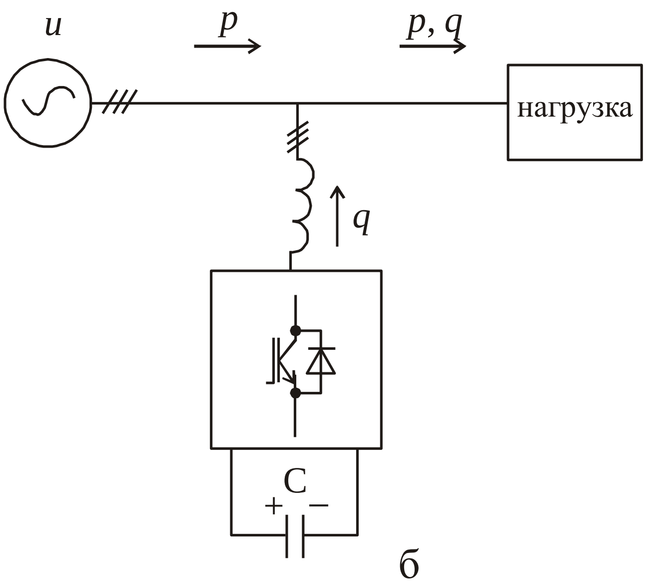


Fig. 1.11. Power flows in a system with an electric generator (a) and with a static converter (b)

In electric generators storage functions are provided by a rotor and other rotating parts of a mechanical system with a kinetic energy $J\omega^2/2$ (Fig. 1.11a). Here *J* – a moment of inertia about an axis of rotation. Part of the reactive electric power load periodically returns to a storage part of a "turbine - generator" and then goes back to the reactive load. A storage ring acts as a lowpass filter and an integrating device of power flow in the system. An analogy of mechanical and capacitive (or inductive) storage rings is clearly illustrated by a fast source of capacitive or inductive current - a static compensator (Fig. 1.11б). On a DC side of the compensator a capacitor is switched on. The capacitor acts as a storage ring in exchange of reactive energy between the network and a converter. Moving parts of an electric generator act the same. They damp oscillations in instantaneous power of reactive type of the load where power flow changes direction at the curve of instantaneous power. Such changes are seen by the analysis of diagrams of current and voltage of static converters AC (DC) [1], working with active-inductive load. Lack of storage ring will result in termination of current transfer or power flow from a source.

1.2.7. Distortion power

Introduction of thyristors and their phase control is accompanied by a deterioration of energy data used by units of resistive type (e.g., furnaces of resistive heating with a thyristor power regulator). In Fig. 1.12 a circuit with opposite thyristors and a resistive load, diagrams of voltage and load current are shown. Circuit current is a non-sinusoidal periodic function depending on time and it is determined by an angle control α. A curve of distorted current is shown in Fourier series (Fig. 1.12b).

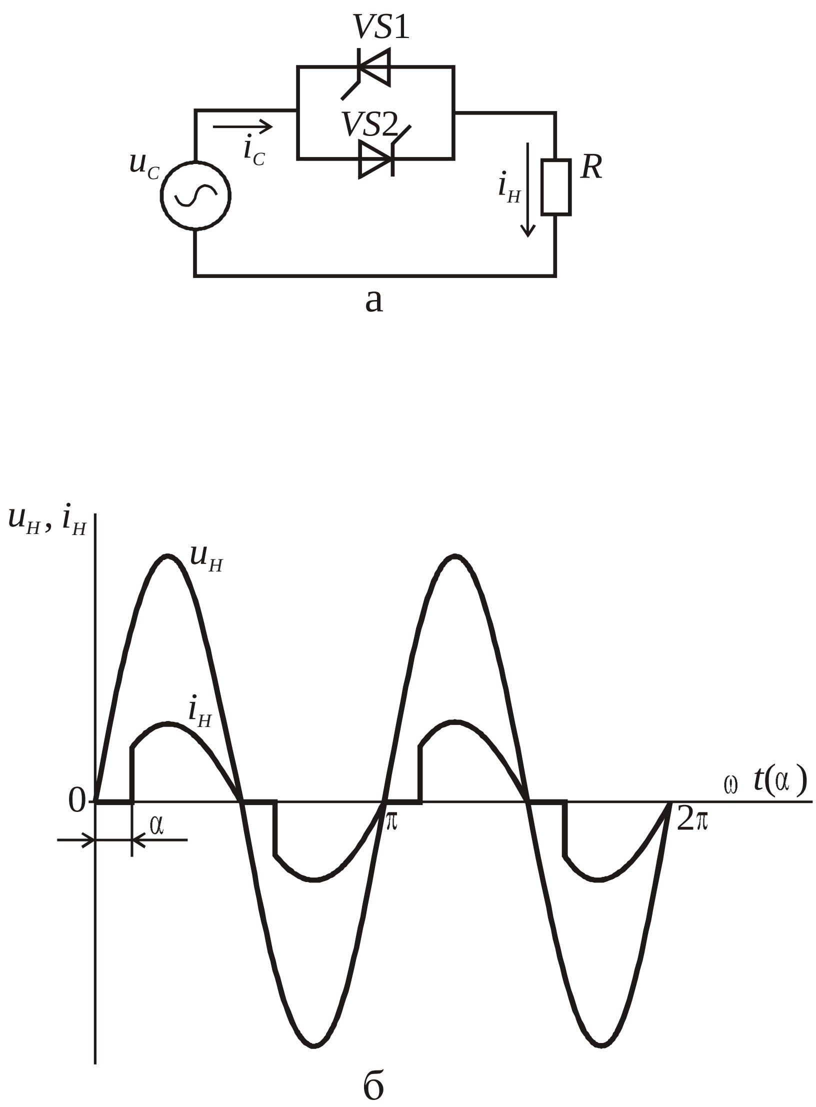


Fig. 1.12. A distortion curve of current in a circuit with a resistive load: a – a circuit with oppositely switched thyristors, b – curves of voltage and load current

and can be represented as a sum of the first harmonic $i_1(\omega_1 t)$ and higher harmonics $i_n(\omega_n t)$. The first harmonic lags behind the angle φ from voltage which curve is made sinusoidal for simplicity reasons i.e. active load becomes inductive. Instantaneous power components appear in a curve. The components are determined as a fundamental harmonic current and its higher harmonics.

In Fig. 1.13 curves of relative values of current harmonics, depending on the angle of thyristor control, are shown. Non-sinusoidal current increases significantly with α increase since much higher relative (relative to the current of the first harmonic) content of higher harmonics. Increase in the angle control reduces an overall installation capacity and hence the level of higher harmonics in the mains.

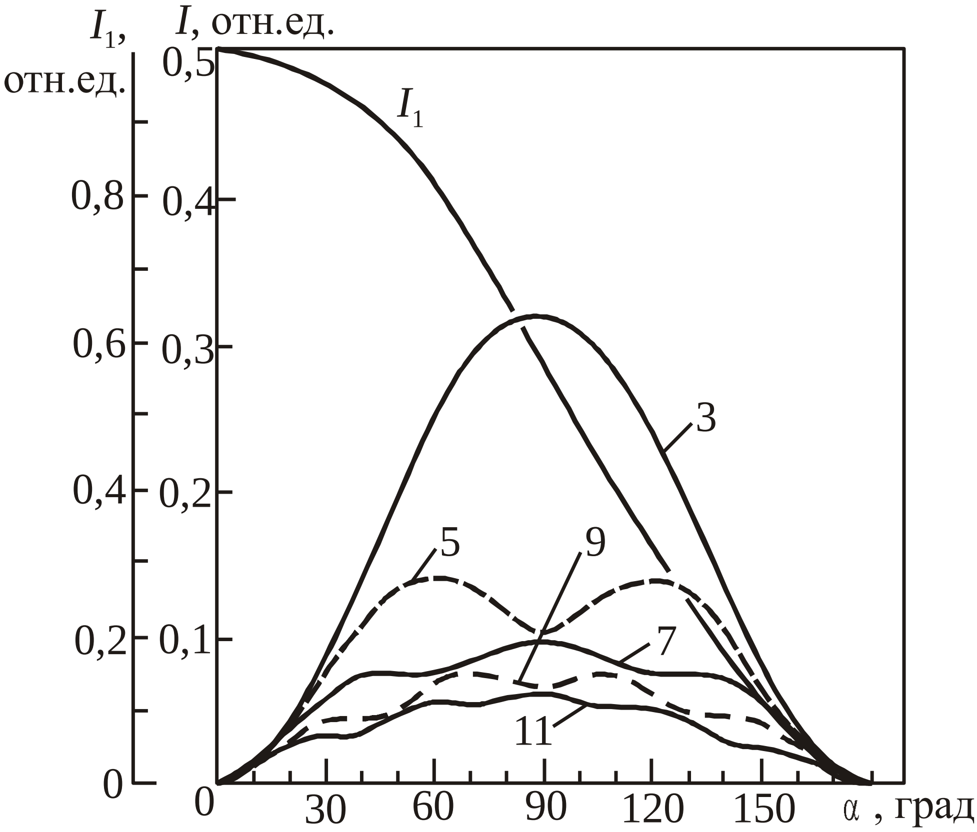


Fig. 1.13. Dependence of current harmonics on the angle control of thyristors α

The average value of instantaneous power of a fundamental component corresponds to active power and its variable part – to reactive at this frequency (similar to power in *RL* -circuit with a sinusoidal current) and higher current harmonics. They create the energy exchange between a load that switches on a thyristor, and a generator (the drive). The current at an interval 0-α is reduced to zero and causes a drop to zero of instantaneous power. It leads to a decrease in average active power supplied by a generator, and then there is a partial compensation for this drop due to an excess of instantaneous power of the desired value. As a result, average power i.e. active power is reduced and in a steady mode equal torque and braking moments are set. Thus there is a periodic exchange of power, which has an inactive character, between a load and generator. Analysis of influence of distorted current curve can be carried out by different methods including its dissolution in Fourier series. However, a linearity of the parameters studied in the entire frequency spectrum should remain. Power of higher harmonics is called distortion power. Full power circuit with a distorted current can be written as:

$$S=\sqrt{P^2+Q_1^2+D^2} \quad (1.50)$$

where P, Q_1 and D - active, reactive and distorted of a fundamental harmonic power, respectively.

The proportion of active power P in the total power S is traditionally estimated by the power factor

$$\chi=\frac{P}{S}=v\cos\varphi_1 \quad (1.51)$$

where $\cos\varphi_1$ - a coefficient of the power factor of a fundamental harmonic; v- a distortion coefficient is determined by:

$$v=\frac{1}{\sqrt{1+\frac{\sum\limits_{n\neq 1}^{\infty} I_n^2}{I_1^2}}}. \quad (1.52)$$

However, the mean value of power of higher harmonics is equal to zero not only for the period T of fundamental frequency as a core of harmonic reactive power

$$P_{\Sigma n}=\frac{1}{T}\int\limits_0^T U\sum_{n\neq 1}^{\infty} i_n\, dt=0 \quad (1.53)$$

but also for a return period of each of the higher harmonics in the whole time frequency spectrum of current:

$$P_n=\frac{1}{T_n}\int\limits_0^{T_n} U\cdot i_n\, dt=0 \quad (1.54)$$

Therefore, distortion power is not manifested in the overall balance of power which is characterized by the symbolic method for sinusoidal currents and voltages, so called "triangle" capacity. As a result of higher harmonics there are dissipation power losses in the system. Due to that a value of power coefficient χ according to (1.51) for practical use is of little information since it reflects influence of various physical phenomena and their consequences. If coefficient $\cos\varphi_1$ reflects a decrease in the proportion of active power when there is an increase in inductive and constant full power, an increase in distortion characterizes the growth of dissipative power losses and other negative phenomena.

1.2.8. Power unbalance

In general, if three-phase currents under asymmetric currents and/or voltage, there

will be a fourth component of total power- power unbalance.
Voltage in a three-phase network can be asymmetric. Asymmetric voltage is normalized by its parameters at a fundamental frequency. If an amplitude of phase (interphase) voltages are equal and a phase shift (the angle between them) is the same, voltage is symmetrical. If any of these indications or even both are violated, then voltage is asymmetrical. A similar definition can be applied to currents.
In evaluating unbalance voltage of a three-phase network in accordance with GOST 1310997 (all-union state standard) the voltage (current) of a fundamental frequency is meant. The unbalanced system can be also formed at a frequency of higher harmonics. This fact must be taken into account when calculating or measuring symmetrical components of voltage (currents) in a network with non-sinusoidal voltage as follows: first is fundamental harmonic voltage and then its symmetric components are calculated.
One of the main causes of voltage asymmetry - asymmetry of currents in a network due to load inequality over phases. A large part of household and industrial power consumers have a one-or two-phase performance and join the network 0,38 kV. To supply power consumers such networks provide voltage of 0.38 kV and four- or even five-wire performance [2]. Transformers winding of 0.38 kV feed these networks and connected in a "star" shape, its neutral is connected by a current-carrying wire. Without a neutral wire network operation is impossible. When a wire is broken, an emergency situation occurs due to a significant asymmetry of voltage. In separate phases voltage is close to a phase to phase (380 V) one, while others - to zero.
Voltage asymmetry is observed in networks of 6 / 10 kV as a result of unbalance load of 0.38 kV networks. Power-consuming equipment connected to 6 / 10 kV networks has a three-phase performance. However, among them there are some that are able to create asymmetry. For example, electric arc furnaces. Current regulation of an electric arc in such furnaces is carried out by a phase. Unbalanced short-circuit can occur in a melting regime. High-performance ДСП-100 and ДСП-200 are powered by the networks of 110-330 kV.
In networks of high voltage unbalance can be caused by a line construction due to inequality of its resistance per phase. Transposition of phase conductors is carried out for resistance balancing of phase lines. It requires construction of special transposition supports. Construction of such transposition supports is complex and expensive; besides, they are elements that are most likely to be damaged. Therefore, there is a tendency to reduce a number of transposition supports. It influences voltage symmetry and increases safety of power supply.
Another reason for voltage asymmetry - single phase conditions in networks with an isolated neutral. They are considered to be special but accepted by the

conditions of operating regimes. These modes are accepted to save electricity of consumers to the detriment of voltage symmetry on the receiving end of such a line. Earth-fault of one phase in the network with an isolated neutral relates to these modes.

Higher harmonic and unbalanced currents and voltages form positive, reverse and zero sequences. In particular, harmonics n = 3к + 1 (к = 0, 1, 2, 3, …) form a symmetrically-sequence system, harmonics n = 3к + 2 (к = 0, 1, 2, 3, …) - reverse sequence and a rate - n = 3к (к = 1, 2, 3, …) – zero sequence. When there is DC voltage in each phase it can be regarded as a zero harmonic (n = 0) of the zero sequence. This fact should be considered when calculating work modes of the mains and identifying different influences on equipment and apparatus.
Direct sequence is a major component. It determines alternation of phase (interphases) voltages and operating (nominal) voltage.
Feedback and zero-sequence voltages should be considered as an obstacle which influences the flow of corresponding currents in a three-phase circuit. These currents do not perform any useful work that results, for example, in reduction of the torque on a shaft of a running motor and their additional heating-up. Three times value of zero sequence currents in the neutral wire networks with a voltage of 0.38 kV leads to an overload. Zero-sequence currents create the effect of magnetic bias field by making of transformer windings that connected in a "triangle". However, due to this zero-sequence currents do not penetrate the network of 6 / 10 kV network of 0.38 kV.
Thus, the total power, that calculates currents and voltage, is transmitted from the load of the active and inactive power components (reactive, distortion and asymmetry). The components adversely affect the modes of the electric grid and power quality. Out of the four components of total power useful work is performed only by active power. The other three should be excluded. For their compensation the following procedures are used:
• sources of reactive power;
• filters of higher harmonics;
• balance sets.
In subsequent chapters issues of reactive power compensation in the distribution networks of industrial enterprises are discussed.

1.3. A principle of reactive power compensation

While considering circuits with an ideal inductor and capacitor it was shown that the instantaneous power circuits with a capacity is negative with respect to the instantaneous power in a circuit with inductance. This fact is of great practical importance.
In the circuit shown in Fig. 1.14a the current $\dot{I}$ in a single path is equal to geometrical sum of currents $\dot{I}_L$ and $\dot{I}_C$ in parallel branches of the circuit. If circuit conductivity with inductance b_L and capacitance of the circuit b_C, then

$$\dot I = \dot I_L + \dot I_C = \dot U (b_L - b_C) = \dot U\left(\frac{1}{x_L}-\frac{1}{x_C}\right) = \dot U\,\frac{x_C - x_L}{x_C\cdot x_L} \quad (1.55)$$

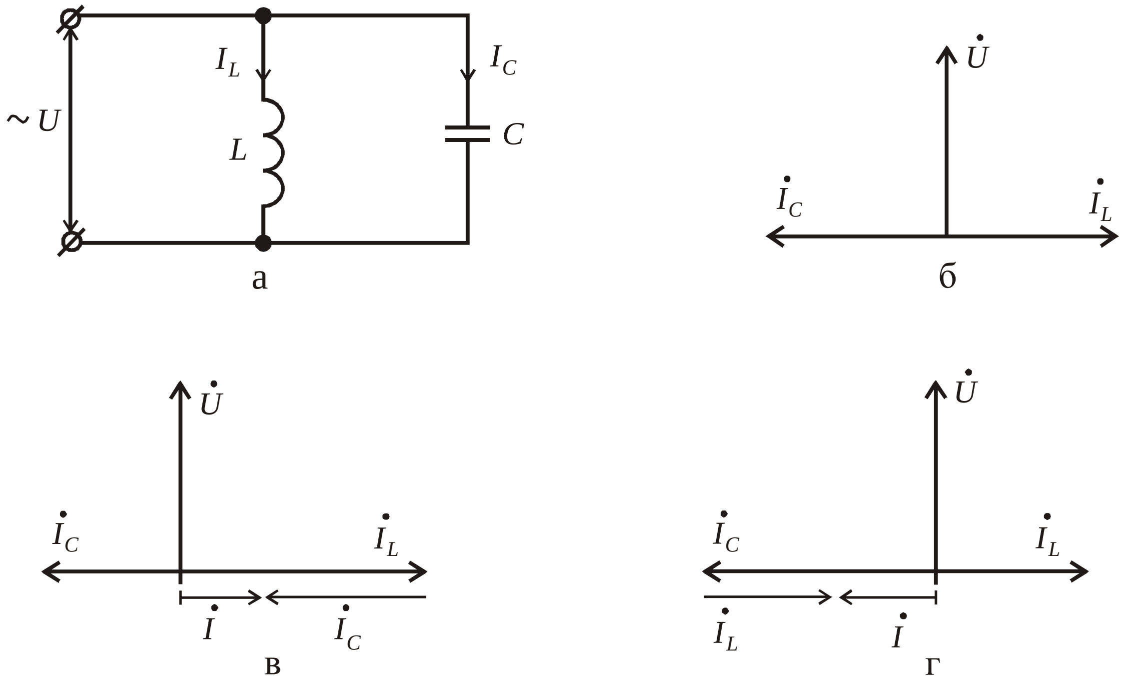


Fig. 1.14. Circuit (a) and vector diagrams of currents and voltages (б,в,г) of a subdivided circuit with inductance and capacitance

In case when $x_C = x_L$ current $\dot I$ is in a single path of the circuit is zero. This is called currents resonance. Vector diagram of currents and voltages of this mode is shown in Fig. 1.14b. If $x_L < x_C$, then the current is of inductive type, and if $x_C < x_L$ is is of capacitive type. Vector diagrams for these two cases are shown in Fig. 1.14в and 1.14г.

From the diagram in Fig. 1.14в it is clear that $x_L < x_C$ current $\dot I$ in a single path of the circuit is less than the current $\dot I_L$ flowing in the branch with inductance. In this case,

$$\dot I_L = \dot I + \dot I_C, \quad (1.56)$$

that is, by switching on in the circuit capacitance in parallel with an inductance, we can compensate a need of inductor in reactive current required to create a magnetic field, due to capacity and thus reduce the value of reactive power consumed by the inductance of the source.

In this case energy exchange will take place between circuit inductance and capacitance, between inductance and a power source there will be an exchange only of uncompensated energy.

Reactive power in a single path of the circuit in Fig. 1.14a is:

$$Q = U \cdot I = U\left(I_L - I_C\right) = U\left(U \cdot b_L - U \cdot b_C\right) = U^2\left(b_L - b_C\right) =$$
$$= \frac{U^2}{x_L} - \frac{U^2}{x_C} = Q_L - Q_C \; . \qquad (1.57)$$

Reactive power Q from the expression (1.57) represents a portion of uncompensated reactive power Q_L. Q_C power can be called a compensating power or power of a direct power plant.

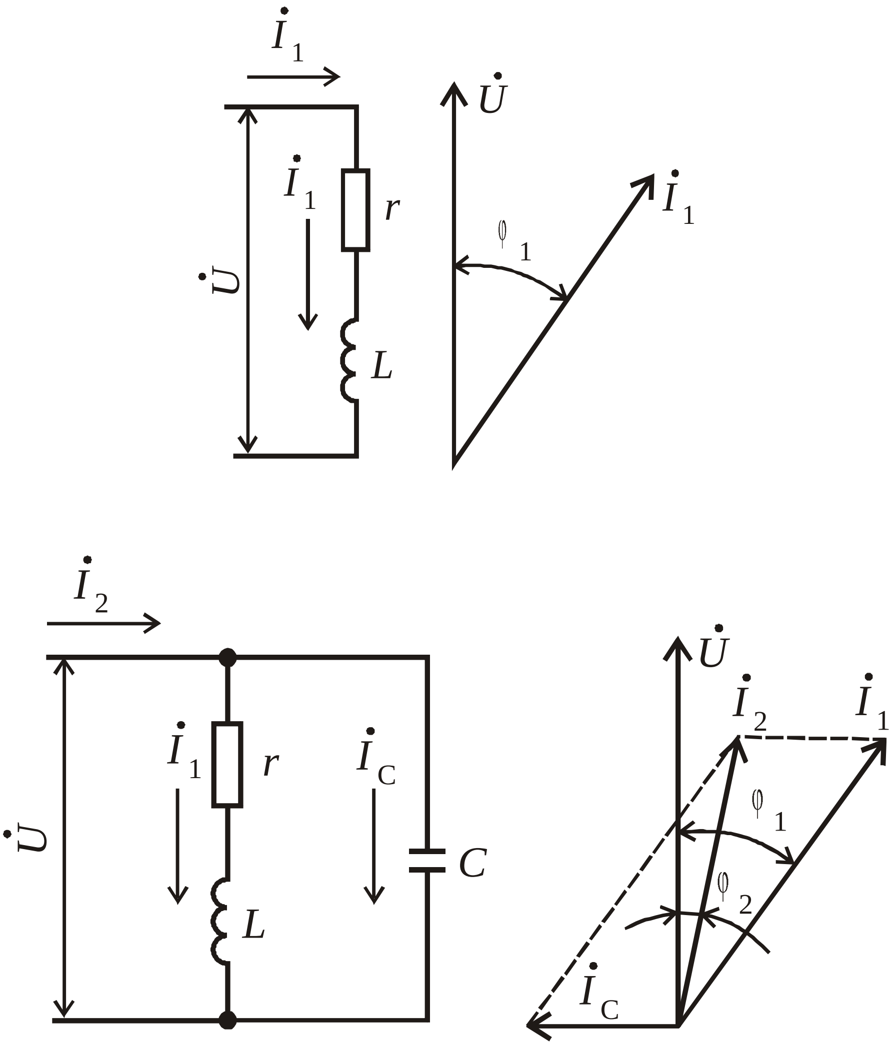
In general, reduction of reactive power circulating between a power source and a receiver, and hence reduction of reactive current in a generator and the network is called reactive power compensation.

In Fig. 1.15 the principle of compensation for the magnetizing current with the help of power capacitor current is clarified by a vector diagram. Capacity of a condenser C, connected in parallel with *r* and *L*, is chosen in such a way that the current $\dot{I}_C$ passing through it would be as close as possible to the absolute value of the magnetizing current $\dot{I}_L$, consumed by inductance. Connection of a capacitor (Figure 1.15б) allows reduction of a phase angle between voltage and current loads and thus to increase ratio power. By increasing capacity we can fully compensate for the reaction-setting power of the load.
To estimate reactive power consumption a power coefficient $\cos\varphi = P/S$ has been introduced − an indicator of maintenance quality of electrical installations of alternating current. However, this factor does not sufficiently reflect its use since when values are cosφ, close to one, reactive power consumption is still quite high. For example, when a high value of cosφ = 0,95 reactive power consumed by the load is 33% of consumed active power (see the table). When cosφ = 0,7 quantity of reactive power consumption is almost equal to the value of active power.

Table

Values of reactive power depending on cosφ
(percentage of active power)

cosφ	1,0	0,99	0,97	0,95	0,94	0,92	0,9	0,87	0,85	0,8	0,7	0,5	0,316
tgφ	0	0,14	0,25	0,33	0,36	0,43	0,484	0,55	0,6	0,75	1,02	1,73	3,016
Q=Ptgφ, %	0	14	25	33	36	43	48,4	55	60	75	102	173	301,6



б

Fig. 1.15. The principle of compensation of reactive magnetizing current: a – circuit before compensate, φ_1 - phase angle between current $\dot{I}_1$ and voltage $\dot{U}$, б - circuit with compensation. A phase angle φ2 between $\dot{I}_2$ and voltage $\dot{U}$ has decreased ($\varphi_2 < \varphi_1$) and the power factor has increased ($cos\varphi_2 < cos\varphi_1$)

A better indicator of the amount of reactive power consumed is the ratio of reactive power $tg\varphi = Q/P$.

According to values of cosφ and tgφ one can judge how much of the energy consumed is used to perform useful work.

2. SOURCES OF REACTIVE POWER AT INDUSTRIAL ENTERPRISES

A concept of reactive power sources (RPS) refers to any device capable of influencing balance of reactive power in electric power system or power-supply system. This effect can be achieved by increasing (decreasing) as generated as well as consumed reactive power. A source of reactive power must be a regulated unit, that power can be changed manually or automatically, discretely (in discrete steps) or smoothly (in smooth steps). The main parameter regulating RPS is the voltage at its connection or reactive power load, which it was intended to compensate for, or a combination of both. A RPS control device is equipped with channels responsive to the rate of voltage change or reactive power in order to increase the sensitivity control. The structure of a RPS control unit and the implemented control law is determined by its purpose. With the ability to control reactive power RPS is considered as a multifunctional device.

In electrical systems, RPS is used in networks of 110 kV and above for the following tasks:

- reduce active power and energy losses;
- voltage regulation at load nodes;
- increase capacity of transmission lines;
- increase stock of static stability of power transmission lines and power plants generators;
- improve dynamic stability of power transmission lines;
- surge suppressor;
- balance regime.

In industrial electric power supply RPS is also used to compensate reactive power consumed by a powerful load. In addition, in systems with nonlinear (nonsinusoidal) load that generates higher harmonic currents, RPS could perform the role of filter compensating devices.

2.1. Types of reactive power sources

Adjustable compensation of reactive power is provided by shunt devices connected to a substation or load buses in parallel. These devices can be divided into two groups. The first group of RPS is introduced by rotating synchronous machines: power station synchronous generators, synchronous compensators, synchronous motors. These devices allow regulating reactive power smoothly in either generation or consumption regimes. The second group includes static RPS or static compensators of reactive power. To the second group belong such devices as capacitor banks, reactors (not current-limiting), converter based devices (rectifiers, inverters) with a forced thyristors commutation or their combinations. Figure 2.1 depicts effectiveness of regulatory systems.

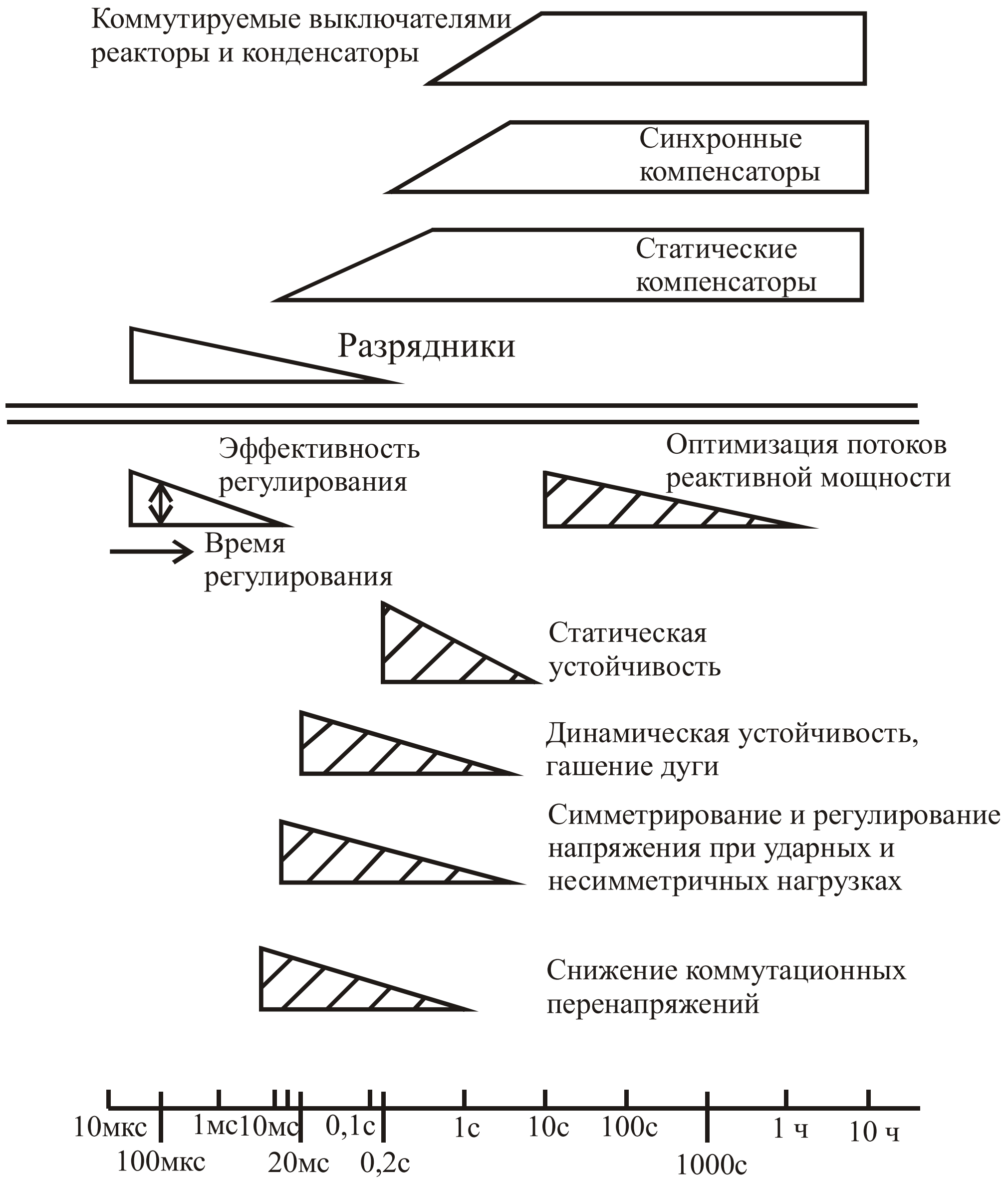


Рис. 2.1. Эффективность регулирования компенсирующих установок

Fig. 2.1. Effectiveness of compensating systems control

Reactors and capacitors commutated by circuit breakers – коммутируемые выключателями реакторы и конденсаторы

Synchronous capacitors – синхронные компенсаторы

Static capacitors – статические компенсаторы

Switching tubes – разрядники

Effectiveness control – эффективность регулирования

Optimization of reactive power flows – оптимизация потоков реактивной мощности

Response time – время регулирования

Steady-state stability – статическая устойчивость

Transient stability, Arc blowout- динамическая устойчивость, гашение дуги

Balancing and voltage regulation during impact and unbalanced loads – симметрирование и регулирование…

Reduction of switching surges – снижение коммутационных перенапряжений

Мкс – microsecond

Мс - millisecond

Capacitor banks are able to regulate generated power only in steps. For their commutation (switching on/off), in networks up to 1000 V, contactors are used. In networks of 6/10 kV and above – circuit breakers or thyristor keys (two thyristors or thyristor back-to-parallel units) are used.
Reactive power consumed by the reactors can be adjusted in steps by switchgear - the same switchgear is used for capacitors, it also can be adjusted smoothly through thyristors. A special group is introduced by saturable reactors capable to vary consumed reactive power parametrically without a regulator depending on the voltage applied to it at the connection point.

In the majority of system tasks, especially tasks connected with electricity supply systems of industrial enterprises, RPS capable of generating reactive power should be applied. Such RPS include synchronous machines and capacitor banks. Synchronous machines are able to adjust reactive power smoothly (their advantage). They have a greater inertia due to the time constant of excitation system (their disadvantage). Capacitor banks, especially commuted by thyristors, have a high speed (10 – 20 ms) with stepwise regulation of reactive power. In some applications, for instance providing static stability, stepwise control is almost unacceptable. Use of combined RPS, capable of smooth reactive power regulation at high speed, can assist in solving the problem. Such RPS usually consist of stepwise variable capacitor bank and smoothly controlled reactor in parallel.

In contrast to a capacitor bank, direct compensations devices or combined RPS are called indirect compensation devices i.e. a reactor in such RPS has an ancillary character: it provides smooth control, while the rest of RPS generate reactive power. Reactive power sources of indirect compensation depending on the ratio of installed capacity of capacitors and reactors can not only generate but also consume reactive power with a smooth transition from one regime to another.

However, combined RPS become sources of higher harmonics at relatively high power of reactors controlled by thyristors. It is considered to be their disadvantage which is possible to offset by installing filters of higher harmonics. Usually the role of filter compensating devices perform partitioned capacitor banks. Small reactors in series with the capacitors provide conditions under which resistance in capacitor - reactor is close to zero at a frequency adjustment to compensated harmonica.

2.2. Main sources of active and reactive power

Energy systems are the main suppliers of electric power for industrial enterprises. In power grids synchronous generators produce active and reactive power needed for enterprise operation. Industrial enterprises that consume a large amount of thermal energy have their own thermal power plants; in this case there must be a connection to the grid for getting missing amount of electricity and for the transfer of its surplus.

Synchronous generators are the main source of reactive power. Their reliability, automation control, lower unit capital cost of reactive power predetermine use of synchronous generators as the main sources of reactive power (in conjunction with additional sources).

Synchronous generators are characterized by certain limits of available active and reactive power which vary in regulation of their work regime. Synchronous electrical machines can generate and transmit reactive power to the network when they operate in overdrive regime. In an underexcitation regime they consume reactive power in amounts that depend on the active load. Zones of permissible operation regimes and limits of reactive power Qг of a synchronous generator depend on active Pг. The boundaries of these zones are defined by nominal values of three main parameters of a generator regime: excitation current, voltage and stator current. Stator rated value Iном и Uном can be summarized by one parameter - total nominal capacity of a generator. For a three-phase synchronous generator:

$$S_{\text{ном}} = \sqrt{3} \cdot U_{\text{ном}} \cdot I_{\text{ном}} \quad (2.1)$$

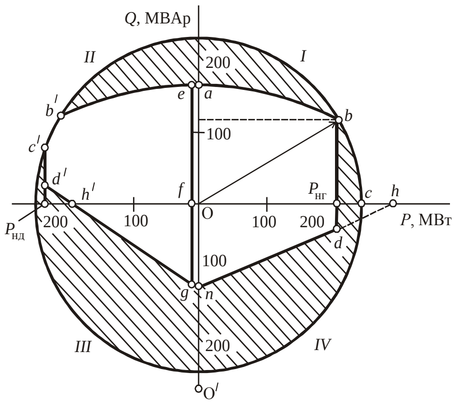


Fig. 2.2. Zones of acceptible regimes of a reversible synchronous motor

Nominal capacity limits stator load of a synchronous generator in any regime of its operation.

In Fig. 2.2 stator limit loads of a synchronous generator under normal operating conditions shown as a circle with a radius Snom (see b in Fig. 2.2). Going beyond this limit is allowed only for a limited time under conditions that justify generator overloading. There are commonly known methods that take into account influence of the third parameter of an excitation current Iв on a permissible reactive load of a generator. In fig. 2.2 limit of available reactive power (curve ab) is shown as a circular arc passing through the center of b which lies below the origin of coordinate O at a distance $\overline{O}\,\overline{O'} = S_{\text{ном}}/x_d$ where xd – axial synchronous reactance.

$$Q_{\text{г}} = U^2 / x_{d\Sigma} \qquad (2.2)$$

OabPнг quadrangle is a working area of a generator with an overexcitation zone. Available reactive power of synchronous generator regime is limited to the parties of the OndRнг quadrangle in an underexcitation regime and decreases along ndh line with the growth of active generator load from zero to nominal capacity. Limit of reactive load in an underexcitation regime is due to stability limit of a synchronous generator: maximum load at Pг = 0 is (see point n):

$$Q_{\text{г}} = U^2 / x_{d\Sigma} \qquad (2.2)$$

Point h is determined at Qг = 0 and at 15-fold stability margin as the limit of generator active power:

$$P_{\text{г}} \approx 1{,}77U^2 / x_{d\Sigma} \qquad (2.3)$$

Heating of windings coil ends and mounting parts occurs during operation of a generator with underexcitation. As a result of that, generators consumption of reactive power must be reduced.

Sometimes synchronous generators are used only to produce reactive power (synchronous compensator regime) with closed water or steam access to turbine blades. In this case, synchronous machine consumes electricity from the network to provide its rotation and heating. The losses are 2-5% of the nominal generator capacity. In Fig. 2.2 these losses are represented by a segment Of, the whole area of synchronous compensator regime – by a segment Ofea with overexcitation and Ofgn with underexcitation.

There is another area of generator application in synchronous motor regime with overexcitation and underexcitation. This application appeared due to construction of pumped storage power plant with reversible synchronous machines. These synchronous machines operate in a generator regime when stored in the reservoir of drawdown water and in a synchronous motor regime when a hydro pump runs as a hydroelectric generator while filling a reservoir with water from a tailrace. In fig. 2.2 this zone is represented by the figure $ab'c'd'n$.

Synchronous generators as the main sources of reactive power are also one of the main means of voltage regulation. Capability of a generator as a control device is determined by its performance (hydro- or turbine generator), thermal conditions, excitation system and automatic excitation control. An adjustable parameter of a generator is voltage at its terminals that can vary for most generators by up to $0{,}95U_{ном} \leq U_г \leq 1{,}05U_{ном}$. Given voltage can be maintained if generator reactive power output is within acceptable limits: $Q_{min} \leq Q_г \leq Q_{max}$.

Due to structural features of turbo-generators their reactive power adjustment range can be taken as a function of cosφ (Figure 2.3). Typically total power of hydro-generators does not depend on cos φ. In most cases hydroelectric generators are designed to operate in a synchronous compensator regime, i.e. for them $Q_г = S_{г.\ ном}$.

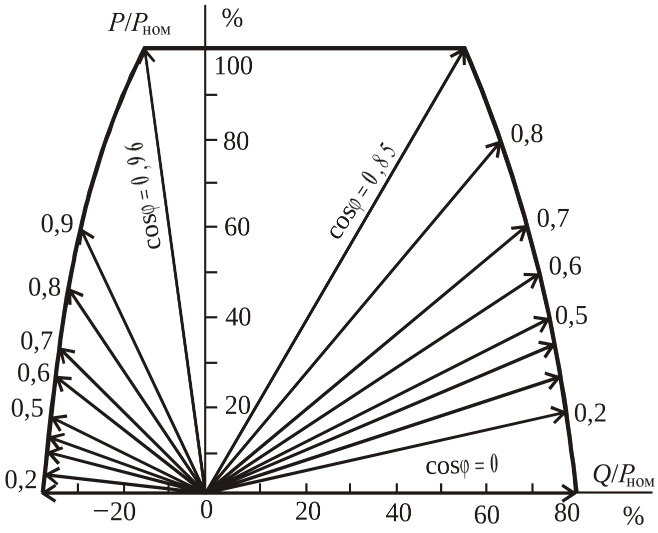
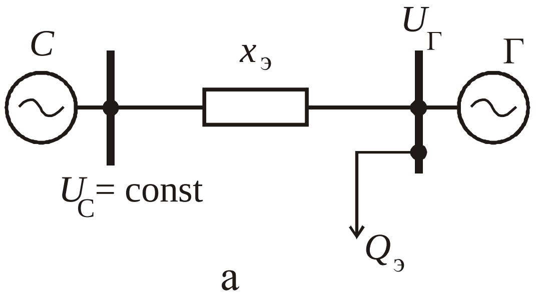
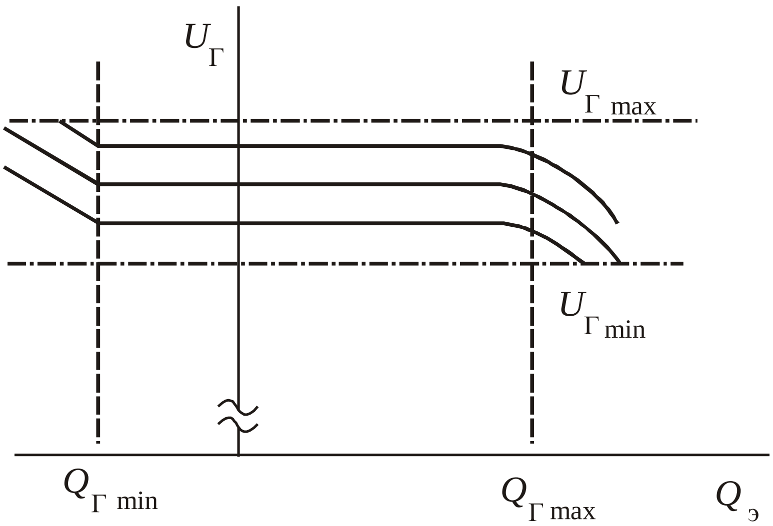


Fig. 2.3. Limited generation and consumption of reactive power for a turbogenerator



а



б

Fig. 2.4. Connection of power station Г with the system C (a) and static characteristics of the generator Г (б)

A turbo-generator can not only generate but also consume reactive power (Figure 2.3). This need is related to regulation (maintenance) of generator terminal voltage (on buses of generator voltage). This generator ability in this respect is illustrated by its static characteristic of $U_г = f(Q_э)$, Fig. 2.4, and provides automatic control of excitation by changing an excitation current. If excitation current increases, reactive power increases as well, changing with the permissible limits from $Q_{г\ min}$ to $Q_{г\ max}$.. If $Q_э$ decreases, generator reactive power decreases to $Q_{г\ min}$, in this case voltage on generator buses begin to increase. On the contrary, if reactive power increases to $Q_{г\ max}$, voltage on generator buses begin to decrease. In the section from $Q_{г\ min}$ до $Q_{г\ max}$ voltage through the operation of the controller is supported with a given excitation statism, determined by the tilting motion of its static characteristics. Such voltage control is possible, as noted in the range (0,95-1,05) · Un.

Above mentioned area of synchronous generators application at power plants and electric power systems take into account only technical limitations and do not take into account economic factors. The main economic factor of reactive power limiting of synchronous generators is a large power loss during transfer of generated reactive power $Q_г$ to consumers. Some energy supplying companies, taking into account these losses, calculate the most advantageous site power in reactive power compensation of enterprises and set them a cross-flow value of not only active power but also reactive power in hours of maximum and minimum power system loads.

2.3. Synchronous compensators and engines

Synchronous compensator (SC) - a type of a synchronous machine that is designed to operate without an active shaft load. SC is used to stabilize voltage at a connection point within ± 5% of a nominal value, as well as for generation and consumption of reactive power, and this affects a mode of power supply system. Synchronous compensators are installed at the points of the energy system or electrical system, where the load curve varies widely, and therefore significantly change balance of reactive power.

Fig. 2.5 shows an equivalent circuit and vector diagrams illustrating the principle of the synchronous machine in a synchronous compensator mode.

By applying Kirchhoff's second law of an equivalent circuit IC (Figure 2.5a), we can obtain the following equation:

$$E_q + U_c = j \cdot I \cdot x_d \tag{2.4}$$

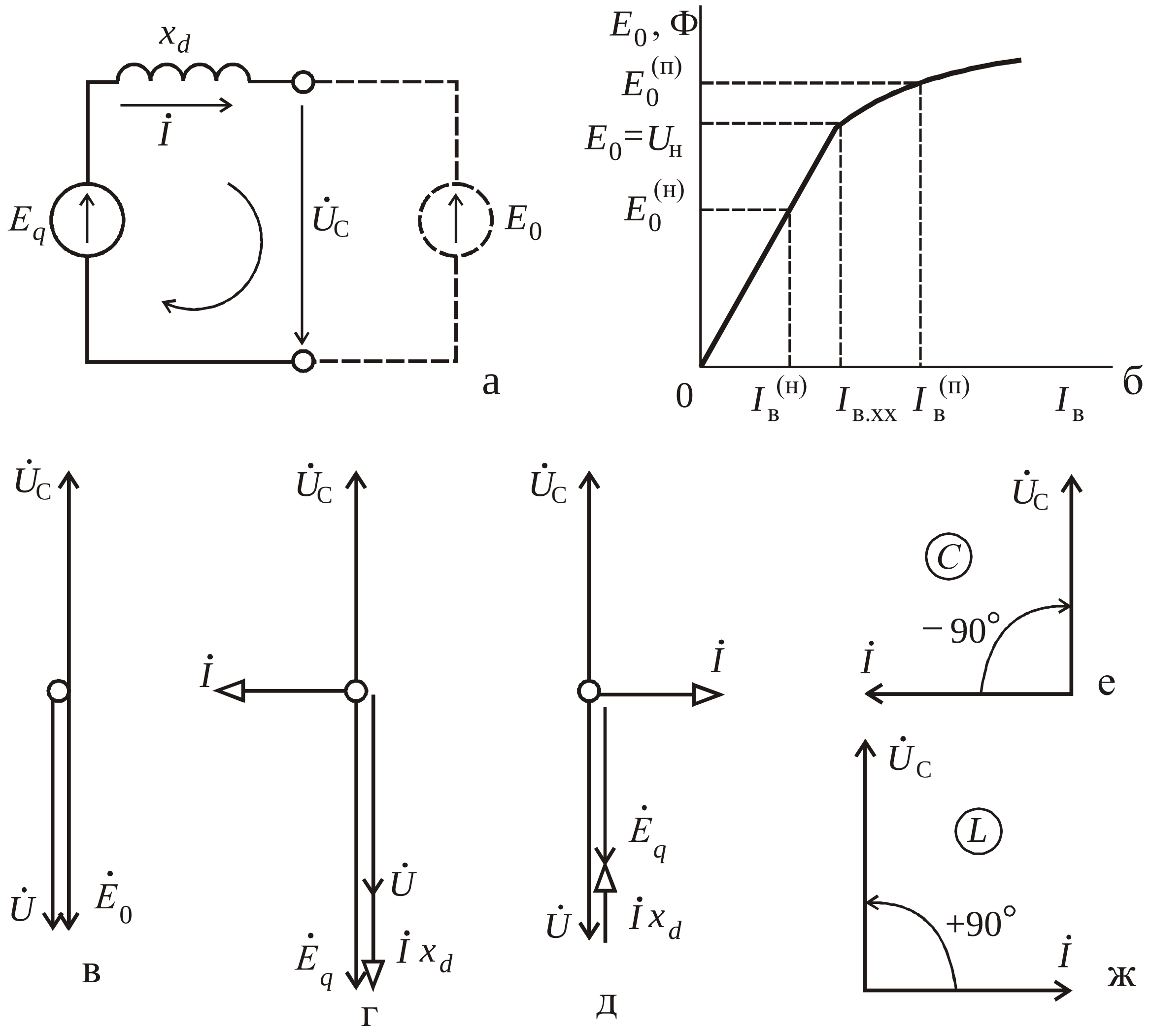


Fig. 2.5. The equivalent circuit (a), no-load characteristic (b) and vector diagram of synchronous machine c: with excited no-load. d,e – with overexcitation. f, g - with underexcitation

This equation will help us to find the expression of stator current:

$$I = \frac{E_q + U_c}{j \cdot x_d} = -j\frac{E_q + U_c}{x_d} \quad (2.5)$$

Next, we will analyze the expression of SC stator current in three different modes of excitation.

When excited by idling $I_{\text{в. хх}}$ (Fig. 2.5b) $E_q = U$, that is, the electromotive force is equal to the rated voltage $U_{\text{ном}}$ which is maintained by the supply voltage U_C, and is in opposition with it. In this case the expression (2.4) will be as follows:

$$E_q + U_C = 0 \text{ or } E_q = -U_C \quad (2.6)$$

In Fig. 2.5c a corresponding vector diagram is shown.

When SC overexcitation occurs, that is when $I_{\text{в}}^{(\text{п})} > I_{\text{в. хх}}$ (Fig. 2.5b), electromotive force $E_q^{(\text{п})}$ is greater than voltage supply multiplied by magnitude of the voltage drop I·xd:

$$E_q + U_C = j \cdot I \cdot x_d = \Delta E^{(\text{п})} \quad (2.7)$$

In accordance with (2.5) under the action of ΔE(п) there is stator current:

$$I = -j\frac{\Delta E^{(\text{п})}}{x_d} \quad (2.8)$$

Stator current is purely reactive, and its value increases along with an excitation current. This case corresponds to the vector diagram in Fig. 2.5г: electromotive force Eq is higher than UC voltage and equals to the sum of the voltage compensator U and the voltage drop Ixd. Current direction in a circuit with an inductive reactance xd is known (see section 1.2.1): current lags behind the voltage by 90°. For comparison, Fig. 2.5e,ж depict vector diagrams of a circuit with capacitance and inductance: a vector diagram overexcited SC coincides with the diagram of a circuit with capacity (see Section 1.2.2).

When SC underexcitation occurs, that is when $I_{\text{в}}^{(\text{н})} < I_{\text{в. хх}}$ (Fig. 2.5б), electromotive force $E_q^{(\text{н})}$ is lower than UC voltage, so their vector sum changes sign: it becomes negative (ΔE(н)).. Direction of the stator current changes accordingly:

$$I = j\frac{\Delta E^{(н)}}{x_d} \qquad (2.9)$$

For this case, in Fig. 2.5д a vector diagram is shown: Eq < UC, and the direction vectors of the voltage $\dot{I}x_d$ and current $\dot{I}$ drop is contrary to the one obtained by overexcitation (Fig. 2.5г). Vector diagram of the input voltage $\dot{U}_C$ and stator current of an underexcitation synchronous machine shown in Fig. 2.5д, coincides with the vector diagram of a circuit with inductance (see Section 1.2.1), Fig. 2.5ж. The underexcitation synchronous machine consumes lagging current like an inductor.

The minimum allowable long-term reactive power IC is not lower than 50% of its rated capacity. Power reduction of consumption in this regime is accompanied by a decrease in EMF of a synchronous machine, and, consequently, stability margin work decreases. The minimum level of reactive power consumption is limited by it.

In the generation regime of reactive power Qmax = Sном and short-term congestion by forcing the field current IC are accepted. IC properties are determined by a regulator excitation. One of the IC advantage is a positive regulatory effect, i.e. the ability to increase generated reactive power in case of voltage reduction on the buses. Parameters of SK regulation are reactive power and voltage limited by the permissible ranges Qmin ≤ QCК ≤ Qmax, 0,95Uном ≤ UCК ≤ 1,05Uном. SC static characteristic is similar to the characteristic of a synchronous generator shown in Fig. 2.4.

When synchronous machines are loaded with not only reactive but also the active load an active current component $\dot{I}_a$ appears. Between current $\dot{I}$ and voltage $\dot{U}_C$ angle φ is not equal to 90 °, in this case reactive component of current is conserved. Accordingly, properties of a synchronous machine as a source of reactive power are also conversed. Vector diagram of a synchronous generator that can produce both active and reactive power are shown in Fig. 2.6. The order of their construction and excitation regimes are the same as for a synchronous compensator regime.

Synchronous motors in electric power systems are used in manufacturing of drive mechanisms that do not require speed control. Their application is useful when power is more than 50 kW. Vector diagrams are shown in Fig. 2.7. A synchronous motor, as a source of reactive power, has several advantages:

• less sensitive to voltage nonsinusoidality;
• is located directly on the shop floor, so the active losses in the transmission of reactive power are minimal;
• unit capital cost of reactive power synchronous motors (and generators) is a lot lower than capacitors, since the change in cosφном engine up to 1 up to -0.9 leads to an increase in its total capacity by 11%, and the reactive power varies from 0 to 48% with respect to Pном;
• in most cases the expenses are lower than for an induction motor in combination with a capacitor bank;
• provides smooth control of reactive power and maintains constant voltage at the connection point to the network;
• increases stability limit of the load.

Synchronous generators have similar qualities: they are sources of reactive power with a low unit cost, with a smooth and automatic control of reactive power generation as a voltage function. In contrast to engines, reactive power transmission from a generator is carried over long distances with heavy losses of power and energy per unit of reactive power. This limits the use of generators as a source of reactive power for industry.

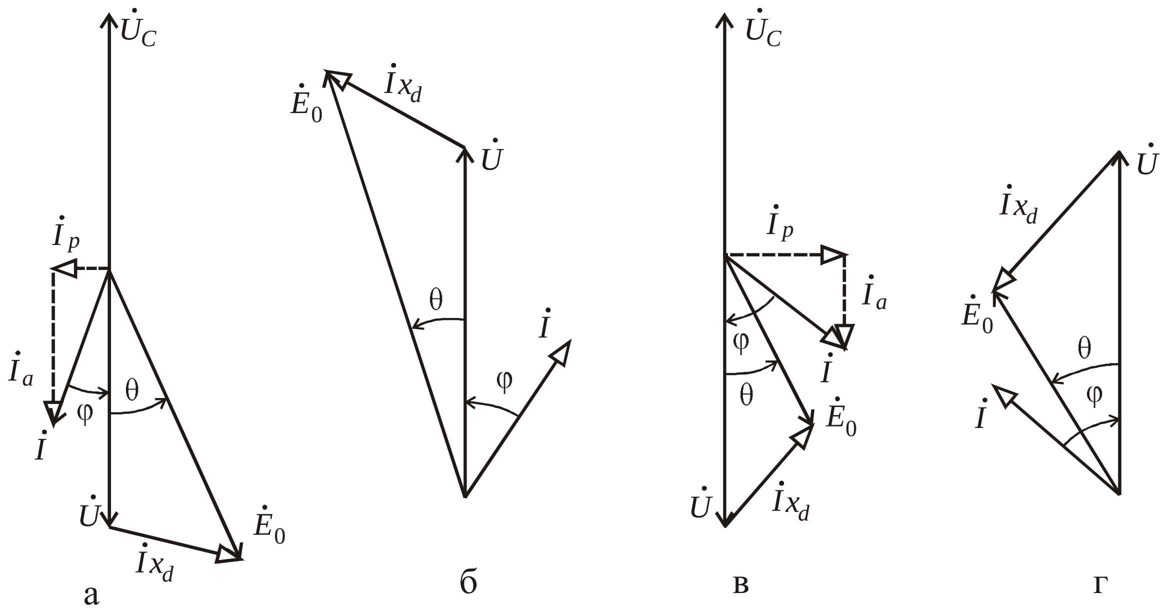


Fig. 2.6. Vector diagram of a synchronous generator during its operation with overexcitation (a, b) and underexcitation (c, d), θ-load angle

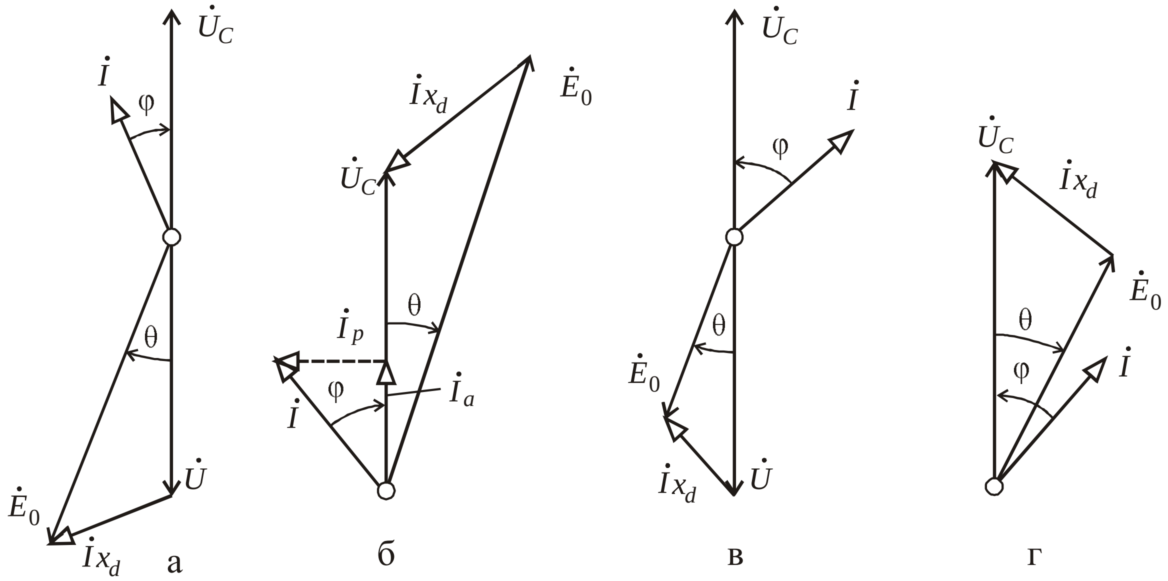


Fig. 2.7. Vector diagram of a synchronous motor during its operation with overexcitation (a, b) and underexcitation (c, d)

Synchronous generators and motors, while performing their main tasks, produce reactive power as a byproduct – generation and consumption of active power, i.e. the transformation of one form of energy into another. Synchronous compensators are installed specifically to produce only reactive power in addition to the primary sources. Therefore, unit costs (rub / kVAr) for production of reactive power by a generator and an engine are practically equal to zero, since the capital cost for their installation are related to application of the machines. СК installation costs are related to reactive power production since production of reactive power is their direct application, and these costs are significant.

2.4. Capacitor banks

Capacitor banks (CB) - a simple and reliable static device. They are assembled from individual capacitors which are produced for various power and voltage ratings.
A capacitor is a device that consists of two conductors separated by an insulator. When voltage is applied to a capacitor, it can store an electric charge (or to charge) and give it away (discharge). In the space between the conductors of different shape an electric field is formed by charging a capacitor. The higher capacitor charge the larger its capacity and voltage wires applied to it. The higher the capacity the bigger the inner surface of conductors that form a capacitor, and the smaller distance between the conductors.

A capacitor is characterized by active power loss that can lead to its heat. The greater the loss the higher voltage applied, its frequency and capacitance. Besides losses depend on dielectric properties of defined dielectric loss tangent (tgδ). Depending on the type and purpose of a capacitor, they range from 0.5 to 4 W/kVAr.
Cosine capacitors are used for reactive power compensation. Cosine capacitors are designed to operate at a frequency of 50 Hz. Their capacity ranges from 2 to 100 kVAr.

Capacitors are classified according to:
• rated voltage;
• installation type (external and internal);
• type of impregnation;
• dimensions.

Capacitors with a rated voltage of 660 V are available in single phase and three-phase versions, and capacitors with a rated voltage above 1000 V - only in a single

phase version. Sections in a capacitor are connected in a triangle in a three-phase version.
Capacitors for voltages up to 1000 included are manufactured with built-in fuses, series-connected with each section. Capacitors of higher voltage do not have built-in fuses and require separate installation.

Overload capacity current can be up to 30% of rated voltage and - up to 10% of voltage.
A group of capacitors connected together in parallel or in series or parallel-series, is called a capacitor bank.
A capacitor bank, equipped with switchgear, protection and control devices, forms a capacitor unit (CU).
Power generated by a capacitor bank, with its set capacitance C is proportional to applied voltage and frequency:

$$Q_{КБ} = U^2 \omega C \qquad (2.10)$$

Therefore, unregulated capacitor banks have a negative regulatory effect that, in contrast to the synchronous compensators, is their disadvantage. This means that voltage of a capacitor bank decreases with a decrease in voltage applied, whereas under the terms of this regime it is necessary to increase capacity.
Regulatory effect of capacitor unit reactive power from one section is shown in Fig. 2.8a.

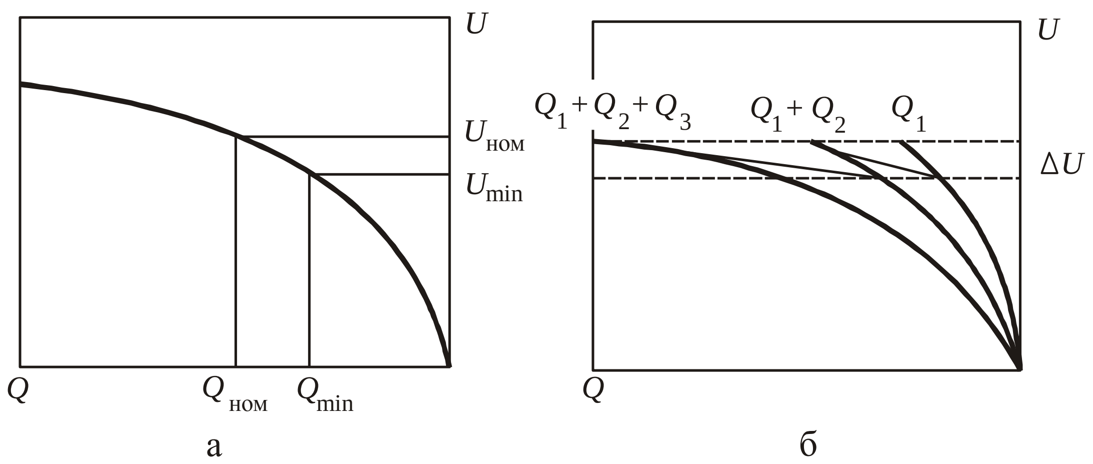


Fig. 2.8. Static characteristics of a capacitor unit consisting of one (a) and three (b) sections

When voltage from $U_{ном}$ to U_{min} is being reduced, reactive power is reduced in proportion to a square of voltage from $Q_{ном}$ до Q_{min}.

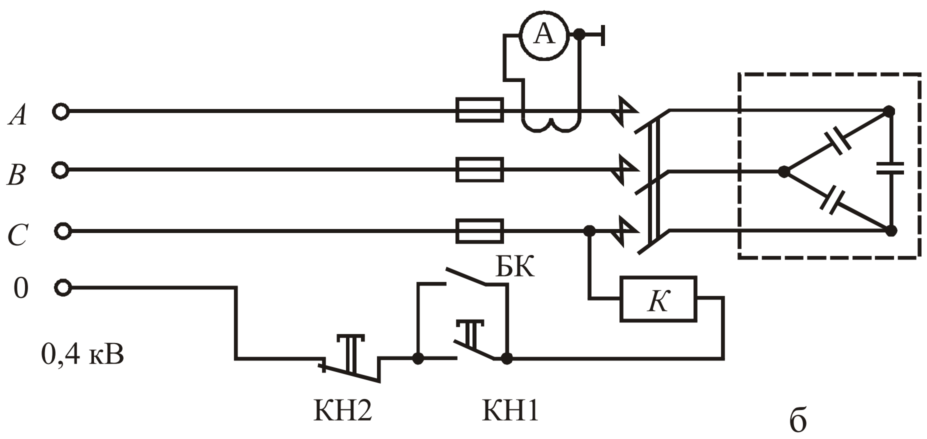
Assembly of a capacitor bank from several sections, each section is controlled by power and / or voltage controllers connected to the network via a switch, thus increasing capacity of a battery as a whole. Static characteristic of a capacitor unit consisting of three sections, is shown in Fig. 2.8b. Capacitor unit capacity increases gradually (stepwise) while voltage is being reduced Q1, Q1 + Q2, Q1 + Q2 + Q3.

Stepwise regulation requires implementation of dead time zone ΔU into a capacitor bank voltage regulator. Within this zone, when voltage drops, connection of one more section is impossible. Failure to do so would lead to unstable operation of a capacitor unit. The width of the dead time zone should be bigger than increment of tension caused by connection of the next section immediately after its incorporation. Otherwise, capacitor unit voltage reaches the voltage setpoint operation to shut down this section immediately after its incorporation. Probability of such an effect is greater if the power plug section is high and the dead time zone of a capacitor unit controller is low.

A capacitor unit consists of several sections with a common control system. Low-voltage capacitor units of 380 V (Fig. 2.9) are assembled from three-phase capacitors in parallel. For protection of such capacitor units from short-circuit and overload protection fuses are applied. High voltage capacitor banks (Figure 2.10) are assembled from single-phase capacitors connected in series-parallel.

Switching on of a capacitor unit is accompanied by surges and its shutdown by overvoltage. It affects lifetime of capacitors and switching equipment. Therefore, capacitor units equipped with switches (contactors) are not recommended to be switched on/off more than 2-4 times per day. To limit current surges capacitors before switching on must be discharged by means of discharge devices (see Section 5.3).

Due to parametric properties capacitors are sensitive to distortions of sinusoidal voltage waveform, i.e. higher current harmonics. The lower resistance of a capacitor xC = 1/(пωC), the higher frequency harmonics пω in a nonsinusoidal curve of applied voltage. As a result, due to higher harmonics that penetrate into a capacitor, power losses ΔP increase and it leads to additional heating: and reduction of service life:



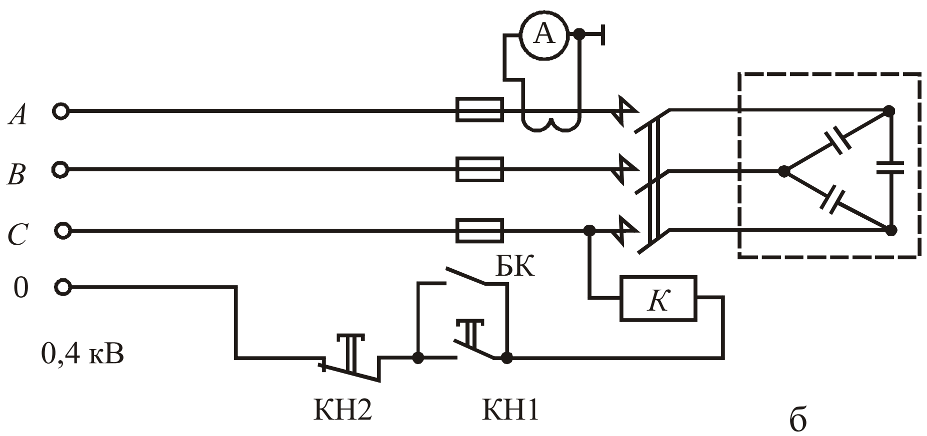
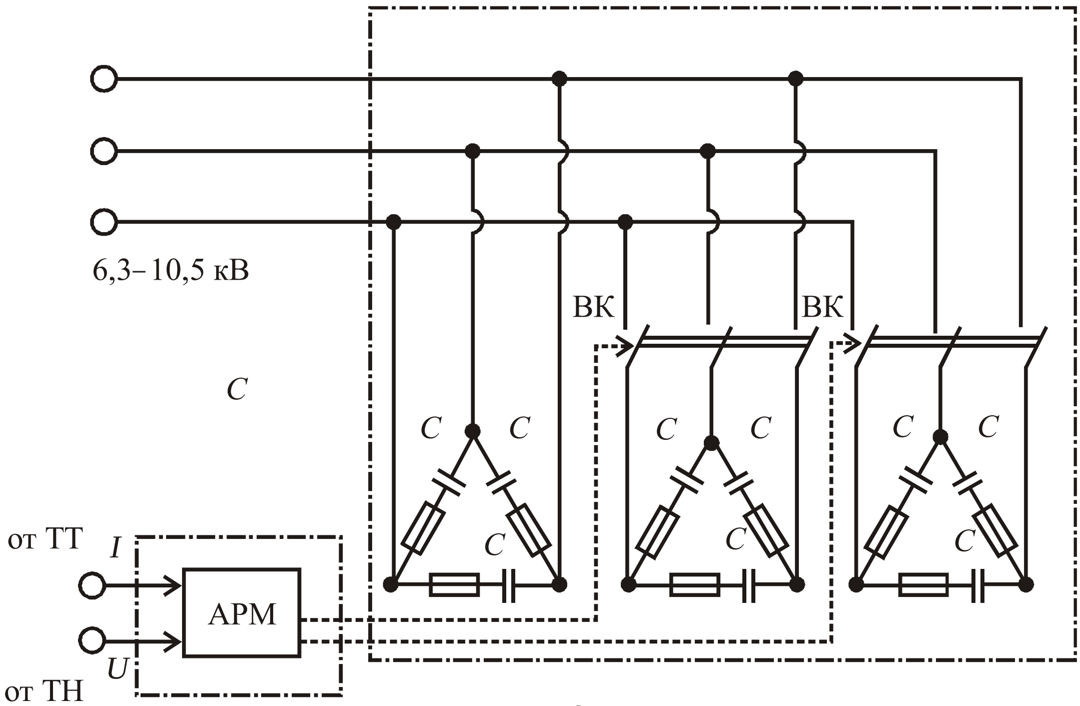


Fig. 2.9. A simplified schematic diagram of a capacitor bank, voltage 0.4 kV

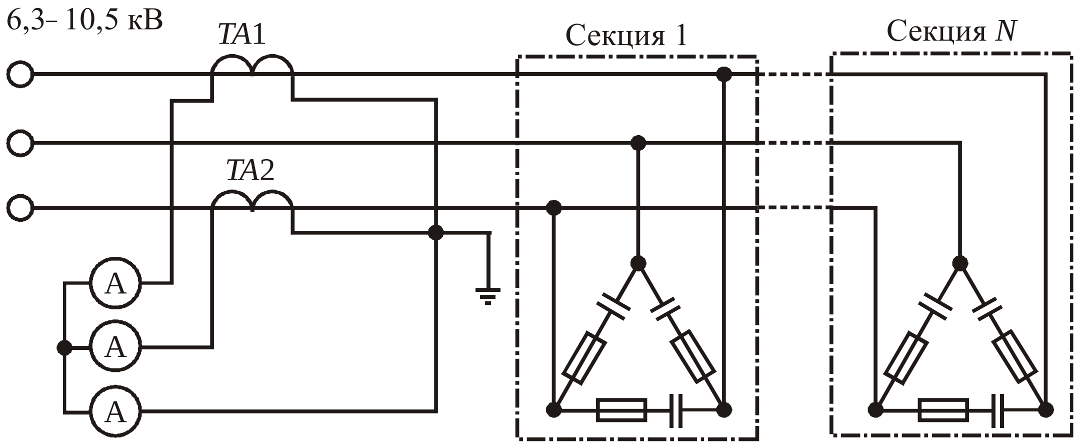
$$\Delta P = \sum_{n=1}^{N} U_{(n)}^{2} n\omega C \text{tg}\delta \qquad (2.11)$$

A parametric property of capacitors is used for production of filter compensating units.

Application of capacitor banks is associated with resonance phenomena due to formation of serial and parallel circuits by inductive and capacitive elements of the network. Resonance phenomena are accompanied by increased voltage (voltage resonance) or current (current resonance) at frequencies above rating if there are sources of higher harmonics in the network. The inductive at resonant frequency



a



б

Fig. 2.10. A simplified schematic diagram of a capacitor bank, voltage from 6,3 – 10,5 kV

XL(n) and capacitive XC(n) resistances are equal, i.e. n ω L = 1 / (n ω), where пωL = 1/(пωC) – input network resistance at a connection point of a capacitor bank, its resistance XC(n) = 1/(пωC). Always make sure that there is no resonance phenomenon when choosing capacitor bank power and, consequently, its resistance, as well as places of capacitor bank’s connection. It also concerns capacitor banks that are a part of filter compensating devices.

2.5. Static thyristor compensators based on capacitor banks

Application of capacitor banks for the tasks of reactive power rapid control, frequent section switching of capacitor banks is almost impossible due to current surges and overvoltage which occur when their commutation takes place by conventional switches. Replacing of conventional switches by thyristor keys, that provide capacitor bank commutation at a time, reduces current surges when capacitor banks are switched and overvoltage when they are switched off, eliminates frequency restrictions of capacitor banks commutation, imparts properties to devices so that they they can be applied in solution to the tasks aimed at reactive power compensation including networks with the loads that can suddenly change.

Thyristor keys are composed of two back-to-parallel thyristors (Fig. 2.11). They are used to regulate capacitor banks and reactors. Power control of capacitors and reactors with the help of thyristors, due to the nature of their commutative properties, is fundamentally different.

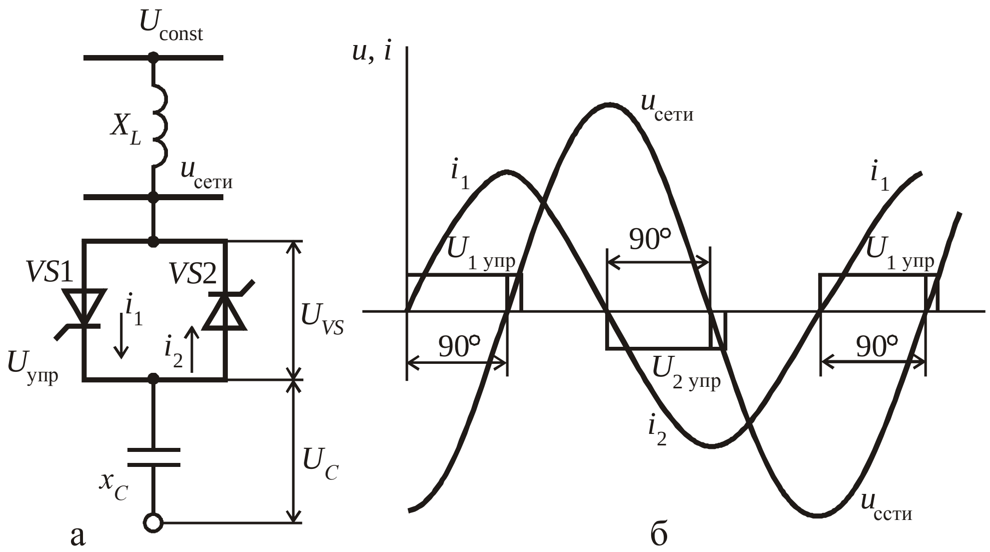


Fig. 2.11. A thyristor switch for commuting capacitor banks: a – a schematic diagram of one phase, b - current and voltage of a capacitor bank in a steady regime.

To limit surges thyristors should be opened at a time when the instantaneous voltage and the voltage on a capacitor bank are equal (an ideal case) or similar. To limit overvoltage, when a capacitor bank is switched off, a thyristor should be closed when current passes through it to a zero value.

Following this principle, we can virtually eliminate current surges and overvoltage by removing the restriction on switching frequency of a capacitor bank. A single-phase scheme of a capacitor bank commutated by thyristors is depicted in Fig. 2.11a. As we can see from Fig. 2.11b, device operation is in a steady state yhat occurs after a thyristor opening after 0,01 –0,02s, and is not accompanied by any surges or overvoltage.

Fig. 2.12. shows a static thyristor compensator (STC) in a single-phase version that consists of three sections of a capacitor bank, each section is commutated by its thyristor key. Static characteristics of these devices are similar to those in Fig. 2.8. And there are still requirements for the controller a dead time zone. However, the number of sections' switching on/off on is not limited and they can take place alternately every 0.02 seconds, that is, through a period of industrial frequency.

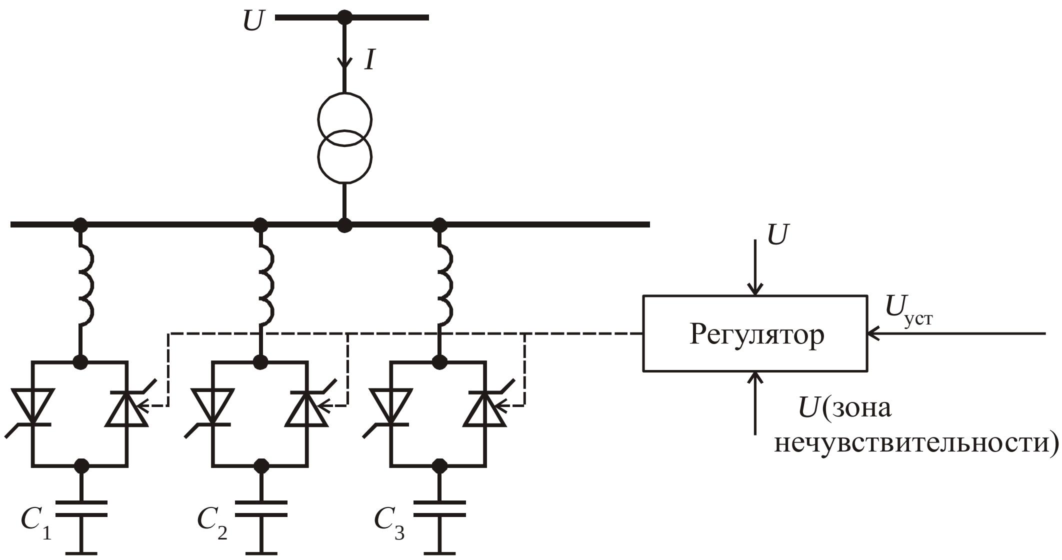


Fig. 2.12. A schematic diagram of the STC that consists of three sections, capacitor banks, and commutated thyristors

Controller – регулятор

Dead band – зона нечуствительности

2.6. Reactors commutated by circuit breakers

Typically, the reactor is connected via a circuit breaker or a separator directly on bus power, or to the tertiary winding of the transformer. A high-voltage reactor can be single or three phase. The core of the reactor is carried out either with a gap, or armor type. Static characteristic of the reactor is linear, i.e. the reactor has a constant reactance XL = ωL, where L - reactor inductance. Low-voltage reactors do not have a steel core. Switches designed for commutating of reactors can be equipped with external resistors and reactors themselves with surge arresters caused by a cut off.

A static characteristic of the reactor with a steel core is linear and beyond working range it can be nonlinear (Figure 2.13). Reactor performance, that is steady state time after its incorporation, is about 100 ms. Such reactor, operating in a working band, is not considered as a source of higher harmonics. Higher harmonics can occur in reactor current if an increase in voltage will bring its characterization to a nonlinear part or so-called saturation regime (section 2 in Fig. 2.13).

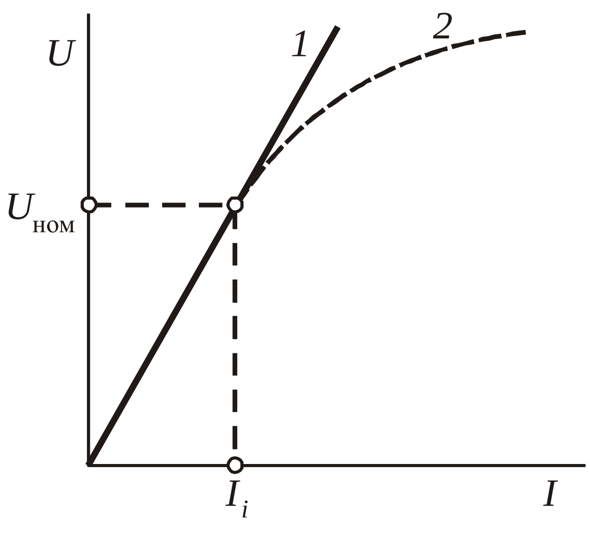


Fig. 2.13. A static characteristic of a shunt reactor: 1 – coreless; 2 - with a steel core

Losses in a reactor are 0,2 – 0,4% of its rated capacity. Such reactors are not sensitive to voltage spikes with a super current.
Reactors have a positive regulatory effect, i.e. they increase consumption of reactive power when voltage is increased, and it contributes to its limit. Therefore, reactors are applied to regulate voltage for long-distance electric transmission of 220 kV and above, as well as to compensate for charge capacity. Installedt capacity of a reactor can be between 10 MVAr in the distribution network to 150 MVAr at 750 kV networks. Reactors are installed terminal and intermediate substations. Their activation and deactivation is performed by maintenance personnel at the direction of a system manager.

2.7. Saturable reactors

A saturable reactor is a reactor that working regulation range is in a saturated part of its static characteristics. Due to it a reactor can be considered as a parametric device that regulates reactive power. Reactor resistance in a nonlinear part of the characteristic changes depending on voltage applied to it. With increasing voltage the current in the reactor rises rapidly, increasing consumption of reactive power and, thus, contributing to stabilize voltage at its connection.

Due to the fact that the operating range of a reactor is in a non-linear part of the characterustic, a reactor should be considered as a source of higher harmonics. For their compensation complex 6 - and 9-rod cores and special connection schemes are used. Application of such reactors is very limited due to their construction complexity.
Fig. 2.14 shows a schematic diagram of the IRM-based reactor. Here, a parallel switched capacitor bank enables parametric regulation as in a consumption regime as well as in a regime of reactive power generation. Corresponding static characteristics are shown in the same figure. Capacity of a capacitor bank, that usually performs a function of a filter compensating device, is chosen so that at nominal voltage the total power of the IRM equals to zero. Then, the source consumes above $U_{\text{ном}}$ when voltage increases, with a decrease below $U_{\text{ном}}$ – it generates reactive power.

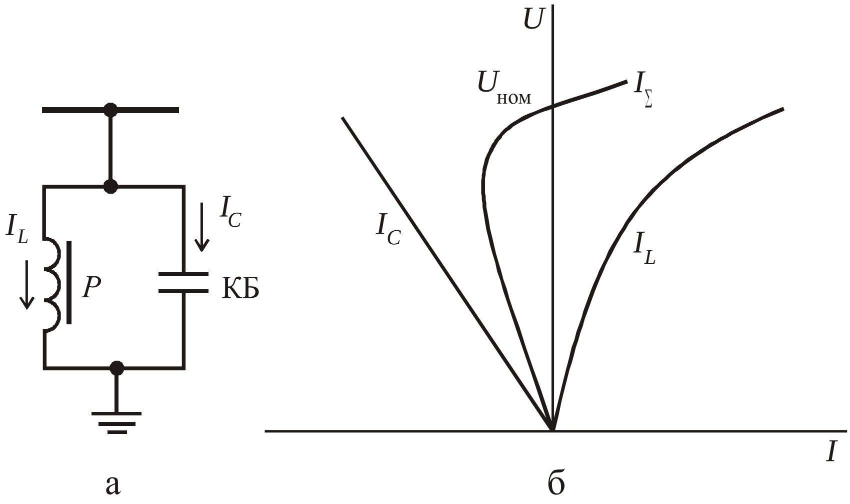


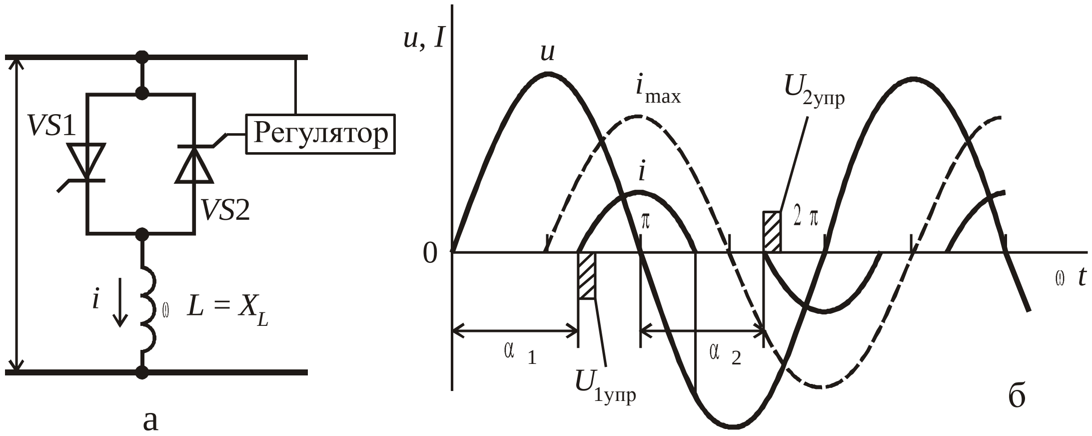
Рис. 2.14. Parametric IRM with a saturable reactor: a - schematic diagram, b - static characteristic

2.8. Thyristor commutated reactors

In Section 2.6 we have viewed the reactors which are used for a stepwise control of reactive power consumption. Disadvantages of such control are considered in Section 2.1. For smooth control reactors, in contrast to capacitors, can be switched on with the help of thyristor keys, changing angle of control provides current change in a reactor.

A schematic diagram of a smoothly controlled reactor is shown in Fig. 2.15a. Regulation of reactor power is provided by varying current in it due to increasing or decreasing angle control α1 and α2 which correspond to thyristors VS1 and VS2 which are switched on back-to-parallel. In this case α1 = α2. If α = π/2 thyristors are opened completely, current in the reactor is maximum and sinusoidal (if voltage is sinusoidal). The current is represented by a dashed line in Fig. 2.15b. When α increases and changes in the range of π/2 ≤ α ≤ π current in the reactor reduces and loses its sinusoidal shape. The shape of this current in Fig. 2.15b is represented by a solid line. The first harmonic of this current with respect to the total current IL = U/XL is

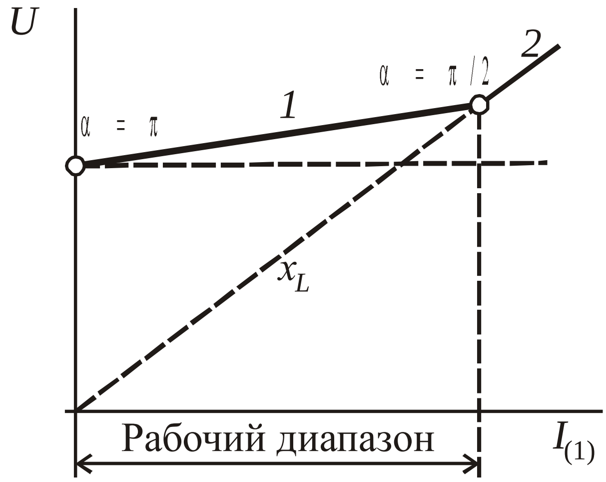
$$\frac{I_{(1)}}{I_{(L)}} = \frac{1}{\pi}\left[2(\pi - \alpha) + \sin 2\alpha\right] \qquad (2.12)$$



Controller - регулятор

Fig. 2.15. Reactor commutated bya thyristor: a - schematic diagram of one phase, b - diagram of currents and voltages with α > 90° (α > π/2)

A static characteristic of a reactor according to the first harmonic current I(1) is shown in Fig. 2.16. Statism of the characteristic, i.e. the angle of its inclination in the working range (section 1) defined by controller settings is chosen so that along with voltage increase



Working range – рабочий диапазон

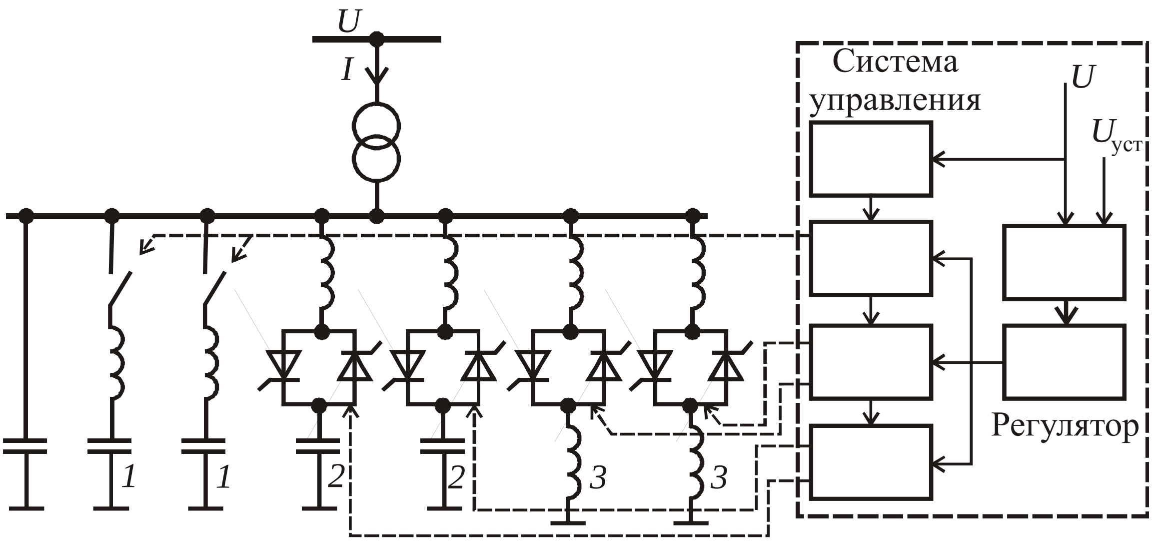
Fig. 2.16. Static characteristic of the reactor with a continuous thyristor control in Fig. 2.15

current in the reactor will increase too. It provides a stabilized voltage in the working control range from $\alpha = \pi/2$ to $\alpha = \pi$. When $\alpha < \pi/2$ reactor loses its control (thyristors are fully open) and moves to a natural characteristic (section 2) which is defined by its own resistance to XL.

A disadvantage of the reactor controlled by thyristors is that when angles are $\alpha > \pi/2$ the reactor becomes a source of higher harmonics. Sequence of harmonics and their values are close to the harmonics generated by 6-pulse converter. For their compensation reactors are switched on in the same way just like converters: by transformers with a split coil, assembled according to the following scheme - Y/Δ/Y. In addition, filter compensating devices are included in IRM structure. Reactive power sources assembled according to the scheme can be referred to combined IRM.

2.9. Combined sources of reactive power

Combined IRM are used when it is necessary to ensure smooth control of reactive power in its consumption and generation regimes. Such IRM consist of thyristor controlled reactors or saturable reactors, and capacitor banks commutated by switches or reactors. A schematic diagram of such IRM, which is known [3] as a static thyristor compensator (STC), is shown in Fig. 2.17.



Control system – система управления

Controller - регулятор

Fig. 2.17. A schematic diagram of a combined static thyristor compensator: 1 – A capacitor bank commutated by switches 2 – A capacitor bank commutated by thyristors 3 - Reactors controlled by thyristors

Working control range of reactive power, total capacity of unregulated or stepwise regulated battery, capacity of the reactors controlled by thyristors are chosen depending on the purpose of a static thyristor compensator.
For example, the following capacity ratios of static thyristor compensators, which consist of unregulated and regulated sections of a capacitor bank and a reactor controlled by a thyristor, are possible:
• total capacity of a reactor and a capacitor bank are Qр = QКБ;
• total capacity of a reactor capacity is than capacity of a capacitor bank, for instance Qр = 2QКБ.
In the first case due to the fact that reactor capacity is adjusted in the range 0 < Qр < 1, а QКБ = 1, total capacity of a static thyristor compensator can vary 1 ≤ QСТК ≤ 0. Working control range of generated reactive power is in the following regime: from power generation which is equal to total capacity of a capacitor bank to zero when thyristors of a reactor are fully open. A static characteristic of such static thyristor compensator is shown in Fig. 2.18a.

In the second case capacity of a reactor can vary in the range 0 < Qp < 2, while capacity of an unregulated capacitor bank remains equal to QКБ = 1. Such static thyristor compensator can operate in the regime of reactive power generation and consumption, so 1 ≤ QСТК ≤ 1 (Fig. 2.18б).

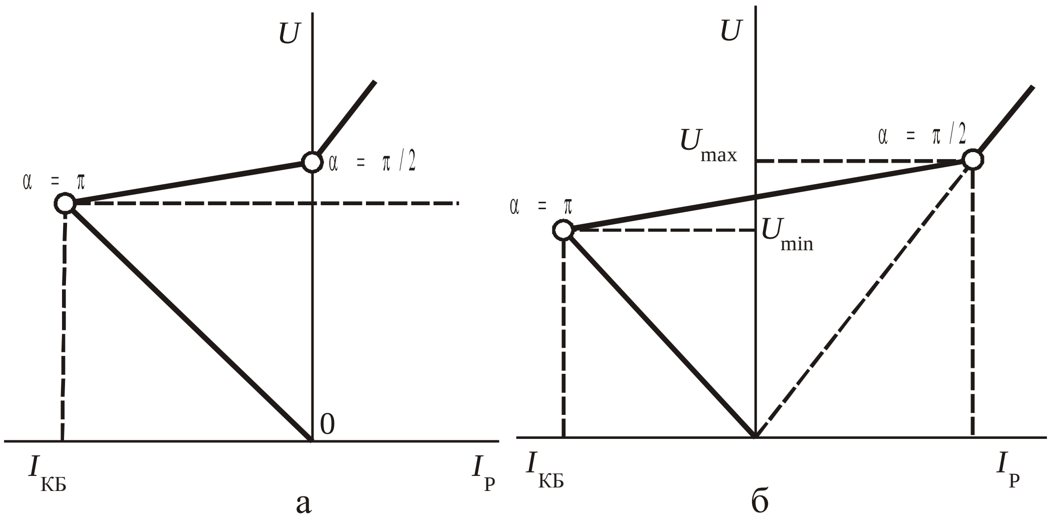


Fig. 2.18. Static characteristics of a combined static thyristor compensator: a - when Qp = QКБ; b - when Qp = 2QКБ

2.10. Transmission lines as a source of reactive power

Transmission lines have inductive and capacitive resistance. Their inductive elements are the receivers of reactive power and capacitive elements - their sources. Inductive power consumed by a line depends on the current square (QL = I2ωL0l), and reactive power generated by a line depends on the square voltage (QC = U2ωC0l). Capacitive power can prevail over the inductive in case of low loads of long high-voltage transmission lines. As the load increases inductive reactive power increases as well, and at some value it will prevail over the charging capacity, causing a positive phase shift.

At idle mode, every line is a source of reactive power. In this mode overhead transmission lines of 110 kV generate about 30kVAr 1 km line.

Reactive power of overhead and cable lines is not regulated and their activation and deactivation is performed regardless of the need of generated reactive power.

Charging capacity of a distribution network line in the hours of a maximum load is approximately equal to the losses in lines induction and is not considered in the calculations for reactive power compensation.

3. Reactive power consumption by industrial power consumers

Electrical part of electric power system consists of energy sources, supply and distribution networks, power consumers. Equal distribution of electric and magnetic fields in the networks is hardly ever possible. They are unevenly distributed along the chain.

On some parts of the chain dominates magnetic field in inductions, and in the forefront phenomena associated with it changes in other areas are brought, for instance electric field dominates in capacitors, and phenomena that occur due to changes in the electric field are formed. In accordance with these phenomena, distribution and consumption of reactive power occur.

Table 3.1 depicts the structure of power consumers in electric power systems of energy system enterprises during load peak hours of a busy winter day.

Table 3.1

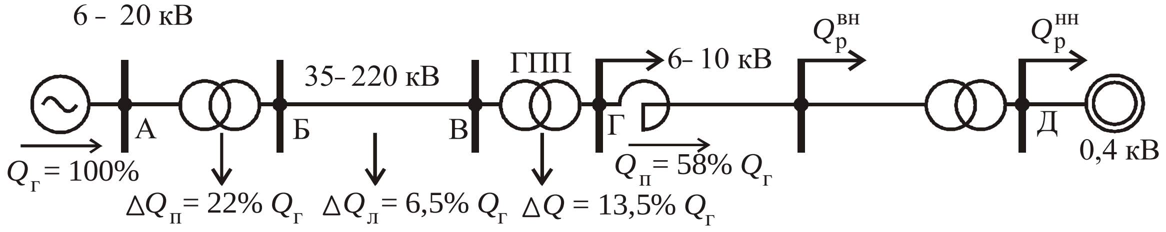
Structure of power consumers in electric power supply of enterprises

Types of power consumers	Total capacity of power consumers of electric power system, %	
	Active	Reactive
Induction motors	30	33
Synchronous motors	23	0
Valve inverters	18	10

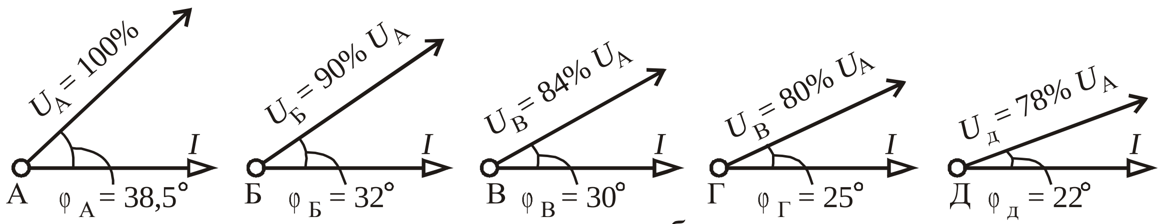
Electric-furnace installations	12	8
Domestic, agricultural, etc.	7	5
Power stations needs	5	2
Losses in electric networks	5	42

Reactive power is consumed not only by power consumers of enterprises but also some elements of supply: in the form of losses Δ*Q* their share constitutes 42% of reactive power systems. From 100% reactive power generated in the power system, 22% is lost in step-up transformers and in autotransformer at substations of 110-750 kW electric power system, 6.5% is lost in the transmission lines of regional networks, 13.5% is lost in step-down transformer and only 58% constitute consumers buses of 6/10 kV.

In Fig. 3.1 distribution of reactive power losses in equivalent station-to-consumer transmission is shown and vector diagrams of currents and voltages for nodes A to D of the transfer are depicted. Even if cos φ = 0,927 consumers (φ = 22 °) transmission sectors are heavily loaded with reactive power: 1,000 kW of active power requires from a station transmission of 800 kVAr of reactive power at the beginning of the transfer, and 400 kVAr at the end. It leads to increased current load of networks and, consequently, an increase in the cost of network building, high losses of electricity, voltage deterioration due to losses in the network elements. Heavy load of reactive power plants leads to current overload of generators, need to use them specifically for reactive power production even in those hours when generators can be disconnected.



a



б

Fig. 3.1. Reactive power flow change (a), voltage and phase shift of voltage and current (b) transmission bus stations system – buses of a receiving substation

Structure of reactive power consumers shows that the major part of reactive power is consumed by devices of four types: asynchronous motors - 40%, electric-furnace installations - 8%, valve inverters - 10%, transformers of all transformation grades (their losses) - 35%, transmission lines (their losses) - 7%. In each specific electric power system percentage may differ slightly from those shown, but the overall trend remains.

3.1. Reactive power consumption by induction motors and transformers

Induction motors and transformers consume about 75% of energy generated in the system of reactive power. Operation of AC machines and apparatus is based on the principle of electromagnetic induction (see Section 1.1.2), accompanied by a process of continuous change of magnetic flux in their magnetic fields and scattering. Therefore supplied power flow must contain not only active component of P, but the reactive component of inductive nature Q_L which is necessary for creation of magnetic fields; without the latter processes of voltage and current transformation are impossible.

Reactive power consumed by a three-phase induction motor can be determined by its equivalent circuit (Fig. 3.2):

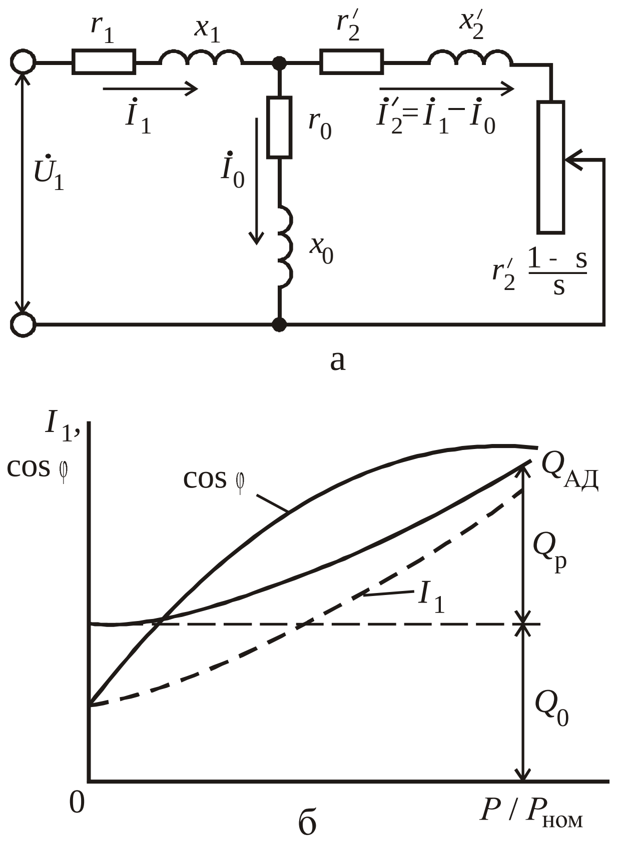


Fig. 3.2. An equivalent circuit (a) and performance capabilities of (b) an induction motor: $\dot{U}_1$ – voltage; $\dot{I}_1$ – stator current; $\dot{I}_2'$ – rotor current; $\dot{I}_0$ – current of magnetization branch; r_1, x_1 *u* r_2', x_2' - respectively active and reactive resistance of stator and rotor windings (reduced); $r_2'(1-s)/s$ - equivalent load resistance (*s* - motor slip); r_0, x_0 - parameters of magnetization branches.

$$Q_{АД} = 3 \cdot I_1^2 x_1 + 3 \cdot I_0^2 x_0 + 3 (I_2')^2 \cdot x_2' \approx 3 \cdot I_0^2 (x_1 + x_0) + 3 (I_2')^2 (x_1 + x_2') = Q_o + Q_p, \quad (3.1)$$

where I_0 - no-load current which can be regarded as purely inductive (cos φ = 0); Q_0 and $Q_р$ - reactive power load and short circuit current (scattering), the value of $Q_р$ depends on reduced current load of an engine, load current I_2' can be regarded as purely active since $r_2'/s >> x_2'$.

Reactive power of an induction motor changes from no-load power Q_0 which does not depend on the load to the power consumed at rated load capacity $Q_{ном}$ (Fig. 3.2b). Moreover, an increase in $Q_{АД}$ at the load growth is due to leakage flux which depends on load current. Among performance capabilities the highest rate of change has cos φ, and at idle it takes the lowest value (Fig. 3.2b).
At rated voltage consumption of reactive power by an induction motor can be expressed as:

$$Q_{АД} = Q_0 + \beta^2 Q_р \qquad (3.2)$$

where Q_0- reactive power no-load engine; $Q_р$ - reactive power of dissipation at rated load (β = 1); β - load factor of an induction motor: $\beta = P / P_{ном}$.
Rated reactive capacity of an induction motor can be determined by its rate details:

$$Q_{ном} = \frac{P_{ном}}{\eta_{ном}} \operatorname{tg}\varphi_{ном} \qquad (3.3)$$

where $\eta_{ном}$ - nominal motor efficiency; $\operatorname{tg}\varphi_{ном}$ - meets $\cos\varphi_{ном}$ indicated on the name plat; $P_{ном}$ - nominal engine active power being developed at the shaft by rated voltage.
For no-load induction motors $\cos\varphi_{хх}$ = 0,1–0,2 which corresponds to $\sin\varphi_{хх}$ = 0,99–0,97. If we ignore the active component of no-load engine current due to mechanical losses and losses in steel, we can take $\sin\varphi_{хх} \approx 1$. Then the reactive three-phase capacity can be determined with respect to the relation:

$$Q_0 \approx \sqrt{3} \cdot I_{хх} \cdot U_{ном}$$

or by analogy with (3.3)

$$Q_0 \approx \sqrt{3} \cdot I_{xx} \cdot U_{ном} = \sqrt{3} \cdot I_{ном} \cdot U_{ном} \cdot \cos\varphi_{ном} \frac{I_{xx}}{I_{ном} \cdot \cos\varphi_{ном}} = \frac{P_{ном}}{\eta_{ном}} \cdot \frac{I_{xx}}{I_{ном} \cdot \cos\varphi_{ном}}. \quad (3.4)$$

An error in determining Q_0 by (3.4) constitutes 1-3%. No-load current should be measured when engine is idle and $U_{ном}$ disconnected from a coupler.
Reactive power of scattering motor flows depends on the load and can be determined from the expression:

$$Q_p = (Q_{ном} - Q_0)\beta^2 = \beta^2 \frac{P_{ном}}{\eta_{ном}} \left(\mathrm{tg}\varphi_{ном} - \frac{I_{xx}}{I_{ном} \cdot \cos\varphi_{ном}} \right) \quad (3.5)$$

If we substitute values Q_0 and Q_p in (3.2), we will get the expression of full reactive power of an induction motor:

$$Q_{АД} = \frac{P \cdot \mathrm{tg}\varphi}{\eta} = \frac{P_{ном}}{\eta_{ном}} \left(\frac{I_{xx}}{I_{ном} \cdot \cos\varphi_{ном}} + \beta^2 \left(\mathrm{tg}\varphi_{ном} - \frac{I_{xx}}{I_{ном} \cdot \cos\varphi_{ном}} \right) \right), \quad (3.6)$$

where P, tgφ and η correspond to the engine load.

Example 3.1.

We need to determine reactive power of an induction motor for loads of 100 and 50%. Motor nameplate data: $P_{ном}$ = 10 кВт, $U_{ном}$ = 380 В, cosφ = 0,89 (tgφ = 0,512); $\eta_{ном}$ = 0,875.

Solution.
For a rated load capacity (3.3):

$$Q_{ном} = \frac{P_{ном}}{\eta_{ном}} tg\varphi_{ном} = \frac{10}{0,875} \cdot 0,512 = 5,85 \text{ kVAr.}$$

Rated motor current:

$$I_{ном} = \frac{P_{ном}}{\sqrt{3} \cdot U_{ном} \cdot \eta_{ном} \cdot \cos\varphi_{ном}} = \frac{10}{\sqrt{3} \cdot 0,38 \cdot 0,875 \cdot 0,89} = 19,6 \text{ A.}$$

Next, we measure load current of the electric motor with a disconnected coupler: : I_{xx} = 5 A.

In this case reactive motor power with β = 0,5 (*P* = 5 kW) (3.6) is:

$$Q_{АД} = \frac{P \cdot tg\varphi}{\eta} = \frac{P_{ном}}{\eta_{ном}} \left(\frac{I_{xx}}{I_{ном} \cdot \cos\varphi_{ном}} + \beta^2 \left(tg\varphi_{ном} - \frac{I_{xx}}{I_{ном} \cdot \cos\varphi_{ном}} \right) \right) =$$

$$= \frac{5}{0,875} \left(\frac{5}{19,6 \cdot 0,89} + 0,5^2 \left(0,512 - \frac{5}{19,6 \cdot 0,89} \right) \right) = 3,9 \text{ кВАр.}$$

Reactive power, consumed by power transformers, is used for magnetization of a core Q_0 and creation of stray fields $Q_р$. Quantitative indicators of reactive power, consumed by transformers and induction motors, are significantly different: power of a transformer magnetization is Q_0 = 2–5% of its rated capacity, and induction motors - about 50%. It is due to the lack of an air gap in a magnetic circuit of the transformer.

The general expression of reactive power three-phase transformer can be represented as:

$$Q_{тр} = Q_0 + Q_р = Q_{xx} + 3 \cdot I^2 x_{тр} = \frac{i_{xx}\% \cdot S_{ном}}{100} + \frac{3 \cdot I^2 \cdot u_{К3}\% \cdot U^2}{100 \cdot S_{ном}} =$$

$$= \frac{i_{xx}\% \cdot S_{ном}}{100} + \frac{u_{К3}\% \cdot S^2}{100 \cdot S_{ном}} = \frac{i_{xx}\% \cdot S_{ном}^2 + u_{К3}\% \cdot S^2}{100 \cdot S_{ном}} = \quad (3.7)$$

$$= \frac{S_{ном}}{100} \left(\frac{i_{xx}\% \cdot S_{ном}^2 + u_{К3}\% \cdot S^2}{S_{ном}^2} \right) = \frac{S_{ном}}{100} \left(i_{xx}\% + u_{К3}\% \cdot \beta^2 \right)$$

where i_{xx}%- no-load transformer current, %; $u_{К3}$% – short-circuit voltage of a transformer%; $S_{ном}$ - rated capacity of a transformer; β – load factor.

Consumption of reactive power by transformers is several times smaller than consumption by induction motors but total consumption of the system as a whole is proportional (see Table 3.1.). Number of system voltage transformations can reach 3-4 and has a tendency to grow up to 5-6. Therefore, total rated capacity of transformers is much more than capacity of induction motors.

To reduce losses of reactive power and energy in transformers it is recommended to turn off transformers when magnetized and loaded less than 40% of their rated capacity, and the load should be transferred to another transformer. If there is no possibility of load transfer it is recommended to replace the transformer by a less powerful one. Increase in the load factor of a transformer to 0.1 leads to improvement of cosφ at 0,040,05.

Example 3.2.
We need to determine reactive power of the transformer ТМ̃630/10, according to nameplate data i_{xx} = 2%, $u_{КЗ}$ = 5,5%.

Solution.
Reactive power of a no-load transformer:

$$Q_0 = \frac{i_{xx}\% \cdot S_{ном}}{100} = \frac{2 \cdot 630}{100} = 12{,}6 \text{ kVAr.}$$

Reactive power depends on the load (for a rated capacity):

$$Q_р = \frac{u_{КЗ}\% \cdot S_{ном}}{100}\beta^2 = \frac{5{,}5 \cdot 630}{100}1^2 = 34{,}65 \text{ kVAr.}$$

Total reactive power for rated capacity:

$$Q_{тр} = Q_0 + Q_р = 12{,}6 + 34{,}65 = 47{,}25 \text{ kVAr.}$$

Total reactive power for a half-load will be:

$$Q_{тр} = \frac{S_{ном}}{100}\left(i_{xx}\% + u_{КЗ}\% \cdot \beta^2\right) = \frac{630}{100}\left(2 + 5{,}5 \cdot 0{,}5^2\right) = 21{,}26 \text{ kVAr.}$$

3.2. Consumption of reactive power by electric furnaces and welding installations

The most powerful electric furnaces for elektrocracking and smelting of ferrous

and nonferrous metals are arc and ore-thermal furnaces. They are large consumers of reactive power which is necessary both to ensure the process of melting and to cover losses of reactive power in the elements of a furnace installation.
In fig. 3.3a an electrical circuit of an arc electric-furnace installation is depicted. Three-phase arc furnace 1 is connected to the network through a step-down transformer furnace 2, switching devices 3 and a line 4. Connection of the transformer with the furnace runs through a short chain 5, which is a low voltage conductor with rated current up to tens of kA. To connect measuring instruments and automatic power control (APC) current transformers 6 and voltage transformers 7 are provided. To control furnace regimes saturation core reactors 8 are provided.

Consumption of reactive power of an arc furnace is caused by the necessity of a sufficiently large angle of current phase shift and voltage in a feed circuit of a furnace. If $\varphi = 0$ (Fig. 3.3b), then arc, twice in one period of the AC, would be interrupted by a Δt in moments of simultaneous transmission of voltage and current sine waves through zero and then arc again. It would be accompanied by a sharp decrease in temperature in interelectrode space, loss of furnace productivity and metal quality. To obtain a continuous arcing and increase in furnace coefficient of efficiency inductance is switched in series 8. Arcing, when voltage passes through a zero, is maintained by energy stored in the inductor. Curves u and i for $\cos \varphi > 0$ are shown in Fig. 3.3в.

Inductance is chosen so as to provide sufficient angle φ phase shift of current and voltage for a continuous arcing

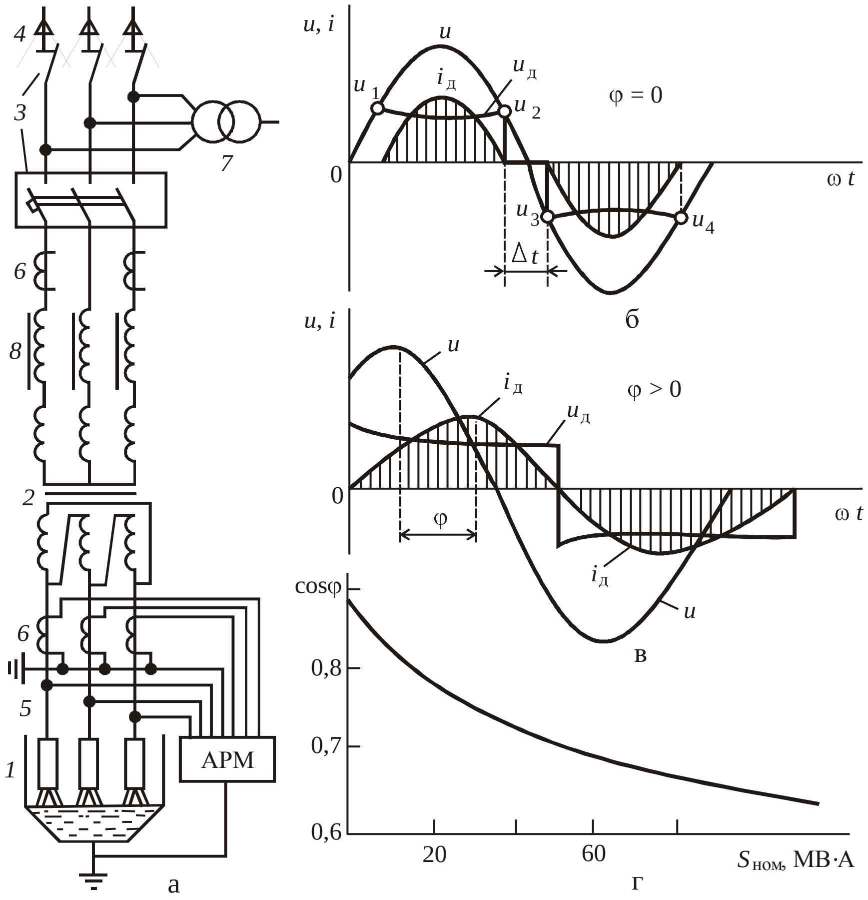


Fig. 3.3. An electrical circuit and characteristics of an arc electric furnace installation

so that the condition is met:

$$U_m \sin\varphi \geq U_д \quad (3.8)$$

where $U_д$ - minimum voltage required for arcing, U_m - peak voltage value. Then

$$\varphi \geq \arcsin\frac{U_д}{U_m} \quad (3.9)$$

Continuous AC arcing is provided by φ ≥ 32°, that is, when cos φ≤ 0,85.

Reactive power in an electric arc furnace is needed not only for inductance charge-discharge while maintaining a continuous arc but also to cover losses in the furnace transformer and a short network which also have inductance. Therefore, the minimum required voltage $U_д$ and angle φ increase even more and cos φ reduces. Per production cycle electric arc furnace load is regulated by changing the height of the electrodes under the influence of ARM (Fig. 3.3a) in a wide range. In idle mode the arc does not burn (I = 0), in a normal load mode $I = I_{ном}$ and during melting (1% of the time) current is $2{,}5I_{ном}$ or even more. Taking into account that reactive power losses in a transformer and transmission lines are proportional to the square of a load factor of $\beta^2 = (I / I_{ном})^2$, electric furnace arc installations, during melting of metals, sharply increase consumption of reactive power. Increase in size and capacity of a furnace lead to a growth of inductance, it reduces cosφ of a furnace unit (Fig. 3.3g).

The induction heating method is based on application of strong magnetic fields and is used for melting of metals by induced currents. A schematic diagram of single phase induction type furnace installation of high frequency is shown in Fig. 3.4. Induction furnace 1 through the switch 2, fuses 3 and contactor 4 are connected to a power source - frequency converter 5 (in the figure-electric frequency converter). Autotransformer 6 is provided for voltage regulation. Induction heating by currents of industrial frequency 50 Hz takes place in hot air furnaces with a steel core. Heating by currents of high frequency 500-104 Hz is produced in crucible furnaces without a steel core. Predominantly single-phase induction furnace

СХЕМУ ВСТАВИТЬ НЕ СМОГ

Рис. 3.4. Схема электропечной установки индукционного типа

Fig. 3.4. A scheme of induction type electric furnace installation

Induction furnaces, predominantly single-phase furnaces, with capacity 250-6000 kW are used for nonferrous metals smelting and up to 1,700 kW - steel furnaces. The power factor of induction furnaces is low: from 0.1 to 0,4-0,66. Therefore, to compensate for consumption of reactive power and to increase cos φ up to 0,95-1,0 individual capacitor banks with unregulated 7 and regulated 8 sections are installed (Figure 3.4). Battery capacity exceeds active power of an installation.

Properties of electric welding units, as consumers of reactive power, are close to those of electric furnace installations. Welding methods are arc and resistance. Units are predominantly single-phase with abruptly variable load and low power factor: cosφ arc welding units 0.30-0.35, and 0.2-0.6 of resistance welding. In cases where the welding units with abruptly variable load at a low cosφ create unacceptable voltage fluctuations and asymmetry across the network, direct current is used and its feeding is provided through an AC to DC converter. It reduces influence of the welding operation network on a total network of an industrial enterprise.

DC thyristor converters are a source of power supply for welding systems. DC thyristor converters also consume reactive power. Their reactive load is more stable than in AC welding units. However, converters are the generators of harmonics voltage and current. Particularly high level of harmonics is obtained by connecting the welding converters for the network of 380 − 660 V, where short circuit power is low.

3.3. Consumption of reactive power by converting units

Consumption of reactive power by converting units with semiconductor rectifiers is due to two factors: natural commutation process and artificial switching delay of valve opening for regulation of rectified voltage. These factors make a current shift in valves circuits with respect to voltage and reduce cosφ in the networks which feed rectifiers, and increase consumption of reactive power.

When a three-phase converter unit is in operation, current transition from phase A to phase B (Fig. 3.5) occurs not at the moment of voltage equality $U_A = U_B$ but it takes some commutation time *t* and

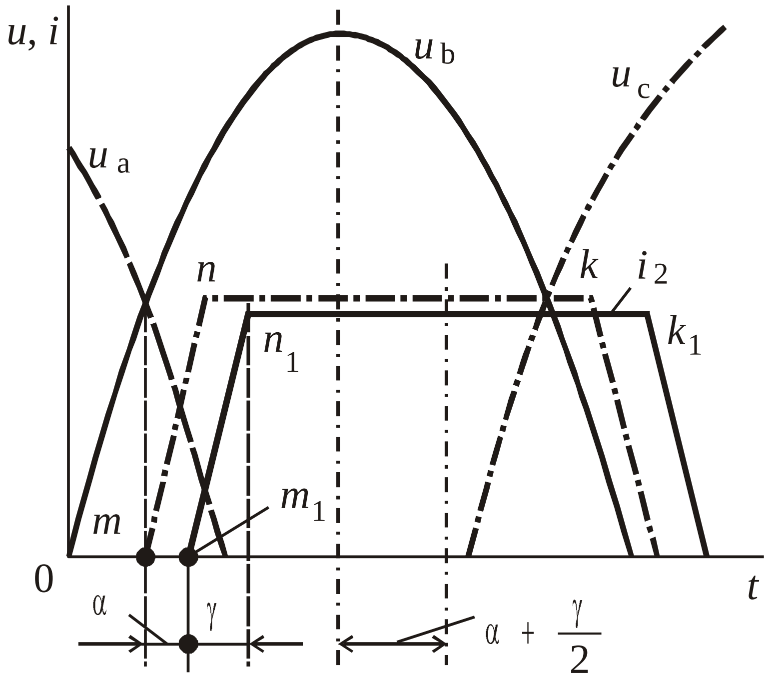


Fig. 3.5. Phase shift of current and voltage rectifier converter

occurs with a delay on a corresponding to this time *t* commutating angle γ. During this time voltage U_B exceeds U_A to an adequate for a current transition value. In Fig. 3.5 current gate is presented in the form of a trapezoid which pitch i_2 depends on switching time *t* and a commutating angle γ.

The commutating angle γ depends on an inductance circuit x_a. Connection between a plate current I_d and the commutating angle γ is defined as:

$$I_d = \frac{\sqrt{2}\cdot U_2}{x_a}(1-\cos\gamma) \tag{3.10}$$

where U_2 – rms value of secondary voltage of a converter transformer. In Fig. 3.5 voltage sinusoids $u_2(t)$ are shown in phases A, B, C, and valve current $i_2(t)$. Current has a trapezoid shape, not a triangle one, because of the commutating angle $\gamma > 0$ which can be increased if induction x_a increases too. Current in a switched valve phase reaches its maximum value not instantly but for the switching time *t* which is proportional to the angle γ.

Opening delay, in controlled valves, is made artificially in order to reduce rectified voltage. It results in a plate current shift of i_2 with respect to a voltage curve at the time measured by the angle α. The angle of phase current shift i_2 (i.e. the middle of a current impulse - see Figure 3.5.) with respect to the voltage amplitude U_2 is equal to:

$$\varphi_2 = \alpha + \frac{1}{2}\gamma \qquad (3.11)$$

A ratio for a plate current is:

$$I_d = \frac{\sqrt{2}\cdot U_2}{x_a}\left(\cos\alpha - \cos(\alpha + \gamma)\right). \qquad (3.12)$$

Primary current $i_1(t)$ of a converter transformer is approximately shifted for the same angle φ to a voltage lag $u_1(t)$. It determines a reactive load network of a converter unit. Power factor λ of a converter unit, taking into account nonsinusoidality of primary current, is determined by the relation:

$$\lambda = \nu \cdot \cos\varphi, \qquad (3.13)$$

where ν is a distortion factor of the primary current i_1 as compared with a sinusoid of the first harmonic of the current i_{11}:

$$\nu = \frac{i_{11}}{i_1}. \qquad (3.14)$$

For a six-phase rectifier mode taking into account only harmonics of canonical series ν = 0,955, for twelve-phase schemes ν = 0,988. In the expression (3.13) $\cos\varphi$ - factor of a current shift relative to the voltage u_1- can be represented as:

$$\cos\varphi = \frac{P_1}{\sqrt{P_1^2 + Q_1^2}} \approx \cos\left(\alpha + \frac{\gamma}{2}\right) \qquad (3.15)$$

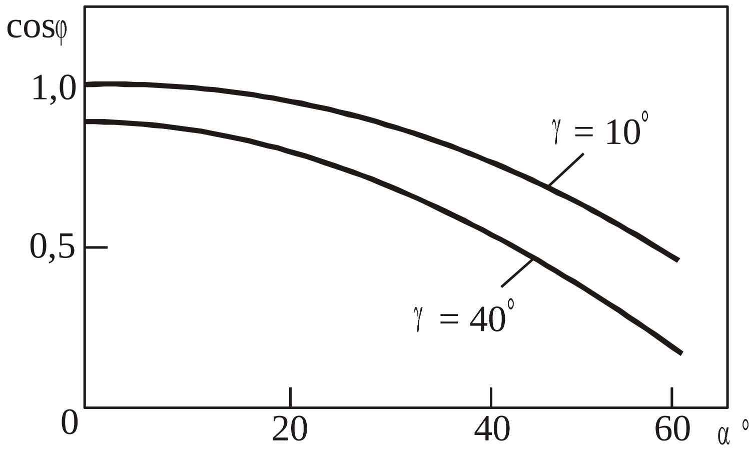
where P_1 and P_1- active and reactive power on the primary side of the converter.

Reactive power consumed by the converter unit is formed by the losses in the converter transformer $Q_{тр}$ and by the costs of switching and voltage regulation in the rectifier $Q_{вып}$:

$$Q_{пр.\ агр} = Q_{тр} + Q_{вып} = S_{ном.\ тр}\left(\frac{i_{xx}\%}{100} + \frac{u_{К3}\%}{100}\right) + P_{вып}\cdot \mathrm{tg}\left(\alpha + \frac{\gamma}{2}\right) \qquad (3.16)$$

where $S_{ном.\ тр}$, i_{xx}, $u_{К3}$ - nameplate data of capacity, no-load current and short-circuit voltage of a converter transformer; $P_{вып}$ - rated power of a rectifier.

In Fig. 3.6a change in cosφ which depends on the angles α и γ is shown, in Fig. 3.6b experimentally obtained dependence of the reactive power consumed by the converter unit of the network is shown, its active load switching at different angles.



a

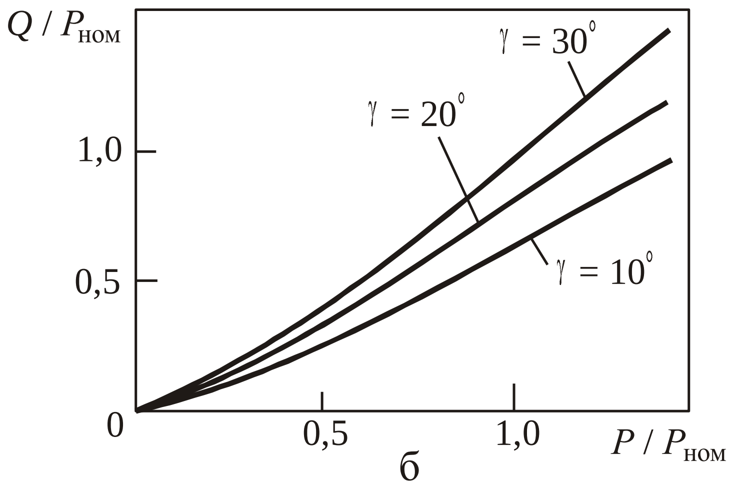


Fig. 3.6. Characteristics of reactive load of a converter unit: a - dependence of a power factor from the angles of control and communication b - dependence of reactive power from active load at different angles of commutation.

Thus, converter units are large consumers of reactive power. Consumption mode is particularly associated with the nonlinearity and instability of the load parameters. An effective way to compensate for their reactive power - construction of a compensation unit converter with an artificial switching and which can generate reactive power.

A schematic diagram of the converter is shown in Fig. 3.7. Unlike a conventional converter unit, a three-phase group of capacitors (C_{ab}, C_{bc}, C_{ca}) is included between phases. The group provides an advanced phase current shift relative to a voltage vector.

In a typical three-phase conversion scheme of current transition from one phase to another occurs when voltages of these phases are compared: $U_A = U_B$. In a null-balance converter due to the action of the capacitor commutation occurs earlier in time when $U_A = U_B + U_{ab\ \text{екм}}$, where $U_{ab\ \text{екм}}$ - voltage on the capacitor C_{ab}.

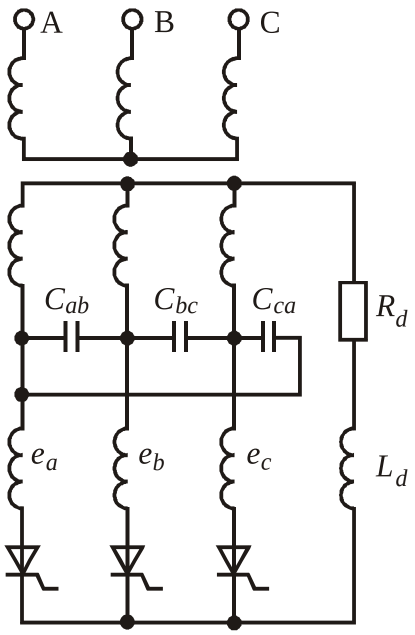


Fig. 3.7. A schematic diagram of a null-balance converter

By adjusting capacitance, one can change $U_{ab\ \text{екм}}$ and obtain compensation current at lower voltage value U_{B} and at lower commutating angle γ. Current phase will be ahead of the voltage, the converter will generate reactive power to the network, and the generated reactive power compensation converter will exceed the capacity that will generate a network of capacitors C_{ab}, C_{bc}, C_{ca}, if they are used as a battery of cross-compensation.

3.4. Lighting units with gas-discharge lamps

Fluorescent lighting is a small-scale consumer of reactive power. Fluorescent lighting is widely used for lighting industrial facilities, streets, and squares. Operation of fluorescent lamps is based on a gas-electrical discharge in the discharged gas space with mercury vapor. As a result of the discharge ultraviolet radiation is formed which, by its influence on a phosphor bulb, causes its intense visible radiation.

Electric discharge in gas is an unstable process and even when small voltage changes occur it either suspends or transfers in an avalanche process leading to deterioration of the bulb. To stabilize a discharge current a limiting ballast resistor is provided in series with a discharge tube. An inductor is used as a ballast (coil on a steel core). It also serves to produce an igniting pulse through EMF self-induction. In addition, a series connection of the inductor reduces current pauses and, hence, the pulsation of a luminous flux. The inductor causes consumption of reactive power which value is determined by the inductor parameters and is in a range of tgφ = 1,31,7 (cosφ = 0,50,6).

Active losses in the inductor (a coil and steel) are about 25% of lamp power.

Example 3.3.

To rate reactive power consumption of a fluorescent lamp 40W rated power, in series with the inductor.

Solution.

Reactive power consumption is:

$$Q = \left(P_{ном} + 0{,}25 P_{ном}\right) \mathrm{tg}\varphi = \left(40 + 0{,}25 \cdot 40\right)\left(1{,}3 \div 1{,}7\right) = 65 \div 85 \text{ Var.}$$

A relatively high consumption of reactive power must be compensated. Therefore, the fluorescent lamp is in series with a starting controller which provides compensation means by switching on a capacitor.
Less commonly capacitors are used as a ballast resistance; it is beneficial in terms of reactive power consumption. A starting controller for gas-discharge lamps with capacitors used as a ballast resistance is short-lived since capacitors have shorter life span than inductors.

Capacitors which are built-in ballast for individual compensation of reactive power increase cosφ up to 0,92–0,95.

In the industrial lighting along with electrical discharge lamps a group of reactive power compensation is used. For mercury arc lamps (DRL) power group of capacitor banks is selected at the rate of 1.1 kVAr at 1 kW of total capacity, for fluorescent tubes 1.2-1.3 kVAr at 1 kW with an increase of cosφ up to 0.95.

3.5. Transmission lines and current-limiting reactors

Magnetic field originates around a conductor where current flows and therefore reactive power is consumed. Forward and reverse wire transmission line can be regarded as a "flattened" coil reels, so that there is a magnetic field between wires, shown in Fig. 3.8. Inductance increases if distance between wires is long. In order to reduce the distance wires must be laid as close as possible to each other.

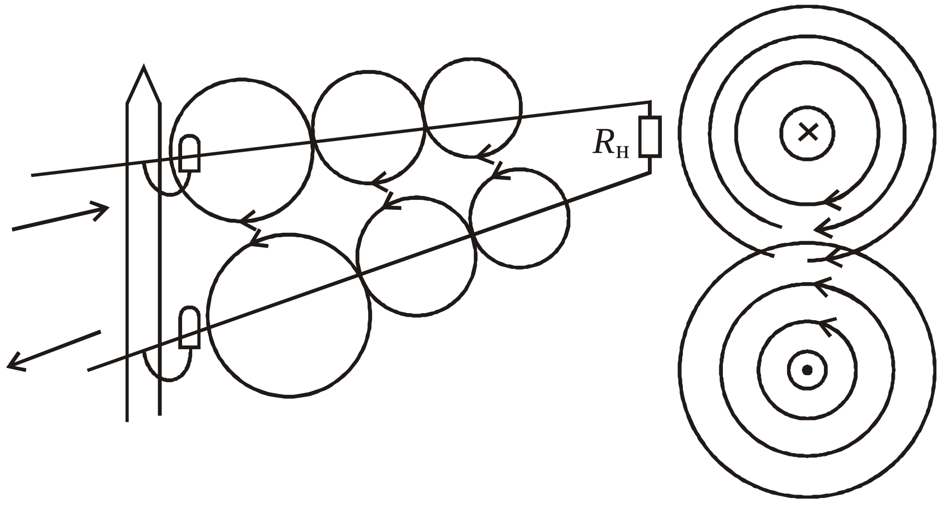


Fig. 3.8. A magnetic field of forward and reverse wires of overhead transmission lines

Reactive power consumed by air-phase medium voltage line can be determined by the formula op, kVAr / km:

$$Q_л = 3 \cdot I^2 \frac{\omega L}{1000} = \left(\frac{P}{U \cdot \cos\varphi}\right)^2 x_L \cdot 10^{-3} \qquad (3.17)$$

where P, U and cosφ – parameters of transmitted load; L and x_L - inductance and line reactance.

Inductance of a three-phase overhead line on 1 km length is calculated by H / km:

$$L = \left(4{,}6 \lg \frac{D_{ср}}{r} + 0{,}5\right) \cdot 10^{-4} \qquad (3.18)$$

where $D_{ср} = \sqrt[3]{D_{AB} \cdot D_{BC} \cdot D_{CA}}$ - average geometric distance between the wires, cm; D_{AB}, D_{BC}, D_{CA} - distance between the wires, cm; r – wire radius, cm

Method of inductance calculating of the cable transmission lines is given in [2]. For overhead lines 6 – 35 kV inductive reactance at 1 km is in the range 0,37 – 0,40 Ohm [4].
For assessment calculations of reactive power consumed by overhead transmission lines the following formula can be used: kVAr/km:

$$Q_л \approx 0{,}0012 \cdot I^2 \qquad (3.19)$$

where I - load current of the line.

For extended and poorly loaded overhead transmission and cable lines capacitive reactive component of the resistance dominates, so that these lines are considered as sources of negative reactive power (see Section 2.10). Current limiting reactors are also consumers of reactive power. Taking into account their inductance, reactive power can be determined using the same formula as for the line (3.17).

Share of various power transmission lines, reactors, induction units constitutes up to 10% of consumed reactive power in power systems.

3.6. Factors that influence the power factor of power systems

In the design of AC machines a high emphasis is put on achieving a high power factor, which varies between 0,80 -0,93.

The main impact on low power factor of power supply systems has an abnormal mode of electric motors and transformers operation. In some cases, transformers and electric motors operate at a much lower $\boldsymbol{cos\varphi}$.

Factors that influence the power factor of power supply systems can be divided into:

- operational;
- defined by technical conditions and quality of equipment maintenance;
- constructive.

3.6.1. Operational factors

Influence of induction motors on $\boldsymbol{cos\varphi}$**.** Presence of the air gap increases the reluctance of the magnetic engines. The air gap is the main reason for the relatively high consumption of reactive power and phase lag of the stator current voltage. Mode of induction motors is reflected in their power factor.

Idling. While operation, electric motors can be switched on in the periods when their mechanisms do not perform any operations, that is they run at idle. Since the active losses in the stator and rotor-load are low, then the load current of induction motors is mainly determined by its component, which is a part of the magnetization of a machine (the stray fields are negligible at idle). Magnetic circuit includes an air gap, which greatly increases the magnetic resistance of the circuit. No-load current has a relatively large value. For various types of engines load current depends on the number of poles and power. For engines with low power I_{xx} is 35 - 80%, while for medium and high engine power is 20 - 35% of the nominal value. Reactive power of idle asynchronous motors is 60 - 70% of the total reactive power.

The phase angle between current and voltage of the idle engine is close to $90°$. Consequently cosφ is extremely low and does not exceed 0,10 - 0,15.

Thus, when the engine is at idle the energy between the motor and power supply will vary, therefore it will not perform any useful work. The power factor of power supply system will be lowered.

Underload of electric motors. Reactive power consumed by the loaded engine from the network is determined by the magnetizing reactive power and reactive power scattering (see (3.1)). Power of the magnetization is due primarily to the magnetic field of the motor. Power magnetization varies slightly with load change from no-load to the nominal value.

Reactive power dissipation is determined by the reduced rotor current. The reactive power depends on the scattering reactance of stator and rotor.

Rotor current, slip, stator current and power factor will vary with load deviation from the nominal value. Reduction of the rotor current takes place when the load is proportional to the reduction of the load. The amount of current idling engine will affect the magnitude of stator current at low loads.

Fig. 3.9 shows the curves of the stator current induction motor according to the load for different values of load current. The greater the underload of the engine to the nominal value, the stronger impact has the value of I_{xx} on consumption from the current network. For example, at a current idling at 30% of motor rated current and at 50% load induction motor consumes 55% of net nominal current with a predominance of the magnetizing component. Consequently, when the motor is underloaded, magnitude of load current slightly varies. Load component of stator current is dramatically reduced. It leads to a decrease in power factor. A slight decrease of reactive power is due to a sharp reduction of reactive power dissipation, which varies roughly proportional to the square of the load factor of the motor at a constant voltage and frequency.

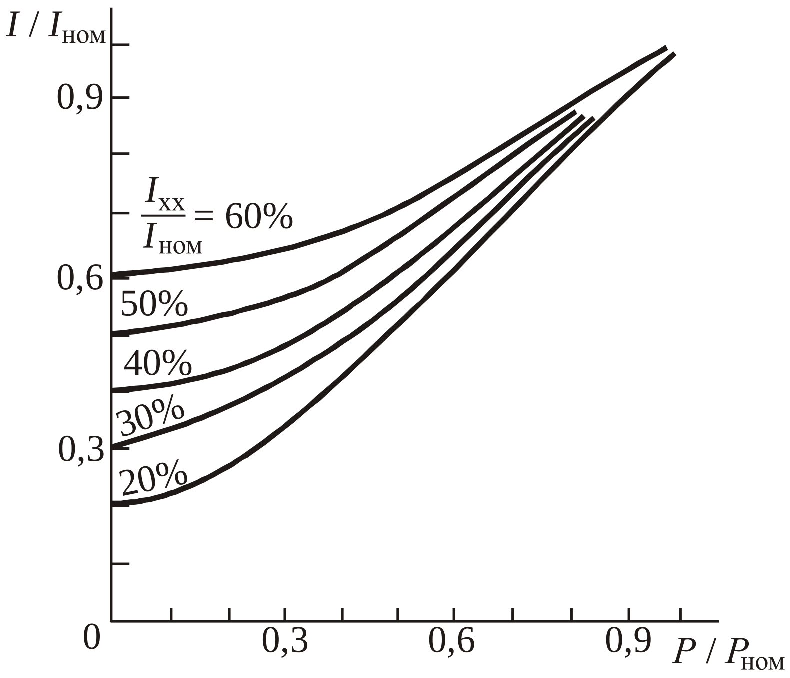


Fig. 3.9. Dependence of stator current of induction motors on the load for different values of load current

Fig. 3.10 shows an effect of load and no-load current to the motor power factor. When load current is high there is a sharp drop in motor power factor. While operation of electric motors with underload 15 - 20% of the nominal value and nominal high values of cosφ consumption of reactive power is not significantly increased and reduction of the power factor of electricity has an insignificant impact.

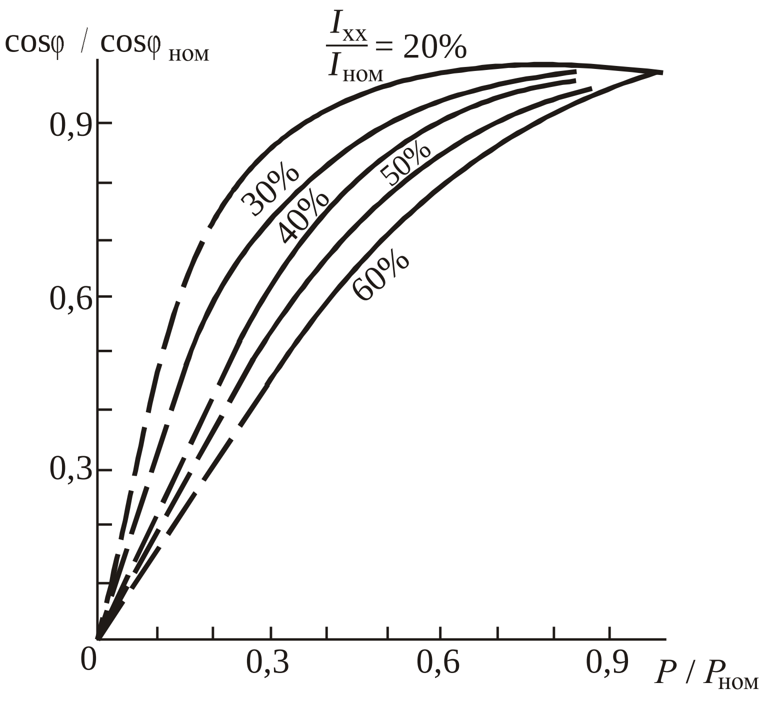


Fig. 3.10. Change of $\cos\varphi$ motor depending on load

However, in practice, operation of electric motors is provided with greater underload. Particularly strong influence on cosφ power supply system has an underload of low power electric motors with low nominal power factor and significantly reduced underload (Figure 3.11). Fig. 3.12 shows a nomogram aimed at calculation of power factor deviation of the unloaded induction motor nominal values from the measured stator current.

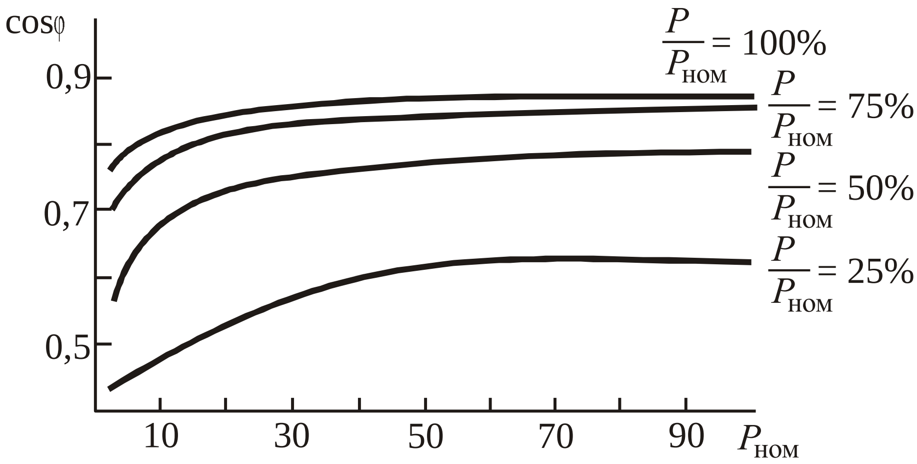


Fig. 3.11. Influence of load and rated power of electric motors on power factor

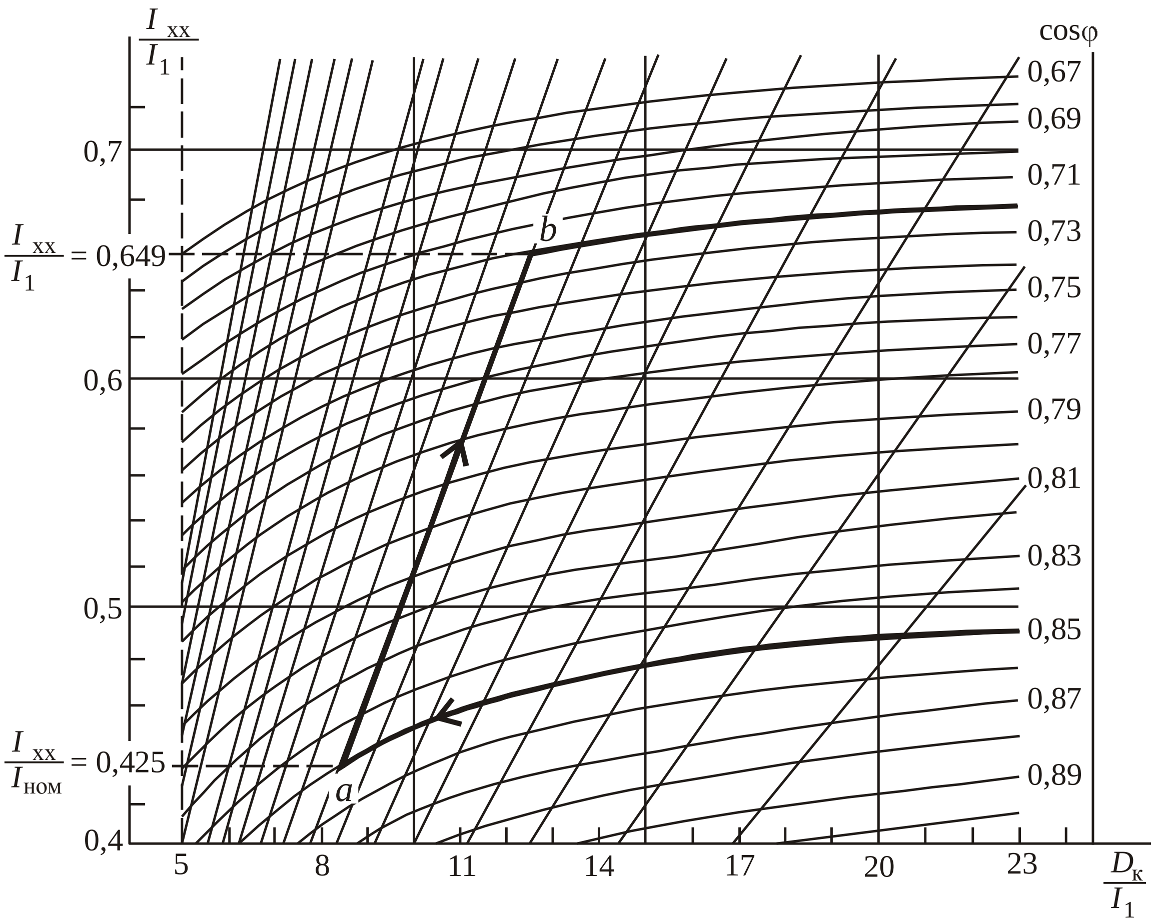


Fig. 3.12. Nomogram aimed for determining the power factor of induction motor stator current magnitude

This nomogram of a simplified induction motor cosφ = $f(I_1)$ expresses the relation $I_{xx} / I_{ном}$ for several fixed values of power factor cosφ. I_{xx} - no-load current, I_1 - stator current, which varies with the work of an induction motor within the $I_{xx} \leq I_1 \leq I_{ном}$, φ - phase angle between the stator current and voltage.

A nomogram of technical data (cosφ_0 и $I_{ном}$)) and the current idling asynchronous motor determine its power factor cosφ_1, with the measured stator current I_1, different from the nominal. To measure the stator current without turning off the engine current clamp is used.

Next we are going to define cosφ_1 for the unloaded induction motor: rated current $I_{ном}$ = 4.0 A, cos$\varphi_{ном}$ = 0.85, measured current I_1 = 2,6 A. With respect $I_{xx} / I_{ном}$ = 0.425 A and cos$\varphi_{ном}$ = 0.85 define the nomogram as a starting point *a*. Then, the support beam, which takes place from the origin through the point *a*, goes up to the point with the ordinate, which is determined by the ratio of I_{xx} / I_1 (point b). The corresponding curve of the nomogram indicates the actual power factor: cosφ_1 = 0,72.

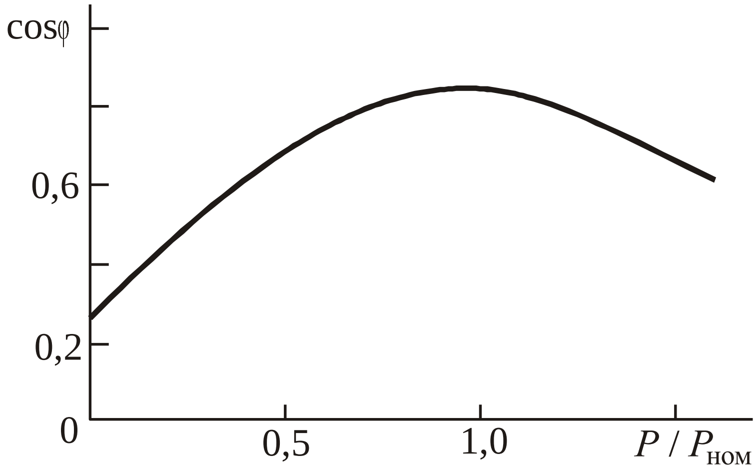


Figure 3.13. Induction motor Cosφ dependence on load

Motor overload. Figure 3.13 represents dependence of the power on the load. Motor power factor, which characterizes the relative consumption of reactive power, reaches a maximum value at a load slightly less than face value. With further increase in load cos φ decreases as the magnetic leakage fluxes are growing and consumption of reactive power increases.

The work of induction motors with heavy starting conditions is also characterized by elevated levels of reactive power.

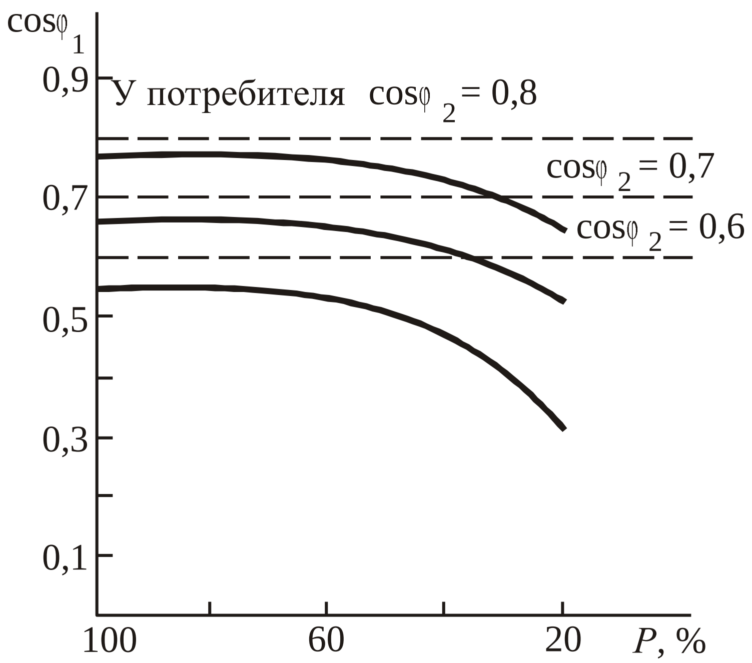
Transformers influence on cos φ. Transformer is an intermediate element in the transmission of electricity from sources to power consumers. Typically, the system power supply company has several transformer substations, so that their modes of operation will significantly influence the power factor.

In contrast to the induction motor in which an air gap is an inevitable element of design, transformers clearances are reduced to a minimum. Therefore, the magnetic resistance in the transformer is considerably smaller than the induction motor and, consequently, consumed reactive power. However, a need for a large number of energy transformations leads to the fact that even the transformers at nominal operating conditions make worse the power factor of the power system and systems of power supply.

The phase shift on the primary side of a transformer is determined by the phase shift in the secondary circuit of the transformer (i.e., load conditions) and the incremental phase shift which is due to idle capacity. This power is the geometric sum of active power, which is spent to cover the losses in copper and iron of the transformer at no load and reactive (magnetizing) power. The latter is much more active power, so the no-load transformer phase angle close to 90 °, and power factor does not exceed 0,1 – 0,2.

As the loading of the transformer increases the reactive power, due to the appearance of stray fields, is significantly increased. Reactive power of transformer is 10 – 15% at idle and under full load varies between 12 – 20% of rated capacity. Idling accounts for 80% of the total power consumption of the transformer.

Figure 3.14 shows change in power factor of the transformer primary side, depending on its load at a constant power factor of the consumer as well as in the case of changing it. Significant reduction in cos φ 1 will occur if the power factor of the consumer and the load at the same time is reduced.
The curves depicted in Figure 3.14 have two zones, regardless of cos φ 2: one of which - with a load less than 60%, where the increase in capacity of the transformer leads to significant improvement of power factor on the primary side, the second of which - with a load greater than 60%, where cos φ 1 with increasing load varies insignificantly.



У потребителя –Consumer's

Fig. 3.14. Change of power factor of transformer's primary side depending on its load

Thus, the operation of transformers with loading up to 60% of their rated capacity will affect a significant change in the power factor of power supply system of the enterprise.

Influence of voltage and frequency on cos φ. Voltage and frequency deviations can be observed while operation of electric installations. Consumption of reactive power idling asynchronous motor associated with frequency and voltage using the relationship:

$$Q_0 = C\frac{U^2}{\mu} f \cdot V \quad , \qquad (3.20)$$

where C - a coefficient which depends on the number of pole pairs, the frequency f, the construction of the motor; U - voltage; μ –magnetic permeability; V - volume of the magnetic circuit.

This relationship implies that:

• Reactive power depends on the square voltage;

• Reactive power depends on frequency: it increases the engines increased frequency of consumption of reactive power;

• Reactive power depends on the amount of magnetic core: this explains the increase in consumption Q0 with decreasingnominal speed (at low speed while maintaining engine power have a greater volume of magnetic core).

Effect of changes in voltage. When the voltage increases the magnetic flux also increases, it creates an electromotive force E1, which is almost completely counterbalances the increased voltage U1. The increase in flux due to the increase of the magnetizingcurrent (Figure 3.15), this entails an increase in the reactive component of power that is consumed by the engine at idle.Magnetizing current increases when the magnetic circuit is saturated not proportional to the voltage, and more. In this case the reactive power dissipation increases in proportion to the voltage (leakage flux is closed primarily by air).

If there is a constant moment of resistance, engine torque, which depends on the square of the voltage fluctuations at this will change, and hence, the slip will change. Moreover, sliding under a constant load change is inversely proportional to the square of voltage (Figure 3.16).

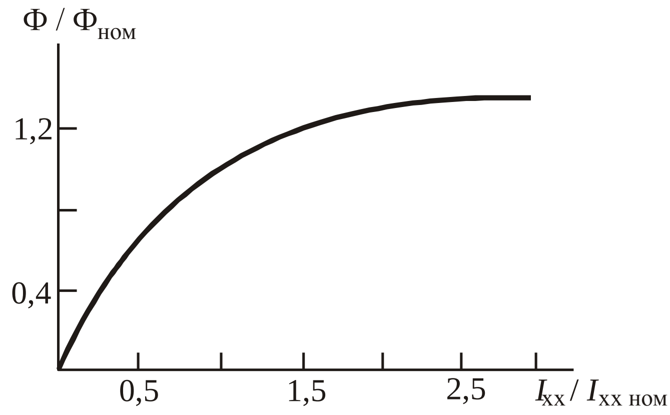


Fig. 3.15. The relationship between the current idle speed and magnetic flux

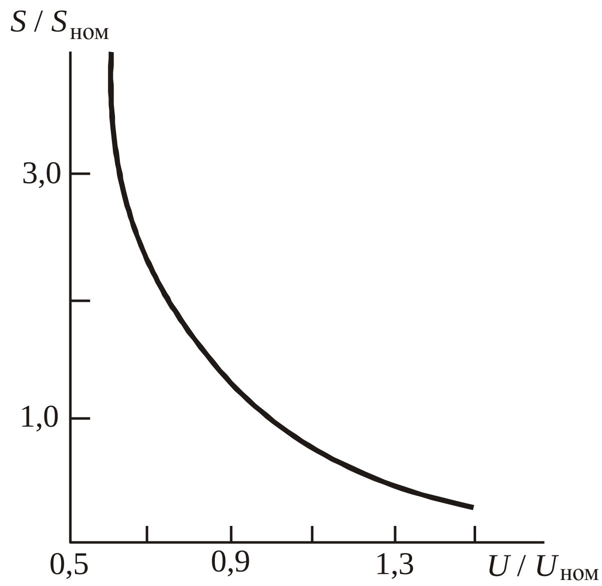


Fig. 3.16. The dependence of slip on the voltage

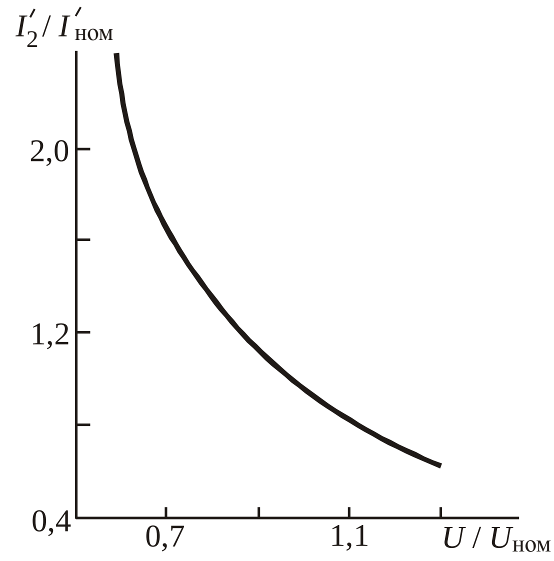


Fig. 3.17. The dependence of the rotary current-voltage

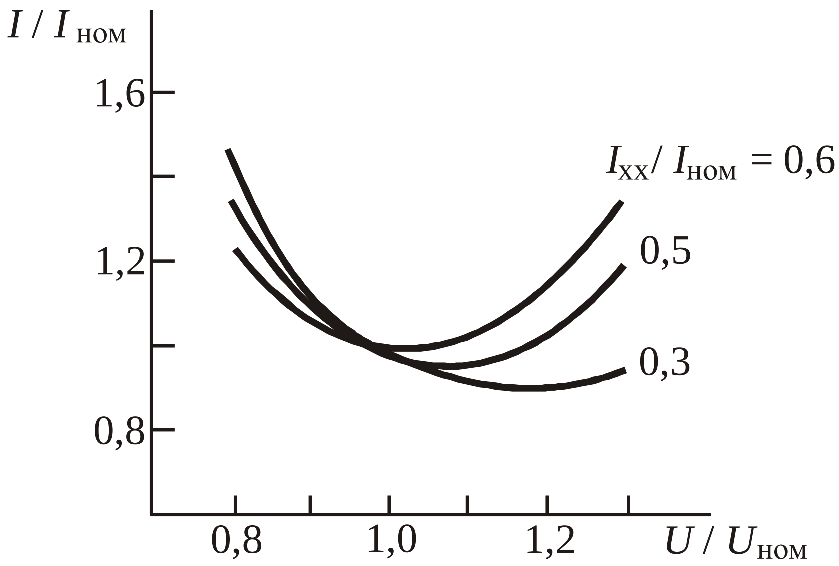


Fig. 3.18. The change of stator current versus voltage

With the change of slip rotor current will also vary inversely to the applied voltage. (Figure 3.17). The numerical value of stator current is the sum of a geometric no-load current
speed and reduced rotor current. When the voltage is increased stator current may increase, but it may decrease, depending on the multiplicity of the applied voltage and the relative importance of load current (Figure 3.18). This behavior is due to the fact that at first increase in the voltage causes a proportional increase in the magnetizing component of idling, and then began to increase the saturation current increases significantly. Therefore, when the voltage is increased to 1,1 · Un stator current drop is due to the reduction of rotor current, and then if the voltage rises more (over 1,1 · Un) increase in the magnetizing component reflects the drop in load current and stator current increases dramatically. Consequently, the change in voltage causes the motor to change the reactive power. This change depends on the ratio of reactive power and reactive power of the magnetization dispersion.

Figure 3.19 is the effect of voltage on the power factor depending on the load of the motor. The sharp decline in cos φ is typical for motors with low load factors. When the voltage decreases the magnetic flux and magnetizing current are reduced. If you do not reduce the load on the shaft at the same time,
the active components of the stator and rotor currents increase (since these currents grow), so that the reactive power component increases, because it is determined by the leakage flux. The total reactive power of the engine is somewhat reduced, depending on the ratio of Q0 and Qr.

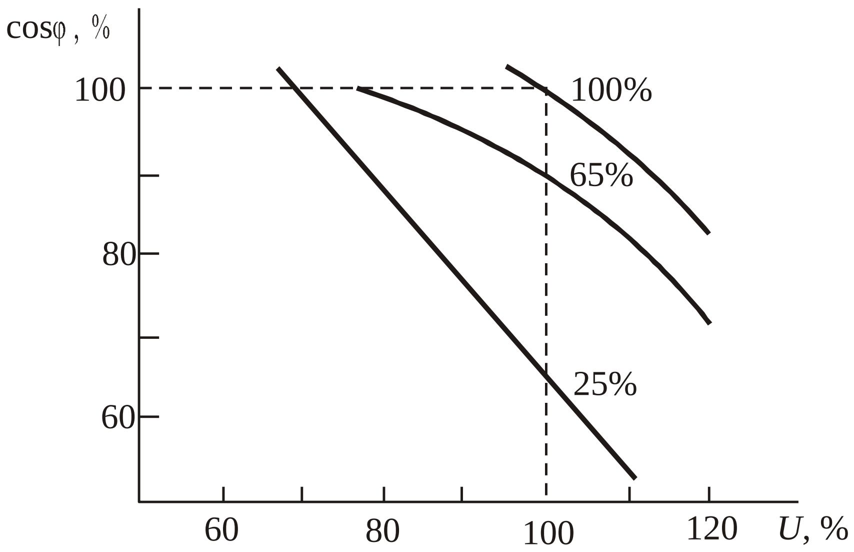


Fig. 3.19. Effect of voltage on the power factor of motors when they have different load

Consequently, cos φ increases when the voltage drops (Figure 3.19), however, the voltage drop reduces torque (start, tilting, nominal), increases the active current consumption, so that the engine starts to overheat winding. Therefore, reducing the voltage to increase cos φ is most effective when underload engine by up to 50%.

Change in frequency. Frequency reduction of the supply voltage will increase the magnetic flux in the engine and increase torque. Since the moment of resistance remains constant, the slip is reduced to maintain equality between the engine torque and torque resistance. No-load current increases due to the increase of magnetic flux. Rotor current changes proportionally to the frequency and stator current will at first decrease and then increase at small values of I_{xx}, and will always increase with larger values of I_{xx} (Figure 3.20).

Thus, a magnetizing component of stator current plays the basic role when frequency decreases, a magnetizing component of stator can sharply increase and causes an increase in consumption of motor power factor. Reactive power of magnetization changes when the frequency changes due to the effect of saturation, but not inversely proportional to frequency, and in more drastic law (Figure 3.21).

Thus, when the frequency supplied to the motor current decreases its power factor is reduced.

Reduction of consumption of asynchronous motors can be achieved by simultaneous and proportional changes in frequency and voltage. In the operation of power systems

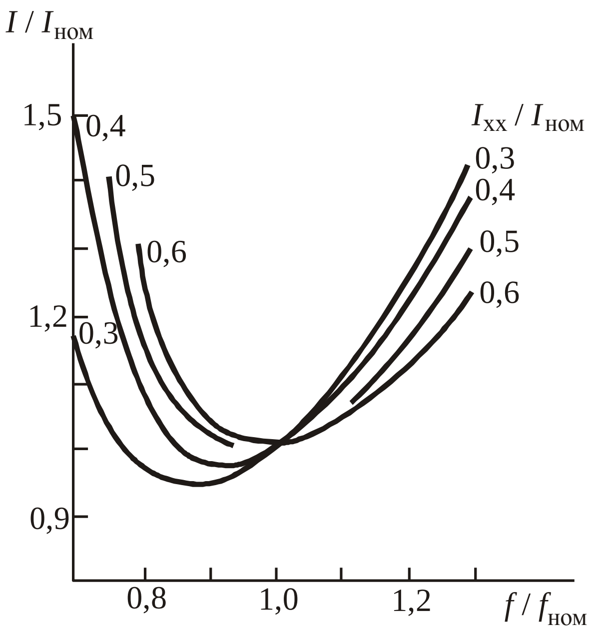


Fig. 3.20. Influence of frequency of supply voltage on stator current of electric engine

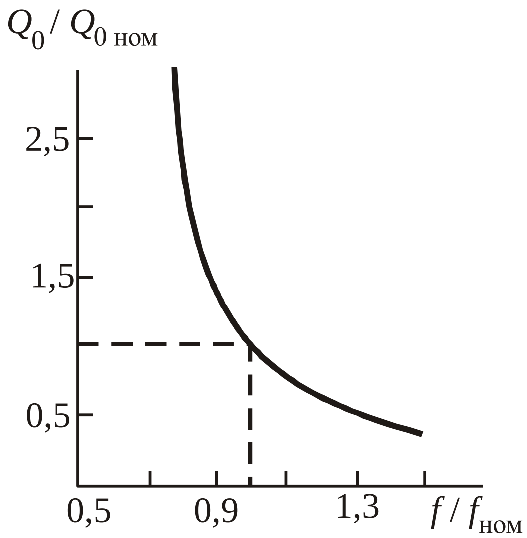


Fig. 3.21. Dependence of reactive power consumed by the engine at frequency changes

voltage deviations from the nominal values are often observed and they influence more significantly on cosφ than frequency deviation.

In transformers voltage increase above the nominal increases the magnetizing current. In some designs of transformers a 10% increase in voltage can increase the magnetizing current to a double value, thereby causing a significant reduction in power factor.

In operation of electrical systems one should take into account that although the voltage drop has a positive impact on cos φ, but is not allowed to have more than 5% of rated power since it is possible to get additional heating of the rotor winding and its premature wear. Therefore, when voltage drops are more than 5% of rated power motor load must be decreased relatively to rated power. Thus, the maintenance of quality voltage and frequency is important to maintain a cosφ of power systems, as well as for its smooth operation.

3.6.2. Technical conditions of electric motors and the quality of their maintenance, their influence on power factor

Increase in the air gap. In the induction motor magnetic resistance of the air gap is 70 – 80% of the total resistance of the magnetic circuit. Its value is determined by the multiplicity and load current with respect to the rated current:

$$\frac{I_{\text{хх}}}{I_{\text{ном}}} \approx \frac{\delta}{\tau} \quad (3.21)$$

where δ – value of the air gap; τ – pole pitch.
Induction motors are constructed with the maximum allowable size of the air gap, which is caused by mechanical factors: vibration and allowable deflection of the shaft, precision surface treatment of the rotor and stator, wear tolerance and drawdown of bearings.
Depending on engine type and number of its speed air gap varies from 0.2 to 1.75 mm. For high-speed machines, it is increased slightly compared with the low-speed (Table 3.2) - this is due to the mechanical properties.

Table 3.2

Air gap of induction motors

Rotation frequency, rev/min	Air gap, mm, motor power, kW									
	0,2	0,2̃1,0	1,0̃2,5	2,5̃5,0	5̃10	10̃20	20̃50	50̃100	100̃200	200̃300
3000	0,25	0,30	0,35	0,40	0,50	0,65	0,80	1,0	1,25	1,50
500̃1500	0,20	0,25	0,30	0,35	0,40	0,40	0,50	0,65	0,80	1,0

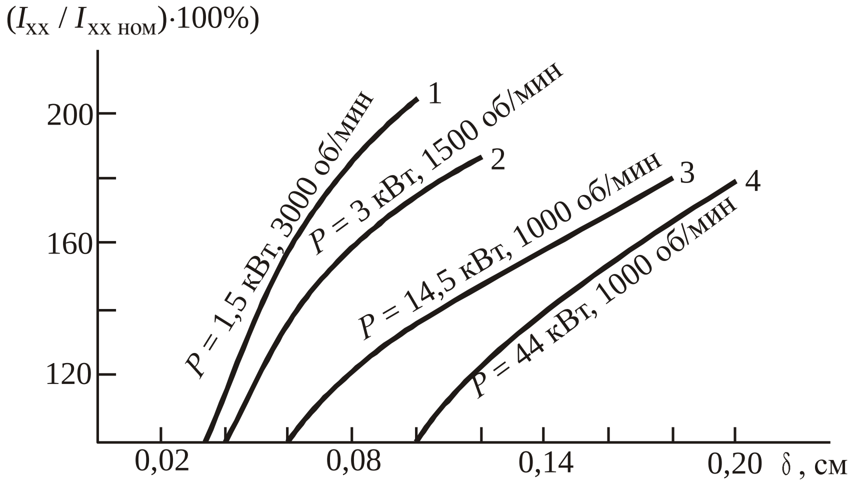


Fig. 3.22. Dependence of noload current on the air gap: 1-3 - for engines under 15 kW, 4 - to 44 kW motors

Due to bearing wear during operation, the air gap in electric motors is increased; it leads to an increase in the magnetizing current and lower power factor. Graphs in Fig. 3.22 illustrate the relative change in no-load current of induction motors depending on the air gap. By the same increase in air gap increase in load current is most sharply manifested in low power engine, thus they have much more reduction in cos φ.

Thus, the operation of engines with larger air gaps leads to a deterioration in technical and economic indices due to low power factor.

The increase in air gap can occur not only as a result of normal wear of bearings, but also as a result of poorly performed maintenance works.

❶ Maintenance works involve some movement of geometric axes of the stator and rotor which can lead to an asymmetry of the air gap.
For a small air gap, even a slight discrepancy axes of stator and rotor results in a sharp inequities in the distribution of magnetic flux in the air gap and the magnetic system of the engine in general: on the one hand there are underutilized motor, and with another - its super saturation. This entails an increase in the magnetizing current and reactive power. During operation it was found out that the resulting asymmetry of the magnetic field causes a decrease in cos φ 0,010 – 0,025 compared to its nominal value and 1,4 – 3,7% efficiency.

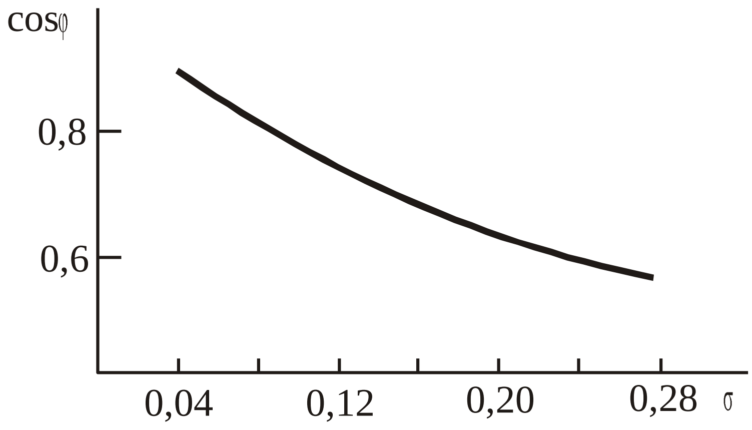


Fig. 3.23. Relationship between power factor and leakage coefficient

❷ An abnormal shear of steel of rotor along motor’s axis is possible.

This shift, sometimes reaches more than 10 mm, doesn’t have an attachment and a lack of a tight press-fit of steel of rotor shaft, and usually occurs while motors maintenance (under the blows of the shaft while removing or coating pulleys and bearings).

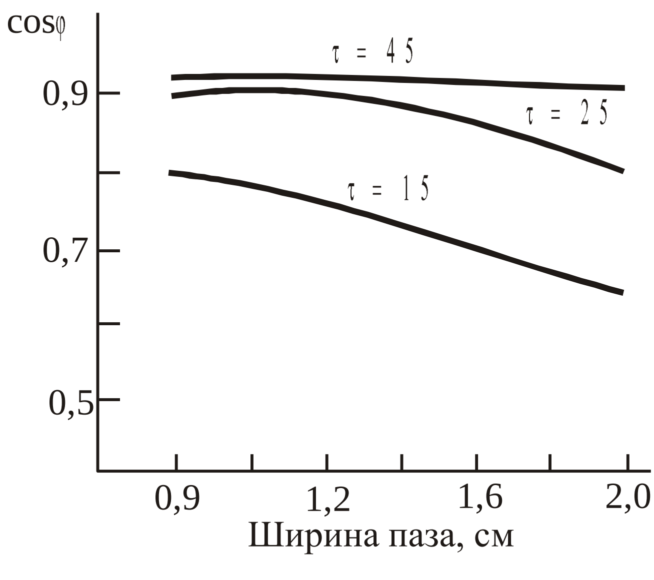
The shift is reflected in the power factor. Current which flows through the windings of stator and rotor creates, apart from a useful magnetic flux, a leakage field around conductors in the slots, between the teeth, and dispersion of winding overhang. In the design and normal operation of the motor cos φ is the ratio of the magnetizing current and short circuit current, i.e., leakage coefficient:

$$\sigma = I_{\mu}/I_{КЗ} = x_{к}/x_{m} \quad (3.22)$$

where xк - reactivity of flux leakage; xт - reactivity of the main stream. When an abnormal shift of rotor's steel occurs, reactivity of flux leakage increases and reactivity of the main stream decreases. It leads to an increase in leakage coefficient, and consequently to an increase in reactive power consumption and reduction of cos φ (Figure 3.23). The shift of the rotor steel in the motors of small power has a particularly strong influence: a decrease in power factor can reach up to 30%.

❸ Replacement of a magnet wire by another one with a new section may be made by cutting slots.

Slots cutting increases magnetic resistance which leads to an increase in load current and reduction in cos φ. The higher the number of pole motor, the greater the power, the less the effect of the slot size (Figure 3.24).



ширина паза – slot width

Fig. 3.24. Influence of slot width on cosφ of induction motor

In low power motors a 0.2 mm slot cutting can reduce the power factor up to 5%. Deviation from the original winding data. Sometimes a burnt stator winding wire is restored with a wire which has the wrong section; in addition fewer conductors are placed into the slots.

If you change the number of windings, the phase diagram and voltage remain unchanged, also unchanged remain:

• Applied voltage (Φ ~ E ~ U) arising in the winding under the action of the rotating magnetic EMF field;

• the number of flux linkages (flux phase with the windings) is determined by the value of the balancing voltage.

If there is a reduction in the number of windings in the phase (10% assumed), magnetic flux and magnetic induction will have a 10% increase. The consequence is an increase in reactive power and no-load current: a 10%decrease in the number of windings, the increase may reach up to 25% taking into account reduction of permeability while saturation. The significant increase of reactive power and no-load current causes a decline in capacity of the motors with a nominal cos φ = 0,86 – 0,87 to 0,80 – 0,82, and the motors with cos φ ном = 0,80 – 0 82 to 0,74 – 0,75, i.e. 9,5 – 10%.

Along with a decrease in cos φ coefficient of efficiency is reduced as the active power losses in steel increase. The losses are proportional to the square of magnetic induction (ΔPст ~ B2). The most significant decrease in the number of windings will affect cos φ and coefficient of efficiency of motors operating with a small load factor.

3.6.3. Design factors

Motors can be of various types: with a squirrel-cage and phase rotor, enclosed-type, open-type, high-speed and slow-speed. These factors affect the value of power factor.

Induction motors with a squirrel-cage and phase-wound rotor. The squirrel cage motors of the same power and speed have a higher power factor (about 45%) and higher efficiency, in contrast to a phase rotor.

A rotor of phase motors is equipped with a large number of conductors. It results in a more extended head-field scattering and greater consumption of reactive power.

In squirrel-cage motors with a deep bar and a double *squirrel-cage* power factor is higher than that of motors with a phase rotor, but lower than that of squirrel-cage motors. This decrease depends on the increased value of induced drag of scattering on the working winding. Table 3.3 shows comparison of power factors and coefficient of efficiency of induction motors.

Power factor and coefficient of efficiency of induction motors

Parameter	Load	Squirrel-cage	Phase rotor	Double squirrel-cage
cosφ	4/4 3/4 1/2	0,92 0,90 0,82	0,85 0,79 0,67	0,86 0,83 0,76
Coefficient of efficiency	4/4 3/4 1/2	0,90 0,90 0,89	0,88 0,88 0,86	0,90 0,895 0,875

According to the table it follows that when cosφ is underloaded, power factor and coefficient of efficiency of motors with *phase-wound rotors* are reduced considerably sharper in contrast with squirrel cage motors.

Thus, availability of motors with phase-wound rotors in electric power supply system results in lower power factor than the use of squirrel cage motors.

Motors speed. High-speed type motors of the same power and performance have higher efficiency and cos φ than slow-moving. Motors with a large number of revolutions have smaller dimensions and a section of the magnetic circuit and hence a smaller magnetic flux.

As was mentioned above (3.21), no-load current depends on the ratio of the gap to the pole division δ/τ. In low-speed motors value δ / τ is higher, unlike the high-speed (with a small number of poles). Consequently, low-speed motors consume more reactive power and have lower power factor. For example, in Table 3.4

change in cosφ of engines with the same power but with a different number of revolutions is shown.

Table 3.4
Influence of revolutions of induction motors on their cosφ

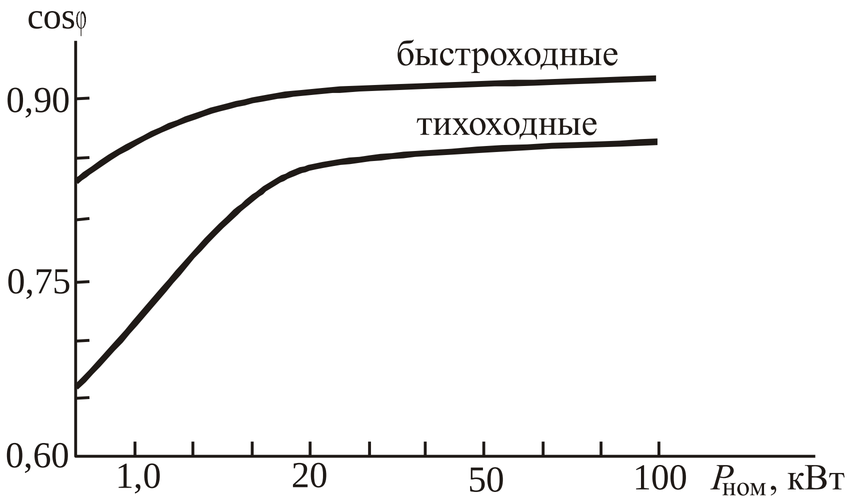
Power, kW	92	92	92	92
Number of rev/min	1500	1000	750	600
cosφ at 100% load	0,92	0,90	0,89	0,88

Motors are rarely mate with working mechanisms without any gear. It is reasonable to select a gear-box with a large gear ratio and to apply a high-speed motor. One should take into account that high- speed motors have a higher coefficient of efficiency.

Motors capacity. The bulk of reactive power consumed by electric motors is used for magnetization of a magnetic circuit; a large part is used for creating a magnetic field in the air gap. Since the magnitude of the air gap of different motors varies only slightly (for example, a medium power motors from 1 to 1.5 mm), and requirement for power magnetization varies only slightly compared to the active. Consequently, the power factor would be higher in heavy-duty motors, especially if they are high-speed motors (Figure 3.25).

For motors from 1 to 20 kW power factor is of 0,63 - 0,90, for high-speed motors below 30 kW is 0,85 - 0,93.

Open-type and enclosed-type motors. Motor closure leads to additional heating and consequently to reduction of load capacity.



Быстроходный – high-speed
Тихоходный – low-speed
Fig. 3.25. Dependence of electric motor’s power factor on its rated capacity

If you open an enclosed-type electric motor, its load within the allowable heating can be increased by 25 -30% against its rated capacity. On equal terms enclosed-type motors require the same reactive power of magnetization as open-type motors but with different allowable loads. Enclosed-type motors have lower power factor than open-type. In Table 3.5 a comparison of different cos φ motor performance is introduced.

Table 3.5
Power factor of induction motors of different performance

Capacity, kW	Open-type		Enclosed-type	
	Squirrel cage	Phase-wound	Squirrel cage	Phase-wound
	Revolutions			
	1000	750	1000	750
10	0,83	0,81	0,78	0,74
4,5	0,81	0,77	0,73	0,72

For open-type motors power factor is generally higher: 0,05 - 0,06.
Thus, to increase power factor of electrical motors it is reasonable to use a regular-type motor on a large scale, providing that the process and safety of operations meet the requirements.

4. COMPENSATION OF REACTIVE LOADS

4.1. Reasons for expedience of reactive power compensation at enterprises

Load power supply system is defined by total power $S = \sqrt{P^2 + Q^2}$, its active component is consumed and does not get back to an electric power supply. Reactive component is required to create electric and magnetic fields in the elements of the electrical network. Virtually, it is not consumed but flows from a power source (generator) to a power consumer and vice versa.

Transmission of a significant amount of reactive power through transmission lines and transformers of the electrical network is not profitable for the following reasons.

❶ There are additional active power losses in all elements of power systems because they are loaded with reactive power.
There are active power losses which can occur while transmission of active and reactive power to consumers:

$$\Delta P = 3I^2R = 3\left(\frac{S}{\sqrt{3}\cdot U}\right)^2 R = \frac{S^2}{U^2}R = \frac{P^2+Q^2}{U^2}R =$$
$$= \frac{P^2R}{U^2} + \frac{Q^2R}{U^2} = \Delta P_P + \Delta P_Q, \qquad (4.1)$$

The first term - losses of active power due to the transmission by a circuit, the second - losses of active power due to the reactive power transmission by the same circuit.

Thus, additional active losses, due to uncompensated reactive power, are proportional to its square:

$$\Delta P_Q = \frac{Q^2R}{U^2}. \qquad (4.2)$$

In addition, Δ PQ losses are also proportional to active resistance of conductors:

$$R = \rho\frac{l}{S}, \qquad (4.3)$$

where ρ is resistivity of conductors materials, l and S - their length and cross-section accordingly.

Compensation of reactive power is particularly relevant when the load is connected by a thin and long cable with an aluminum conductor. Taking into account that load is connected through a conductor composed of segments and the circuit has switching and protective devices, in this case active resistance in the ratio (4.2) is even higher.

Power factor is of great importance in the transmission of electricity from a power supply to a consumer. Power factor is:

$$\cos\varphi = \frac{P}{S} = \frac{P}{\sqrt{P^2+Q^2}},$$

So

$$P^2 + Q^2 = \frac{P^2}{\cos^2\varphi}$$

Or power losses

$$\Delta P = \frac{P^2 \cdot R}{U^2 \cdot \cos^2\varphi}. \qquad (4.4)$$

The value of active power losses in the network is inversely proportional to a square of power load of transmitted power (or $\Delta P = f\left(1/\cos^2\varphi \right)$) if parameters of transmitted power (P), voltage (U) and network resistance (R) are constant.

Taking into account its characteristic curve, table 4.1 presents calculations of useful active capacity of a consumer while transmitting constant active power (P = 100%) through the network, when cosφ are different and provided that the losses of active power in the network are equal to Δ P = 100 % when cosφ = 1.

Table 4.1.

Active losses in the network when cosφ are different and active power transmitted through the network is constant

cos	tgφ	power, %		Active losses, ΔP%=10%/cos2φ	Useful active power of a consumer (P-ΔP) in % from P
		reactive Q = P·tgφ	total S = P/cosφ		
1	0	0	100	10	90
0,9	0,484	48,4	111,1	12,3	87,7
0,8	0,75	75	125	15,6	84,4
0,7	1,02	102	142,9	20,4	79,6
0,5	1,732	173,2	200	40	60

0,316	3,016	301,6	316,5	100	0

According to the calculations one can observe that losses of active power in electrical networks are growing rapidly with a decrease in cosφ.

When cosφ=0,5 losses can reach 40%. When cosφ=0,316 entire active power, transmitted through the network, is consumed to cover losses. The value of reactive power is almost three times higher than the active power.

Additional losses of active power, associated with a cross-flow of reactive power, make it necessary to enlarge sections of conductors. It leads to a waste of nonferrous metal. The enlargement of sections leads to an increase in mass of wires, therefore heavier poles are required.

Net current I is related to the active component:

$$I_a = I \cdot \cos\varphi,$$

hence, total losses of active power depending on power factor will be:

$$\Delta P = 3I^2R = \frac{3I_a^2R}{\cos^2\varphi} = \frac{\Delta P_P}{\cos^2\varphi}. \qquad (4.5)$$

If transmitted power is the same and the active component of the current Ia corresponds to it, in case of power factor decrease from 1 to 0,8 active losses will increase up to 1/0,82 = 1,56 times. It will require an increase in mass of wires $\sqrt{1,56} = 1,25$ or up to 25%.

❷ There are additional losses of reactive power.

Transmission of reactive power to a consumer is accompanied by additional losses ΔQ:

In a line $\Delta Q = 3 \cdot I^2 \cdot x_0 \cdot l$,

where I - current load, x0 - resistance per unit line length, Ohm/km; l - length of a line;

In a transformer $\Delta Q = \frac{S_{ном}}{100}\left(i_{xx} + u_{КЗ}\beta^2\right)$, where ixx – no-load current of a transformer,%; иКЗ - short-circuit voltage of a transformer,%; Sном - rated power of a transformer; β – load factor of a transformer.

Power of load compensating devices should be increased to these values.

❸There are additional voltage losses.

The problem is relevant to long-distance networks made of small cross-section conductors. When transmitting power P and Q via a network element with an active R and reactive X resistor voltage drop will be:

$$\Delta U = \frac{P \cdot R + Q \cdot X}{U} = \frac{P \cdot R}{U} + \frac{Q \cdot X}{U} = \Delta U_P + \Delta U_Q, \qquad (4.8)$$

where ΔUP - voltage losses due to a transmission of active power, ΔUQ - voltage losses due to a transmission of reactive power.

The expression (4.8) shows that losses of line voltage depend not only on the value of transmitted active power, but also on the values of the transmitted reactive power and reactance line. When transmitted reactive power is reduced to zero, there is an increase in voltage of a line

$$\Delta U_Q = \frac{Q \cdot X}{U}. \qquad (4.9)$$

Additional voltage drop ΔUQ increases the range of voltage deviations from a nominal value on the terminals of power consumers with changes in loads and modes of electric networks.

The nature and magnitude of transmitted reactive power impact on losses of voltage in transformers. A change in voltage losses in a transformer, depending on the power factor of consumers is shown in Fig. 4.1

The same transformer with the same load will produce a different voltage on the secondary terminals with a change of cosφ2. The lower the power factor of the secondary circuit, the higher the voltage drop.

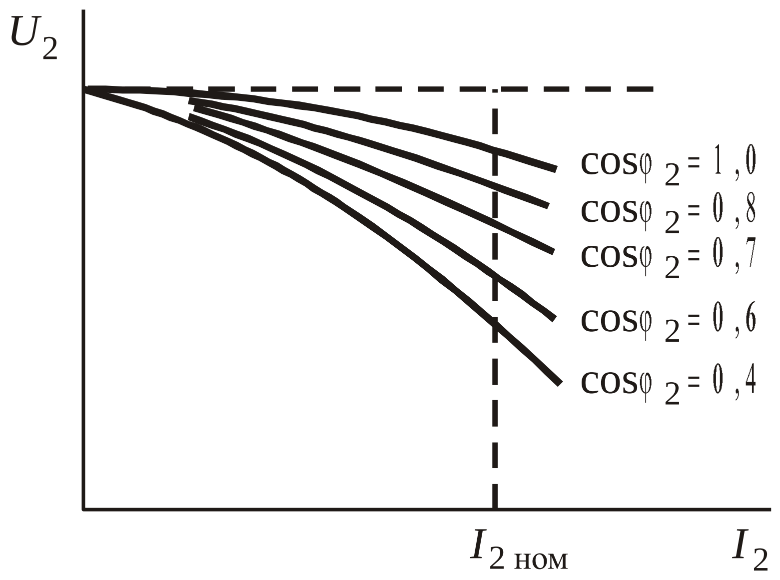


Fig. 4.1. Characteristic curve of the voltage loss in the transformer on the power factor on the secondary terminals

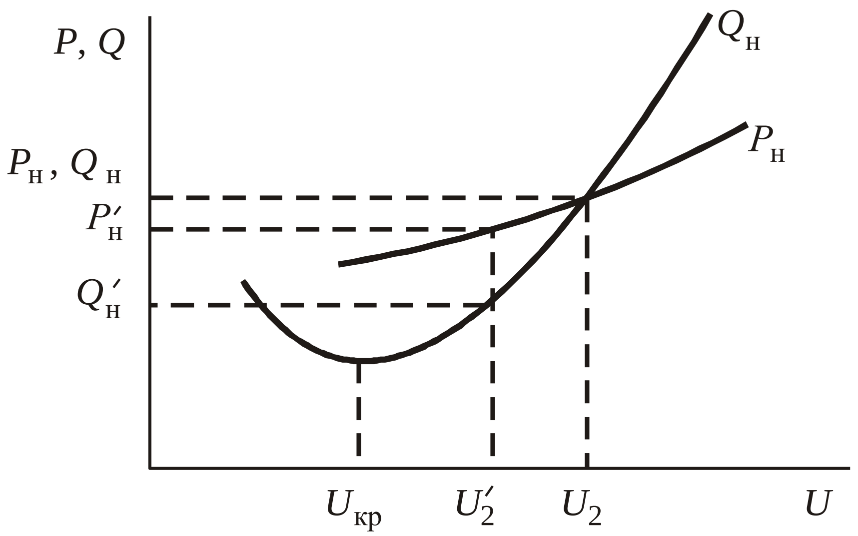


Fig. 4.2. Static characteristics of a complex load

A change in voltage in relation to nominal voltage has an adverse effect on the modes of operation, performance, technical and economic indices of all elements of power supply system.

In accordance with a federal standard 13109-97 in the networks of power supply systems, limit values and admissible limit values of voltage decrease for power consumers should not exceed 5 and 10% of nominal voltage in accordance with a federal standard 721 – 77 and federal standard – 21128-83 (nominal voltage). Static characteristics (Fig. 4.2) of reactive power Qн = f(U) are steeper than the static characteristics of active power Pн = f(U) - voltage change by 1% leads to a change of reactive power at 2 – 5%. Voltage change by 1% leads to a change in active power 0,6–2%. It leads to an additional increase in current of transmission lines and further voltage reduction (Fig. 4.3). When there is a decrease up to U < Uкр in voltage on buses (critical voltage of static characteristics of a load node (Fig. 4.2)), a sharp increase in reactive power consumption occurs. It increases the voltage drop, further voltage reduction and a fast-growing process taking only a few seconds, the process is called avalanche voltage (Fig. 4.4).

Voltage dips can also occur along with deviations in the grid. Voltage dips are caused by short circuits, lightning discharges in power transmission lines and outdoor switchgear (ОРУ –открытое распределительное устройство) buses that can lead to a switch off while automatic transfer switches (АВР – автоматическое включение резерва) and automatic reclosers (АПВ – автомат повторного включения) are in operation. It can also lead to a start-up and a self-start of the powerful electric motors and some electro technology processes where regimes are the same as the regimes of short-circuits (arc furnaces, electric welding).

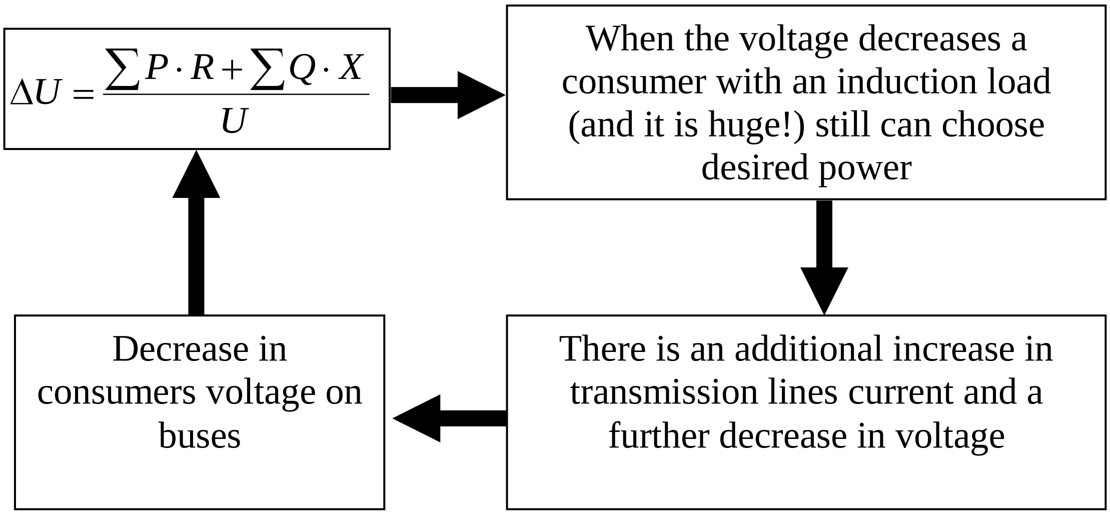


Fig 4.3. Impact of voltage reduction on consumers

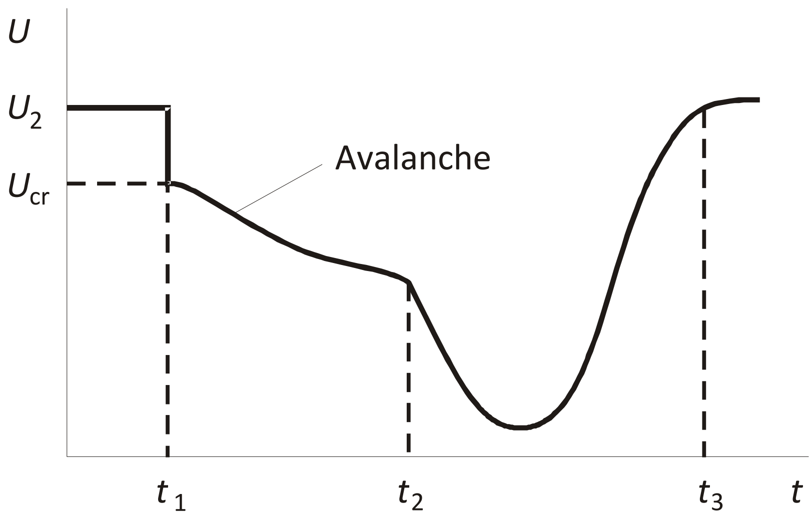


Fig.4.4. Development of avalanche voltage

To minimize the risk of blackouts in power systems a supply of static stability of the load voltage should be maintained during voltage sags:

$$\kappa_U = \frac{U - U_{\text{кр}}}{U} \cdot 100\% \qquad (4.10)$$

where κ_U – a coefficient of static stability; U - voltage at the node; $U_{\text{кр}}$ - critical voltage at the same node where static stability of the load can be interfered.

Due to low voltage level in the steady regimes of the grid (also due to the load of reactive power) this condition is not always maintained.

❹ Load of transmission lines and transformers with reactive power reduces carrying capacity of the networks. In some cases it does not allow applying a total capacity of electric equipment.

The power factor of induction motors used by industrial enterprises is close to 0.7. If only induction motors without capacitors are used at industrial enterprises, the total $\cos\varphi$ will be close to 0.7. Let's suppose that a consumer of industrial enterprises with $\cos\varphi$ = 0,7 is powered by a transformer substation, where total rated power of the transformer is1000 kVA.

In this case maximum active power a consumer can get provided that he is the only consumer of the entire substation will be:

$$P = S \cdot \cos\varphi = 1000 \cdot 0{,}7 = 700 \text{ kW}$$

If one needs to get more active power it is required to use the second transformer substation.

At the same time, reactive power compensation with an increase in $\cos\varphi$ to 0.9 would be provided by

$$P = S \cdot \cos\varphi = 1000 \cdot 0{,}9 = 900 \text{ kW}$$

that is, an additional 200 kW for the same parameters of the transformer.

Required total power will increase if active power of 1000 kW will be transmitted via the transformer (Fig 4.5).

Low $\cos\varphi$ of power system requires an increase in the power rate of transformers or installation of additional equipment.

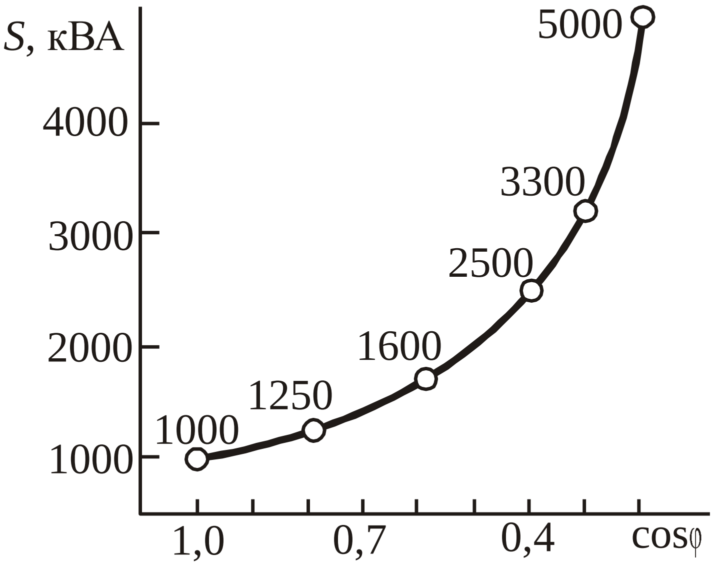


Fig. 4.5. Increase in total power of the transformer depending on $\cos\varphi$

❺ Load of transformers with reactive power reduces their coefficient of efficiency.

Example 4.1

Determine the coefficient of efficiency of the transformer TM 100/10 if $\cos\varphi = 1$ and $\cos\varphi = 0{,}5$.

Solution

According to technical data no-load losses of the transformer are 0.36 kW, and a short circuit - 1.97 kW. Consequently, if $\cos\varphi = 1$, the coefficient of efficiency is

$$\eta = \frac{P_1}{P_1 + P_{xx} + P_{КЗ}} \cdot 100\,\% = \frac{100}{100 + 0{,}36 + 1{,}97} \cdot 100\,\% = 97{,}7\%$$

If $\cos\varphi = 0{,}5$, the maximum active power that can get a consumer will be:

$$P_1 = S \cdot \cos\varphi = 100 \cdot 0{,}5 = 50\,\text{kVt}$$

losses will be the same as if $\cos\varphi = 1$, since current intensity remains unchanged, so the coefficient of efficiency will be:

$$\eta = \frac{P_1}{P_1 + P_{xx} + P_{КЗ}} \cdot 100\,\% = \frac{50}{50 + 0{,}36 + 1{,}97} \cdot 100\,\% = 95{,}5\%$$

Decrease in the coefficient of efficiency is more than 2%. If we take into account the number of energy transformations, decrease in the coefficient of efficiency, due to the load of the transformer with reactive power, can significantly increase operating costs.

❻ Underutilization of generators useful power and increase in gross average fuel consumption.

The active power load must be reduced if reactive power exceeds the nominal value determined by the rated power factor of the generator. Entire load current under the terms of heating coils shall not exceed the rated current of the generator.

Voltage on stator terminals will be reduced if the power factor is lower than the rated as a result of an increase in phase shift due to the intensification of a longitudinal field of an armature (acting against the main field). It will require stronger excitation. Overexcitement with reduced power factor will result in a decrease in the coefficient of efficiency (Fig. 4.6) and increase in power of prime motors.

Example 4.2.

An industrial enterprise is powered by an electric power station which is equipped with two turbine generators of 1200 kVA. The enterprise consumes 11 000 kW. If $\cos\varphi$ of the enterprise will be equal to 0.9, then the active power 11 000 kW will be

$$S = P/\cos\varphi = 11000/0{,}9 = 12000 \text{ kVA}$$

that is, under these conditions, one can work with one unit and fully meet electricity needs of the enterprise.

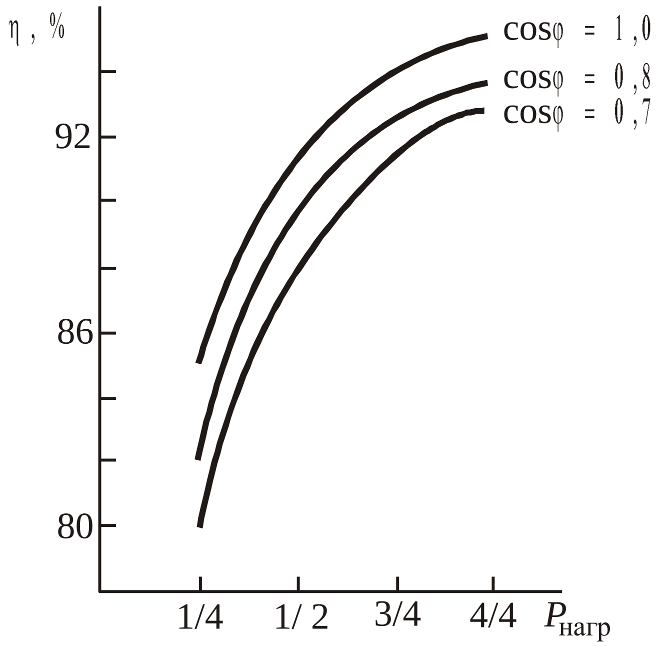


Fig. 4.6. Characteristic curve of the coefficient of efficiency of the generator on the load and $\cos\varphi$

If the power factor of a consumer decreases, for example up to 0.7, in this case the following will be required

$$S = P/\cos\varphi = 11000/0{,}7 = 16000 \text{ kVA}$$

In order to generate this power it is required to involve two units but they will be loaded with

$$\frac{P}{n \cdot S} = \frac{11000}{2 \cdot 12000} = 0{,}46$$

that is less than half of the rated power.

Specific steam consumption with the load reduction from 1.0 to 0.7 is approximately increased by 18%. When a turbine generator is fully loaded generation of 1 kilowatt per hour requires about 5 kg of steam. If a power factor is 0.9 and only one turbine generator runs, steam consumption will be 5×11 000 = 55000 kg per hour, in the second case, if cosφ = 0,7, the same amount will be produced i.e. 11 000 kW, steam consumption will be increased by 18% and it will require additional 55 000×0,18 = 9900 kg of steam per hour, so at least 3 tons of fuel per hour will be overspent on its generation.

Thus, reduction of the power factor affects all operational indices of a power station: fuel consumption and lubricants use are increased, the coefficient of efficiency is reduced, and costs of electricity and general operating expenses are increased.

In Fig. 4.7. there is an overview of the problems that cause network loads and loads of electrical power systems with reactive power. These negative factors are forcing the reactive power sources to be placed closer to the places of consumption. It unloads equipment from overflows which is equal to an increase in the power factor.

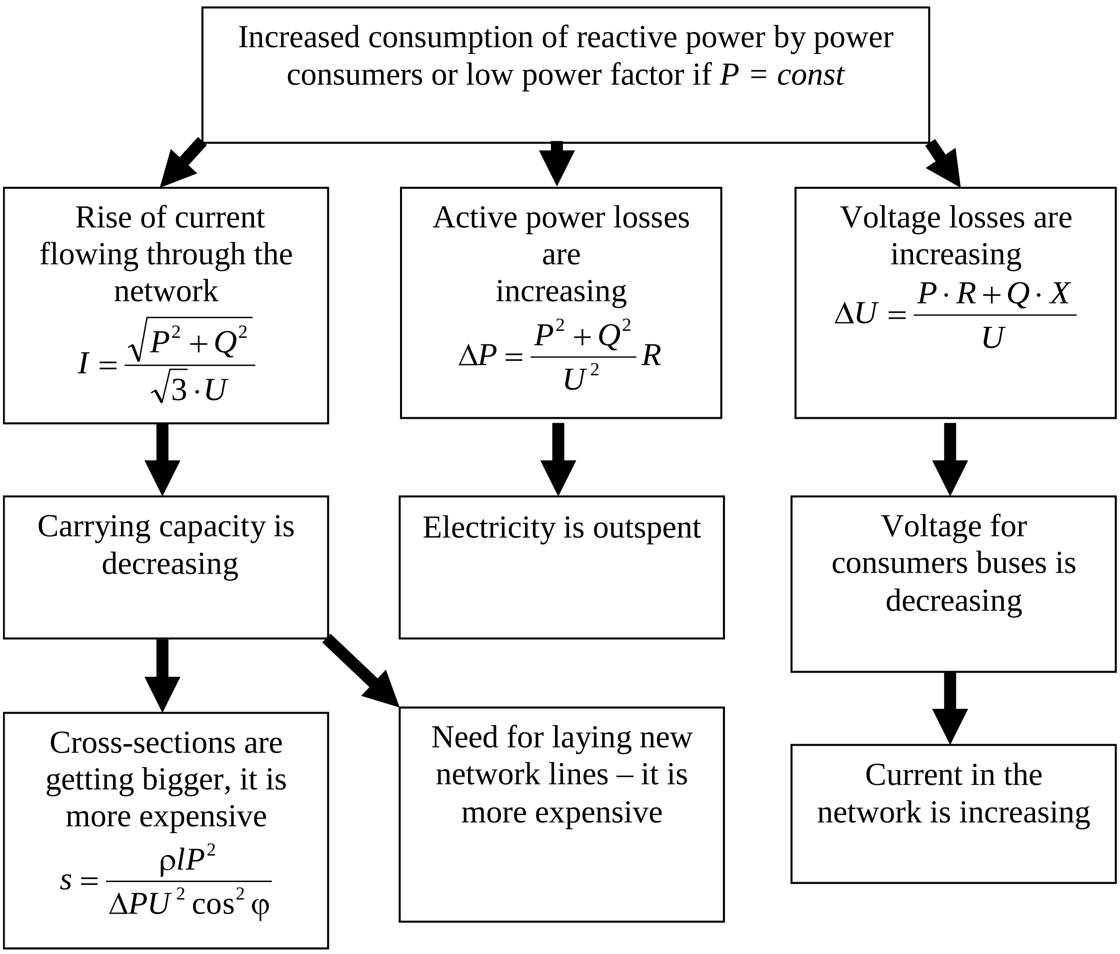


Fig. 4.7. Consequences of increased transmission and reactive power consumption

There are two complementary ways of reduction of reactive load in networks and generators.

❶ Simulated/forced compensation - special compensating devices that are installed at industrial enterprises.

The following devices are used by industrial power systems as their own sources of reactive power in (see Chapter 2):

• Generators of power stations and synchronous motors;

• overhead and cable lines of electric networks;

• compensating devices that are installed additionally: synchronous compensators, capacitor banks, high and low voltage rectifier devices with a special regulation.

❷Natural compensation - a reduction of reactive power by power consumers.

Activities of the natural compensation are:

- streamlining the process leads to an improved energy regime of the equipment and equalization of the load curve (even distribution of loads, time shift of lunch breaks, start and end of the shift of individual shops and sites, avoiding hours of peak power by energy-intensive large-scale power consumers, maintenance of power consumers in hours of peak power);
- introduction of a rational scheme of power supply by reducing the number of stages of transformation;
- replacement of old equipment by the new designs with lower losses in magnetization reversal;
- replacement of low loaded transformers and motors by less
- powerful or their full load;
- use of synchronous motors instead of asynchronous when it is permissible under the terms of the process;
- limit duration of idling motors and welding transformers;

- reduction of duration and different time starts of large power consumers;
- improvement of the quality of motors maintenance;
- shutdown of transformers if load is low.

Part of the activities aimed at natural compensation of reactive power does not require large material costs and should be conducted at enterprises in the first place.

The problem of reactive power compensation includes a variety of technical and economic problems, such as:

- actions for implementation of natural compensation;
- selection of types and kinds of compensation devices;
- location of compensation devices in the network;
- optimization modes of compensation devices

Selection of the most effective compensation option of necessary capacity and type of a compensation device should be based on analysis of circuit power network of the industrial enterprise.

4.2. Shunt capacitive reactive power compensation

The main purpose of shunt compensation is to increase the power factor. The capacitors are located according to the principle aimed at reduction of power losses in electric networks. Increase in the voltage level is of great importance since it accompanies installation of capacitors. In some cases, arrangement of capacitors may be a subject to this condition.

4.2.1. An equivalent circuit and a vector diagram of a direct compensation

plant

Alternating current circuit with parallel connection of the receivers of electricity and the capacitor bank is considered for calculation and analysis of cross-compensation as a source of reactive power of (Figure 4.8a).

For the node "A" of the equivalent circuit line current $I_л$ line is determined by the first Kirchhoff's law:

$$\dot{I}_l = \dot{I}_b + \dot{I}_{cb} \tag{4.11}$$

$\dot{I}_l$ – vectors of the current in line

$\dot{I}_b$ – vectors of the current in the branches of burden

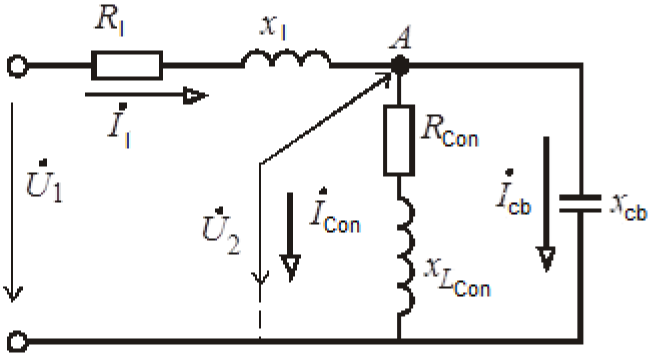
$\dot{I}_{cb}$ – vectors current in the capacitor bank

Construction of vector diagrams and vector addition for the current expression (4.11) are shown in Fig. 4.8b. Vector diagram was constructed for the line at the end of the load in the presence of cross-compensation of $x_{БК}$ (resistance of the battery can be ignored). Capacity is included in parallel with the load. An angle φ_1 is decreased to φ_2, load current of the receiver from I_1 was reduced to I_2, line-current discharge on the magnitude has occurred on the value $\Delta I = I_1 - I_2$. Power system generators due to generation of capacitor bank with power $Q_{БК}$ in the place of installation for power consumers have been discharged at the same current value. The network and the generators were discharged and it led to reduction in losses in the $\Delta P_к$ and $\Delta Q_к$, as the flow of reactive power has been decreased by $Q_{БК}$:

$$\Delta P_c = \left(\frac{Q_{cb}}{U}\right)^2 \cdot R; \quad \Delta Q_c = \left(\frac{Q_{cb}}{U}\right)^2 \cdot x \qquad (4.12)$$

where R and x are equivalent circuit resistance of the power grid - consumer.

Decrease in the current ΔI makes it possible to reduce the conductor cross-section lines on ΔF:



a

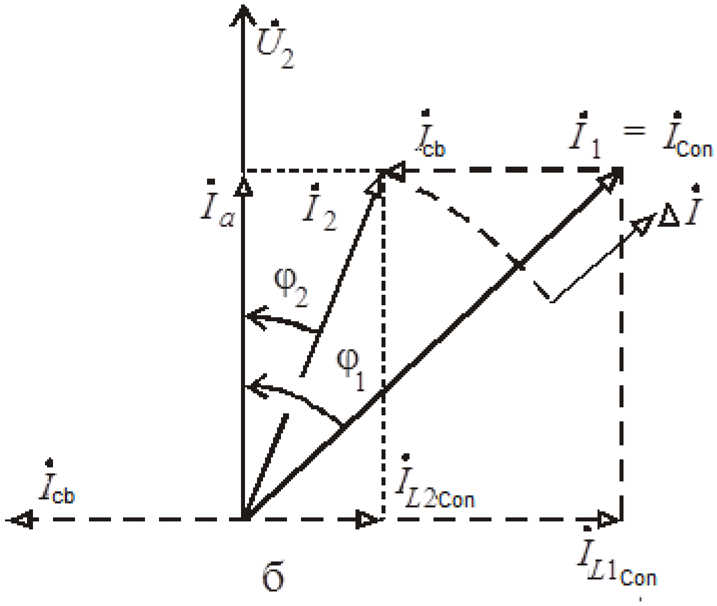


Fig. 4.8. Crosscut capacitive compensation: a - equivalent circuit, b - vector diagram of the circuit

$$\Delta F = \frac{\Delta I}{J_e}$$

where $J_э$ - economic current density in the line.

Accordingly, the installed capacity of the transformer is reduced. Loss of voltage is reduced by flow decrease in reactive power at $Q_{БК}$ to the value

$$\Delta U = \frac{PR + \; Q - Q_{cb} \;\; x}{U} \tag{4.14}$$

The diagram (Fig. 4.8b) shows that if the capacity of the capacitor bank is too large, the current $I_{БК}$ will be higher consumer inductive load $I_C > I_{пL}$. Then, the angle $\varphi_2 < 0$ and the power factor goes through the value of $\cos\varphi = 1$ in the capacitive quadrant. In this case overcompensation takes place: capacitive current flows from the consumer to the source, line current $I_л$ will be increased as the capacity grows. This implies that an increase in the capacitance C and the dependent variables of current line $I_л$ and φ_2 will be useful only within certain limits, not beyond the value $\varphi_2 \geq 0$ and $\cos\varphi \leq +1$.

The capacitance C and the reactive power $Q_{БК}$ of a capacitor needed to improve the power factor $\cos\varphi_1$ to the value $\cos\varphi_2$, exceeding the natural value of $\cos\varphi_п$ n consumer to enable cross-compensation can be determined from the vector diagram. From the diagram we find:

$$I_{cb} = I_{L1con} - I_{L2con} = I_a \mathrm{tg}\phi_1 - I_a \mathrm{tg}\phi_2 = I_a \left(\mathrm{tg}\phi_1 - \mathrm{tg}\phi_2 \right)$$

Taking into account $I_{cb} = U/x_{cb} = U\omega C$ and $I_a = P/U$, we get $U\omega C = \frac{P}{U}\left(\mathrm{tg}\varphi_1 - \mathrm{tg}\varphi_2 \right)$.

Consequently,

$$\left. \begin{aligned} C &= \frac{P}{\omega U^2}\left(\mathrm{tg}\phi_1 - \mathrm{tg}\phi_2 \right); \\ Q_{\text{cb}} &= U^2\omega C = P\left(\mathrm{tg}\phi_1 - \mathrm{tg}\phi_2 \right). \end{aligned} \right\} \qquad (4.15)$$

If the load of the consumers is of a capacitive type, then to compensate for the excess capacitive current component I_{CK} (to approximate the power factor to unity) the inductance is used, which is switched on to a parallel load.

Such cases occur if plants have at their disposal long distance cable lines of high voltage during periods of reduced network load, as well as when power of capacitors is saved during hours of minimum load at enterprises.

Crosscut compensation affects not only the current loads of all elements of power, but also voltage losses, voltage ratio at the beginning and the end of transmission.

Fig. 4.9 shows a vector diagram of voltage at the end of the line for two cases: in the absence of cross-compensation (solid lines) and with compensation that improves the power factor to $\cos\varphi = 1$. The diagram is designed for constant values of voltage at the end of the power line U_2 and the active power of the consumer. The diagram shows that the absolute values of voltages U1 and U2, even with a significant change in the angle φ (from φ to 0) due to crosscut compensation vary within a limited range, voltage U2 is less than voltage U1.

Crosscut capacitive compensation is provided by complete sets of capacitor banks, which are installed in certain places of a power supply scheme (see Section 4.2.3).

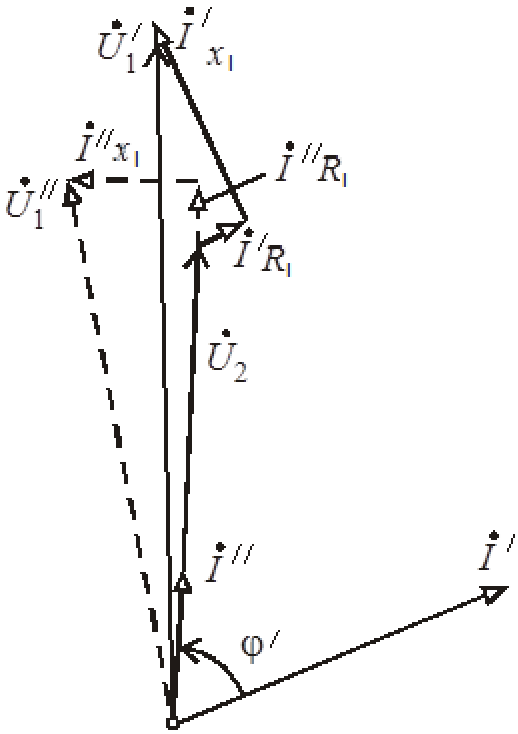


Fig. 4.9. Voltage at the beginning and the end of the line by crosscut compensation

4.2.2. Features of crosscut compensation

A schematic diagram of the capacitor is shown in Fig. 2.9 and 2.10, and the scheme of switching-on in the load circuit in Fig. 4.10.

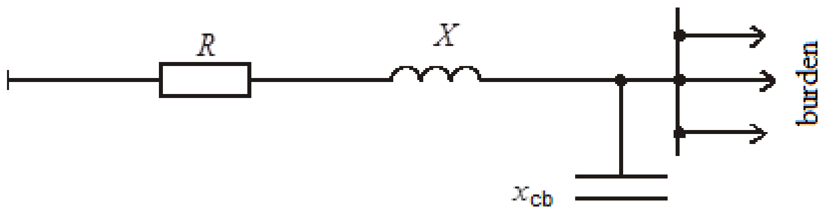


Fig. 4.10. A scheme of a capacity switching-on in the load circuit by crosscut compensation

Power of a single-phase capacitor with sinusoidal voltage which is attached to its terminals is determined by the relation:

$$Q = \omega \cdot C \cdot U^2 . \quad (4.16)$$

Power of a three-phase capacitor (which is connected to a triangle) is determined by the same formula. In this case, the U - this is line voltage, and C is the sum of capacities of all three phases of the capacitor. A three-phase power capacitor (which is connected by a spider) with equal capacities for all three phases is determined by the ratio:

$$Q = \frac{1}{3} \cdot \omega \cdot C \cdot U^2 \qquad (4.17)$$

where C is the sum of capacities of all three phases.

Then the coefficient of reactive power before compensation tgφ_1 = Q / P, and after compensation tgφ_2 = (Q $Q_{\text{БК}}$) / P. Since tgφ_2 < tgφ_1, то cosφ_2 > cosφ_1.

Power losses in the network before compensation

$$\Delta P_1 = 3 \cdot I^2 R = \frac{S^2}{U^2} \cdot R = \frac{P^2 + Q^2}{U^2} \cdot R,$$

and after compensation

$$\Delta P_2 = \frac{P^2 + (Q - Q_{\text{БК}})^2}{U^2} \cdot R.$$

Reduction in power losses after compensation is

$$\Delta P_1 - \Delta P_2 = \frac{P^2 + Q^2}{U^2} \cdot R - \frac{P^2 + (Q - Q_{\text{БК}})^2}{U^2} \cdot R = \frac{(2Q - Q_{\text{БК}})Q_{\text{БК}}}{U^2} \cdot R.$$

Full load before compensation $S_1 = P/\cos\varphi_1$ and after compensation

$S_2 = P/\cos\varphi_2$, that is $\dfrac{S_2}{S_1} = \dfrac{\cos\varphi_1}{\cos\varphi_2}$.

Since cosφ_2 > cosφ_1, then $S_2 < S_1$. Full load after compensation is reduced in inverse proportion to power factor after compensation.

Thus, crosscut compensation reduces the power losses while maintaining the value of transmission capacity or within the same loss, increases throughput ability of networks, increases the transmission power.

Voltage losses in the three-phase line can be determined by the relation:

- before compensation $\Delta U_1 = \sqrt{3} \cdot I (R \cdot \cos\varphi + X \sin\varphi)$ or after conversion

$$\Delta U_1 = \frac{P \cdot R + Q \cdot X}{U}; \qquad (4.18)$$

- after compensation $\Delta U_2 = \dfrac{P \cdot R + (Q - Q_{БК}) \cdot X}{U}$. (4.19)

In accordance with (4.13) and (4.14) reduction in voltage loss and, consequently, increase in voltage by a consumer

$$\Delta U_1 - \Delta U_2 = \frac{P \cdot R + Q \cdot X}{U} - \frac{P \cdot R + (Q - Q_{БК}) \cdot X}{U} = \frac{Q_{БК} \cdot X}{U}. \qquad (4.20)$$

Consumer load change causes voltage fluctuations in the line. Voltage drop at full load before compensation according to the relation (4.18) will be

$$\Delta U_1 = \frac{P \cdot R + Q \cdot X}{U},$$

and at partial load

$$\Delta U_1' = \frac{k \cdot (P \cdot R + Q \cdot X)}{U},$$

where k – a coefficient which takes into account the proportional decrease in the load.

Reduction in voltage losses at partial load

$$\Delta U_1 - \Delta U_1' = \frac{P \cdot R + Q \cdot X}{U} - \frac{k \cdot (P \cdot R + Q \cdot X)}{U} = \\ = (1 - k)\frac{P \cdot R + Q \cdot X}{U} = (1 - k)\Delta U_1 . \qquad (4.21)$$

Voltage drop at full load after compensation according to the relation (4.19) will be

$$\Delta U_2 = \frac{P \cdot R + (Q - Q_{БК}) \cdot X}{U},$$

and at partial load

$$\Delta U_2' = \frac{kP \cdot R + (kQ - Q_{БК}) \cdot X}{U}.$$

Reduction in voltage losses at compensation and partial load

$$\Delta U_2 - \Delta U_2' = \frac{P \cdot R + (Q - Q_{БК}) \cdot X}{U} - \frac{kP \cdot R + (kQ - Q_{БК}) \cdot X}{U} = \\ = \frac{P \cdot R + Q \cdot X - Q_{БК} \cdot X - kP \cdot R - kQ \cdot X + kQ_{БК} \cdot X}{U} = \\ = \frac{P \cdot R + Q \cdot X - k(PR + QX)}{U} = \frac{(1 - k)(P \cdot R + Q \cdot X)}{U} = (1 - k) \cdot \Delta U_1 \qquad (4.22)$$

According to the relation (4.22) if voltage is reduced, voltage fluctuations after compensation will be the same as before compensation (see relation (4.21)), but voltage level will be higher. It follows from the relation (4.20), since the decrease in voltage drop depends only on $Q_{БК}$ and X that are constant values for electrical systems.

Thus, crosscut compensation of the input voltage increases to a constant value in dependence of the capacity of installed capacitors and the reactance elements of the unit.

Example 4.3.

A high-voltage transmission line, voltage 6 kV, made of aluminum conductors 3x70 mm2 (running active resistance r_0 = 0,445 Ohm/km) length 2 km, feeds a load located at the end, load active capacity is 600 kW, reactive – 700 кVAr and full – 920 кVA. In order to increase cosφ, reduce power and voltage losses it is planned to connect a capacitor bank of 400 kVAr in parallel to the load.

To define how the specified parameters are changed for:

• A cable line: $x_{0\text{ кл}}$ = 0,08 Ohm/km;

• An air-line: $x_{0\text{ вл}}$ = 0,37 Ohm/km.

Solution

The power factor before the installation of a capacitor bank is

$$\cos\varphi_1 = \frac{P}{S_1} = \frac{600}{920} = 0{,}652$$

after installation is:

$$\mathrm{tg}\varphi_2 = \frac{Q_1 - Q_{\text{БК}}}{P} = \frac{700-400}{600} = 0{,}5 \text{ or } \cos\varphi_2 = 0{,}895.$$

After installation of a capacitor bank the line will transfer the total power

$$S_2 = \frac{P}{\cos\varphi_2} = \frac{600}{0{,}895} = 670 \text{ кVA.}$$

Thus, full load and current will decrease

$$\frac{S_1 - S_2}{S_1} \cdot 100\,\% = \frac{920-670}{920} \cdot 100\,\% = 27{,}2\%.$$

Active line resistance is equal to

$$R = r_0 \cdot l = 0{,}445 \cdot 2 = 0{,}89 \text{ Ohm.}$$

Power losses before compensation:

$$\Delta P_1 = \frac{\left(P^2 + Q_1^2\right) \cdot R}{U^2} = \frac{\left(600^2 + 700^2\right) \cdot 0{,}89}{6^2} \cdot 10^{-3} = 21 \text{ kW},$$

and after installation of capacitor banks will decrease:

$$\Delta P_2 = \frac{P^2 + \left(Q_1 - Q_{БК}\right)^2}{U^2} \cdot R = \frac{\left(600^2 + (700 - 400)^2\right) \cdot 0{,}89}{6^2} \cdot 10^{-3} = 11{,}1 \text{ kW},$$

that is decreased by

$$\Delta P_1 - \Delta P_2 = 21 - 11{,}1 = 9{,}9 \text{ kW}$$

Or

$$\Delta P_1 - \Delta P_2 = \frac{\left(2Q_1 - Q_{БК}\right) Q_{БК}}{U^2} \cdot R = \frac{\left(2 \cdot 700 - 400\right) 400 \cdot 0{,}89}{6^2} \cdot 10^{-3} = 9{,}9 \text{ kW}$$

Thus, the power losses have decreased from 21 to 11.1 kW, or

$$\frac{\Delta P_1 - \Delta P_2}{\Delta P_1} \cdot 100\,\% = \frac{21 - 11{,}1}{21} \cdot 100\,\% = 47\%$$

A cable line. The inductive resistance of the line is equal to

$X = x_{0\,кл} \cdot l = 0{,}08 \cdot 2 = 0{,}16$ Ohm.

Voltage losses before compensation:

$$\Delta U_1 = \frac{P \cdot R + Q_1 \cdot X}{U} = \frac{600 \cdot 0{,}89 + 700 \cdot 0{,}16}{6} = 108 \text{ V},$$

after installation of capacitor banks

$$\Delta U_2 = \frac{P \cdot R + (Q_1 - Q_{БК}) \cdot X}{U} = \frac{600 \cdot 0{,}89 + (700 - 400) \cdot 0{,}16}{6} = 97 \text{ V}$$

Decrease of voltage losses is

$$\Delta U_1 - \Delta U_2 = 108 - 97 = 11 \text{ V}$$

or

$$\Delta U_1 - \Delta U_2 = \frac{Q_{БК} \cdot X}{U} = \frac{400 \cdot 0{,}16}{6} = 11 \text{ V}$$

Voltage losses have decreased and, consequently, voltage has increased by

$$\frac{\Delta U_1 - \Delta U_2}{U} \cdot 100\% = \frac{108 - 97}{6000} \cdot 100\% = 0{,}18\% .$$

An air-line. The inductive resistance of the line is equal to

$$X = xal \cdot l = 0{,}37 \cdot 2 = 0{,}74 \text{ Ohm}$$

Voltage losses:

•before compensation

$$\Delta U_1 = \frac{P \cdot R + Q_1 \cdot X}{U} = \frac{600 \cdot 0{,}89 + 700 \cdot 0{,}74}{6} = 175 \text{ V}$$

• after compensation

$$\Delta U_2 = \frac{P \cdot R + (Q_1 - Q_{БК}) \cdot X}{U} = \frac{600 \cdot 0{,}89 + (700 - 400) \cdot 0{,}74}{6} = 126 \text{ V}$$

• losses reduction

$\Delta U_1 - \Delta U_2 = 175 - 126 = 49$ V or $\Delta U_1 - \Delta U_2 = \frac{Q_{БК} \cdot X}{U} = \frac{400 \cdot 0{,}74}{6} = 49$ V.

The voltage level is increased by

$$\frac{\Delta U_1 - \Delta U_2}{U} \cdot 100\% = \frac{175 - 126}{6000} \cdot 100\% = 0{,}81\% .$$

4.2.3. Installation sites of compensating devices

Fig. 4.11 shows a single line of a corporate network with possible installation sites of compensating devices. The border of balance inventory may be in the points 1-4. If compensating devices are installed at the border of balance inventory, the loss of active energy in a consumer network will not decrease, and network capacity will not increase. The only positive effect - partial voltage normalization.

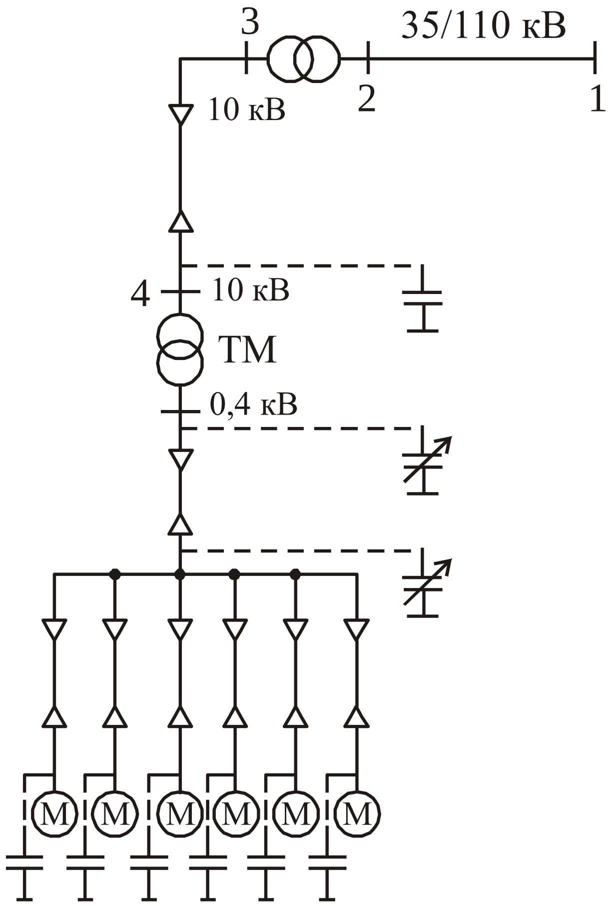
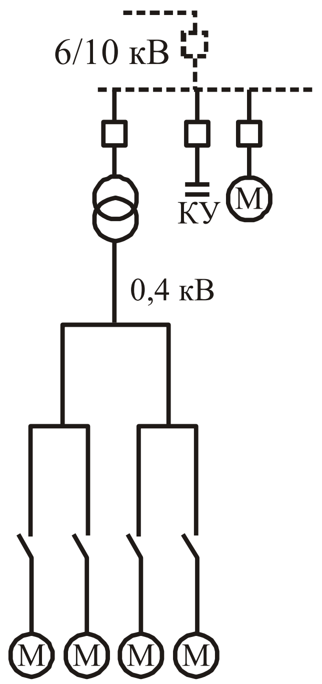


Fig. 4.11. A single-line diagram of the enterprise network

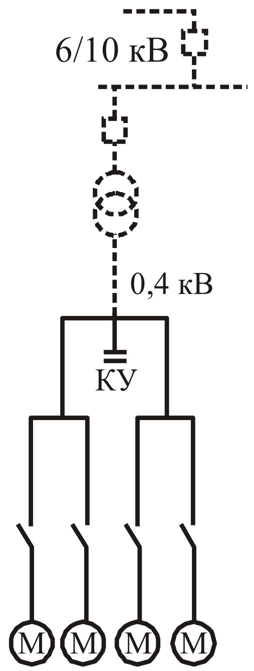
When you transfer installation sites of compensating devices from the border of balance inventory closer to the customer, there are network places unloaded from the flows of reactive power. In these places active power losses are reduced. It results in reduction of the payback period of compensating devices and more efficient electricity use.

For a consumer it is recommended to install compensating devices as far as possible from the boundaries of the balance section.

Selection of the site of the capacitor bank connection is based on the analysis of power supply scheme. In this case we consider several ways of reactive power compensation: central, group, individual (Figure 4.12) and combined - centralized in conjunction with a group or individual.



а



б

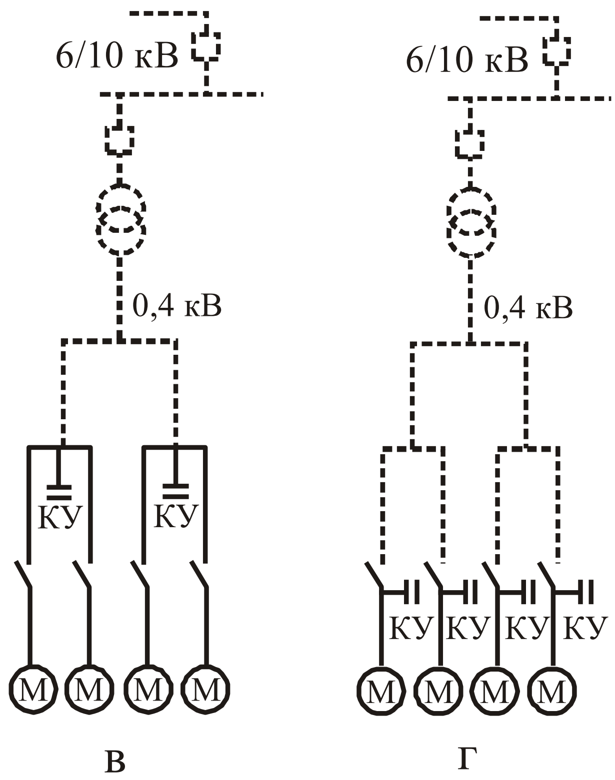


Fig. 4.12. Methods of reactive power compensation: a - central (high voltage), b - central (low voltage), c – group, d - individual, dashed line shows the parts of the network unloaded from the flows of reactive power

With a large number of consumers individual compensation is less effective than group compensation. Individual compensation is suitable for large power consumers with a small power factor and a large number of hours per year. The group compensation has a slightly greater compensation pay-back period. It does not require daily maintenance (manual switching on and off) through the use of plants with automatic control of reactive power. It is a preferred option of compensation.

4.3. Series capacity of reactive power

4.3.1. An equivalent circuit and vector diagrams of a direct compensation plant

Capacitors are connected to the net consistently with series compensation. A full-load line current runs through them.

A scheme of a direct compensation plant and its equipment is shown in Fig. 4.13. The equivalent circuit of the direct compensation plant, where in series with the line resistance R and x_L series capacity x_C is switched on is shown in Fig. 4.14a.

Current and voltage values on the sites of the series circuit are determined by the following:

$$I = \frac{U}{Z} = \frac{U}{\sqrt{R^2 + x^2}}; \ U_R = I \cdot R; \ U_L = I \cdot x_L; \ U_C = I \cdot x_C;$$

$$x = x_L + x_C; \ x_L = \omega L; \ x_C = 1/\omega C; \ \varphi = \text{arctg}\,\frac{x}{R}.$$

Depending on the relationship between the inductive and capacitive resistance vector diagram of R, L, C - the circuit has three types:

- inductive nature of the circuit when $x_L > x_C$, angle $\varphi = \text{arctg}\,\frac{x_L - x_C}{R}$, current *I* lags behind the voltage *U* (Fig. 4.14b);
- in capacitive circuits when $x_L < x_C$, angle $\varphi < 0$, current *I* lags the voltage *U* (Fig. 4.14c);
- When $x_L = x_C$ is equal, angle φ = 0, current *I* is in phase with the voltage *U*, and the voltage drop in the inductor $I \cdot x_L$ and capacity $I \cdot x_C$ are equal and compensated as they are mutually opposite in terms of their directions (Fig. 4.14d).

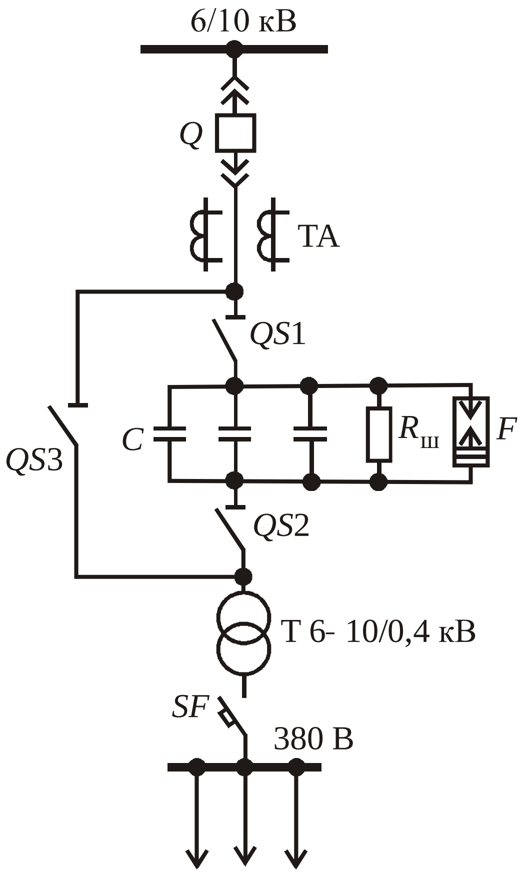


Fig. 4.13. A scheme of a direct compensation plant

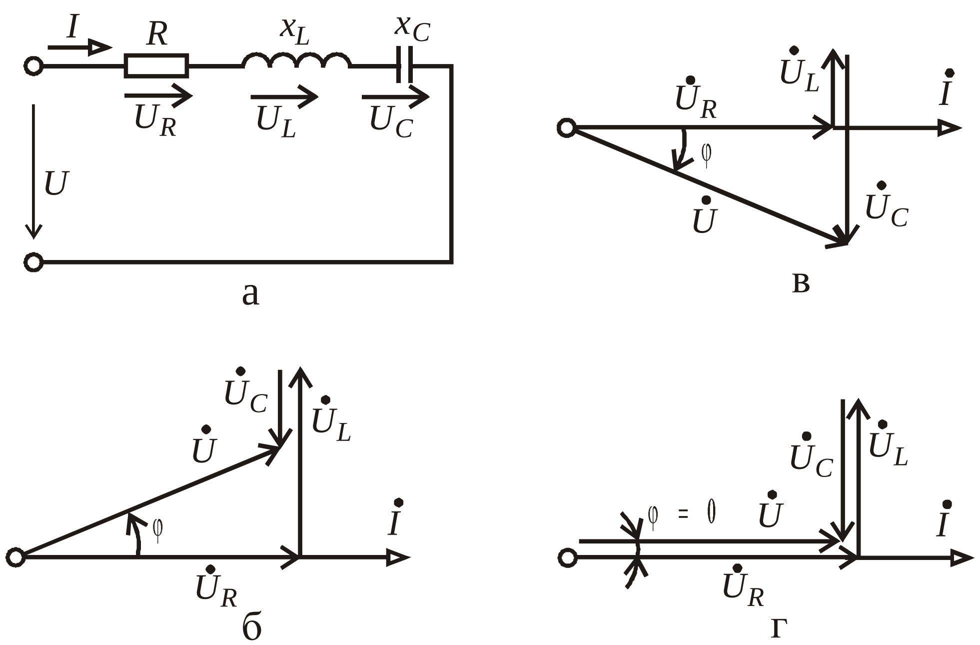


Fig. 4.14. The equivalent circuit and vector diagrams of series compensation devices

The latter case is called the resonance voltage. It is characterized by a maximum value of current in the circuit at U = const.

$$I = \frac{U}{\sqrt{R^2 + (x_L - x_C)^2}} = \frac{U}{R} \quad (4.23)$$

In power systems where resistance is small compared with the inductive transformer resistance, when voltages are different in a short-circuit mode short current can be very large and there is a chance of unacceptable increase in voltage on the inductance and capacitance: if $R \to 0$, $I \to \infty$, $U_L = U_C \to \infty$.

Therefore, capacity of direct compensation plants is chosen on the basis that the voltage on the capacitors $U_C = I \cdot x_C$ would be 5 -20% of nominal voltage. Capacitance of the direct compensation plant will compensate only part of reactive power losses equal to

$$Q_C = \omega C U_C^2$$

that is, the direct compensation plant is hardly a source of power.

Resistance $R_{ш}$ (Figure 4.13), which exceeds the resistance of the capacitor, restricts the resonance phenomena at direct compensation plants.

The main purpose of the series compensation - partial compensation of inductance sections in order to reduce their voltage losses. Influence of a direct compensation plant on the voltage ratio at the beginning of U1 and U2 at the end of the network section illustrates the vector diagram in Fig. 4.15.

If in a circuit there are only resistors $R_{л}$ and $x_{л}$ voltage U2 at the end of the line voltage is less than U1 at its beginning on the value of the voltage drop on the active $I_2 \cdot R$ and inductance $I \cdot x_L$ (solid lines in Fig. 4.15b), with $U_1 > U_2$, $\varphi_1 > \varphi_2$. If capacitance x_C is turned in series, there will be another component of the voltage drop $I_2 \cdot x_C$. Its direction in the diagram is opposite to inductive component $I_2 \cdot x_L$ (dashed lines in Fig. 4.15b). By x_L selection voltage difference U1 and U2 can be reduced. Direct compensation plant has the most significant impact on the voltage U2 if cosφ_2 is low.

Inductance compensation of circuit capacitance leads to higher short circuit currents in all elements of the transformer substation. And it is especially dangerous to direct compensation plant capacitors, as their voltage in case of led-through currents $\Delta U_C = I_{К3} \cdot x_C$ increases in proportion to the multiplicity of short-circuit current ($I_{К3}$ / $I_{ном}$).

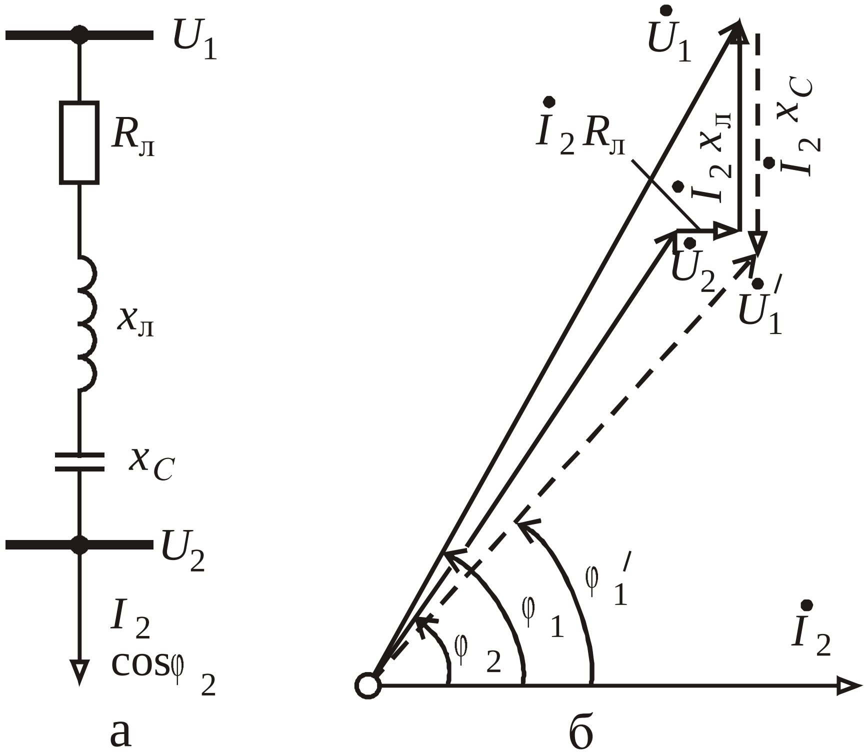


Fig. 4.15. Influence of series compensation on voltage ratio at the beginning and the end of the line: a - scheme of the load-carrying capacity, b - vector diagram

To protect the capacitor by bridging them with led-through currents spark arresters, for example, can be used (see Fig. 4.13). After firing spark arresters are temporarily removed from work by disconnectors QS1, QS2 and QS3 to recover their arresting properties.

The advantage of a direct compensation plant is its ability to stabilize the voltage if the load changes sharply. If, for example, $x_L = x_C$ current *I2* will increase dramatically, that change only the value of $I_2 \cdot R_л$ (Figure 4.15), which is unimportant at low values of resistance $R_л$. Increase in the voltage in the inductor $I_2 \cdot x_L$ is compensated by an increase in voltage drop in the capacitance ($I_2 \cdot x_C$). At the same time voltage U2 does not differ much from U_1'.

4.3.2 Features of series compensation

A scheme of the load capacity of the circuit in series compensation is shown in Figure 4.15a.

Capacitor power is determined by the ratio of:

$$Q_к = \omega C U^2 \qquad (4.24)$$

on the other hand

$$Q_к = I_к \cdot U \qquad (4.25)$$

Where $I_к$ –current flowing through the capacitor, from expression (4.25)

$$\boldsymbol{U = \frac{Q_к}{I_к}} \qquad (4.26)$$

By substitution in the formula (4.24) value U from expression (4.26), we get

$$Q_к = \omega C U^2 = \omega C \frac{Q_к^2}{I_к^2} = \frac{I_к^2}{\omega C} \qquad (4.27)$$

Current of a capacitor $I_к$ with series compensation is equal to total current of load line I_2 (Figure 4.15,a), that

$$Q_к = \frac{I_2^2}{\omega C} \quad (4.28)$$

Thus, power of capacitors with series compensation is a variable value and depends on current of load line.

Before compensation voltage losses in a three-phase line are calculated by the expression

$$\Delta U_1 = \frac{P \cdot R + Q \cdot X}{U} \quad (4.29)$$

After compensation

$$\Delta U_2 = \frac{P \cdot R + Q \cdot (X - X_{\text{БК}})}{U} \quad (4.30)$$

Reduction in voltage losses

$$\Delta U_1 - \Delta U_2 = \frac{P \cdot R + Q \cdot X}{U} - \frac{P \cdot R + Q \cdot (X - X_{\text{БК}})}{U} = \frac{Q \cdot X_{\text{БК}}}{U} \quad (4.31)$$

From the expression (4.31) it can be concluded that voltage level increases not by a constant value, as with series compensation, but by the value which can vary in proportion to a change of a variable reactive load line (as a constant value $X_{\text{БК}}$ for installed capacitors).

By selection of capacitors power we can achieve equal voltages in the supply and receiving end of the line. If in expression (4.30) value ΔU_2 equals to zero, that

$$P \cdot R + Q \cdot (X - X_{\text{БК}}) = 0 \text{ and } X_{\text{БК}} = \frac{P \cdot R}{Q} + X$$

that is $X_{\text{БК}} > X$.

Let’s consider how load change influences voltage losses in the line:

Before compensation voltage losses are:

- At full load $\Delta U_1 = \frac{P \cdot R + Q \cdot X}{U}$;
- At partial load $\Delta U_2' = \frac{к \cdot (P \cdot R + Q \cdot (X - X_{\text{БК}}))}{U}$; where k – a coefficient which takes into account proportional voltage decrease
- Decrease in voltage losses

  $$\Delta U_2 - \Delta U_2' = \frac{P \cdot R + Q \cdot (X - X_{\text{БК}})}{U} - \frac{к \cdot (P \cdot R + Q \cdot (X - X_{\text{БК}}))}{U} = = (1 - к)\frac{P \cdot R + Q \cdot (X - X_{\text{БК}})}{U} = (1 - к)\Delta U_2;$$

  Voltage losses with regard to series compensation

- At full load $\Delta U_2 = \dfrac{P \cdot R + Q \cdot (X - X_{БК})}{U}$;
- At partial load $\Delta U_2' = \dfrac{к \cdot (P \cdot R + Q \cdot (X - X_{БК}))}{U}$;
- Decrease in voltage losses

$$\Delta U_2 - \Delta U_2' = \frac{P \cdot R + Q \cdot (X - X_{БК})}{U} - \frac{к \cdot (P \cdot R + Q \cdot (X - X_{БК}))}{U} =$$

$$= (1 - к)\frac{P \cdot R + Q \cdot (X - X_{БК})}{U} = (1 - к)\Delta U_2$$

As $\Delta U_2 < \Delta U_1$, and (1 к)- a constant value, that

$$\Delta U_2 - \Delta U_2' < \Delta U_1 - \Delta U_1' \quad (4.32)$$

The expression (4.32) makes it possible to conclude that if the load is changed voltage fluctuations in the line with series compensation will be lower.

If we achieve voltage equality by the selected resistances on supply and receiving ends of the line ($\Delta U_2 = 0$), than for any load change there will be no change in voltage on supply and receiving ends of the line – voltage remain stable:

$$\Delta U_2 - \Delta U_2' = (1 - к)\Delta U_2 = 0$$

A degree of system stability for other conditions being equal is inversely proportional to a value of systems reactive resistance. Since with series compensation reactive line resistance as well as systems resistance reduces, but in this case stability of the system increases. Series compensation can increase systems stability and also increase voltage level and reduce voltage fluctuations, also series compensation can solve problems associated with long-distance transmission lines.

Disadvantages of series compensation:

- A new element is implemented in a system network (it consists of great number of capacitors), which must have the same level of reliability in operation as other elements
- Working conditions for capacitors with series compensation are heavier than for shunt compensation: in case of short circuit, voltage on capacitors terminals increases; it requires interference of a protection device, in particular, bridging capacitor banks by the arresters.

- Bridging of a direct compensation plant puts it out of action at the moment when power supply system needs it.

A valuable feature of series compensation is its property to stabilize voltage when a sharp change load occurs.

Example 4.4

Determine the number and total power of capacitor banks implemented in the network in series and designed for voltage regulation. In case of maximum load, voltage losses should be reduced by 50%.

Network voltage 3 kV. Active resistance of the network is R=4 Ohm. Reactive resistance of the network is X_L = 4 Ohm . Transmitted power via the line is P=100 kW. Load power factor equals to 0.8.

Check the possibility of using capacitors with operating voltage 600 V, power 8,5 kVAr , capacitance 75 microfarad.

Solution:

By using initial data and expressions (4.29), (4.30), we can determine required capacitance and reactive capacitors resistance.

Voltage losses before compensation

$$\Delta U = \frac{P \cdot R + Q \cdot X_L}{U_{\text{ном}}} = \frac{100 \cdot 4 + 75 \cdot 4}{3}$$

Where, $Q = P \cdot \text{tg}\varphi = 100 \cdot 0{,}75 = 75$ kVAr

Voltage losses after compensation

$$0{,}5 \cdot \Delta U = \frac{P \cdot R + Q \cdot (X_L - X_C)}{U_{\text{ном}}}$$

By adding numerical values in the last formula we get,

$$0{,}5 \cdot \frac{100 \cdot 4 + 75 \cdot 4}{3} = \frac{100 \cdot 4 + 75(4 - X_C)}{3}$$

Capacity reactance will be

$$X_C = \frac{350}{75} = 4{,}67 \text{ Ohm}$$

Required capacitance of a capacitor bank for one phase can be determined from the expression

$$X_C = \frac{1}{\omega \cdot C}$$

That is, $C = \frac{1}{\omega X_C} = \frac{10^6}{314 \cdot 4{,}67} = 682$ microfarad

Taking into account the capacitance of one capacitor C_0 = 75 microfarad the required number in parallel connection can be calculated

$$n = \frac{C}{C_0} = \frac{682}{75} = 9,\ n_\Sigma = 3 \cdot n = 3 \cdot 9 = 27$$

Operating current of one phase of the transmission line

$$I_{раб} = \frac{P}{\sqrt{3} \cdot U_{ном} \cdot \cos\varphi} = \frac{100}{\sqrt{3} \cdot 3 \cdot 0{,}8} = 24$$

Current in each branch of the capacitor bank

$$I_C = \frac{I_{раб}}{n} = \frac{24}{9} = 2{,}67$$

Resistance of each capacitor

$$X_{C0} = \frac{1}{\omega C_0} = \frac{10^6}{314 \cdot 75} = 42{,}5 \text{ Ohm}$$

Capacitors voltage in operating mode

$$U_C = I_C \cdot X_{C0} = 2{,}67 \cdot 42{,}5 = 113 \text{ V}$$

Total capacity of the capacitor bank

$$Q_C = 3 \cdot I_{раб}^2 \cdot X_C = 3 \cdot 24^2 \cdot 4{,}67 \cdot 10^{-3} = 8{,}05 \text{ kVAr}$$

According to the calculations there is no need to install capacitors (intended for network operating voltage) for compensation of inductive resistance. Voltage between their armatures is not determined by operating voltage but by multiplication of operating current by resistance. If in 10 kV crosscut line, for example, lower voltage capacitors are switched, the whole bank should be safely insulated.

If in the example 4.4 we consider a possibility of a network accident due to a short circuit current of a two or three-fold value, than voltage of capacitors will be kept in working range. Capacitors banks with series compensation should be calculated in terms of power transmitted through the line.

Example 4.5

An overhead transmission line 24 km long has an active resistance of 7,44 Ohm, and reactive resistance of 9.9 Ohm. Transmitted active power is about 10000 kW, reactive 9000 kVAr, and total power is 13450 kVA, the load is concentrated at the end of the line. Voltage at the beginning of the line is $U_a = 36$ kV, and at the end of the line $U_b = 31{,}5$ kV. We need to calculate required power for capacitor banks with series compensation (single-phase КПМ-0.6-50-1 capacitors), so that voltage losses with full load at the end of the line will be $\Delta U_2 = 0{,}5$ kV after compensation. In case of shunt compensation implementation the result must be compared with the power of the capacitor bank.

Solution:

Line voltage losses before compensation

$$\Delta U_1 = U_a - U_b = 36 - 31{,}5 = 4{,}5 \text{ kV}$$

Defined reduction of voltage losses

$$\Delta U_1 - \Delta U_2 = 4{,}5 - 0{,}5 = 4 \text{ kV}$$

From the expression $\Delta U_1 - \Delta U_2 = \frac{Q \cdot X_{\text{БК}}}{U_a}$ (see relationship (4.31)) we find $X_{\text{БК}}$

$$X_{\text{БК}} = \frac{(\Delta U_1 - \Delta U_2) \cdot U_a}{Q} = \frac{4 \cdot 36}{9000} = 16 \text{ Ohm}$$

Technical information of single-phase capacitors КПМ 0,6501 with series compensation:

$Q_{к1}$ = 50 kVAr-power of one capacitor

U=0,6 kV-operation voltage

C=442 microfarad- capacitance of one capacitor

$$I_{к1} = \frac{Q_{к1}}{U} = \frac{50}{0,6} = 83 \text{ A}$$

$$X_{к1} = \frac{1}{\omega C} = \frac{1}{314 \cdot 442 \cdot 10^{-6}} = 7,2 \text{ Ohm}$$

Next we are going to determine a required number of in series capacitors connected to one phase:

$$n = \frac{I}{I_{к1}} = \frac{S}{\sqrt{3} \cdot U_b \cdot I_{к1}} = \frac{13450}{\sqrt{3} \cdot 31,5 \cdot 83} = 2,97$$

Find n=3

Then, we are going to calculate a required number of in series capacitors connected to one phase:

$$m = \frac{X_{БК}}{X_{к1}/n} = n\frac{X_{БК}}{X_{к1}} = 3\frac{16}{7,2} = 6,67$$

Find n=7

Total number of capacitors connected to one phase

$$n \cdot m = 3 \cdot 7 = 21$$

entire bank

$$3 \cdot n \cdot m = 3 \cdot 21 = 63$$

Overall power

$$Q_{БК} = 3 \cdot n \cdot m \cdot Q_{к1} = 3 \cdot 3 \cdot 7 \cdot 50 = 3150 \text{ kVar}$$

Total capacity reactance of one phase will be:

$$X_{БК} = \frac{m \cdot X_{к1}}{n} = \frac{7 \cdot 7,2}{3} = 16,8 \text{ Ohm}$$

Let's check the value of a decrease in voltage drop:

$$\Delta U_1 - \Delta U_2 = \frac{Q \cdot X_{БК}}{U_a} = \frac{9000 \cdot 16{,}8}{36} \cdot 10^{-3} = 4{,}2kV$$

instead of defined 4 kV.

We obtained capacitors of higher power $Q_{БК}$ = 3150 kVAr as a result of a rather harsh environment of voltage loss reduction and voltage maintenance at the required level.

If the power of the capacitor bank is $Q_{БК} = 3nmQ_{к1}$ = 2250 kVar, then for n = 3

$$m = \frac{Q_{БК}}{3 \cdot n \cdot Q_{к1}} = \frac{2250}{3 \cdot 3 \cdot 50} = 5$$

$$X'_{БК} = \frac{m \cdot X_{к1}}{n} = \frac{5 \cdot 7{,}2}{3} = 12 Ohms$$

$$\Delta U_1 - \Delta U_2 = \frac{Q \cdot X'_{БК}}{U_a} = \frac{9000 \cdot 12}{36} \cdot 10^{-3} = 3kV$$

$$\Delta U_2 = \Delta U_1 - 3 = 4{,}5 - 3 = 1{,}5kV$$

$$U_2 = U_a - \Delta U_2 = 36 - 1{,}5 = 34{,}5kV$$

Next we are going to define capacitors power for a shunt compensation from the following formula

$$\Delta U_1 - \Delta U_2 = \frac{Q_{БК} \cdot X}{U_a}$$

where X - line reactance (see the conditions given in the example).

Bank capacity will be

$$Q_{ВК} = \frac{(\Delta U_1 - \Delta U_2) U_a}{X} = \frac{4 \cdot 36}{9{,}6 \cdot 10^{-3}} = 15000\ kVAr$$

Thus, shunt compensation for the conditions given in the example, requires capacitors power that is almost five times higher (1500 / 3150) than series compensation.

For shunt compensation when $\Delta U_1 - \Delta U_2 = 3$ kV a capacitor bank will require power of

$$Q'_{БК} = \frac{(\Delta U_1 - \Delta U_2)U_a}{X} = \frac{3 \cdot 36}{9{,}6 \cdot 10^{-3}} = 11250\ kVAr$$

Table 4.2 shows voltage fluctuations for different load lines

1 - before compensation $\Delta U_1 = U_a - U_b = 4{,}5$kV;

2 – as a result of series compensation $\Delta U_1 - \Delta U_2 = 4{,}2$ kV;

3 – as a result of series compensation $\Delta U_1 - \Delta U_2 = 3$ kV;

Table 4.2

Voltage losses before and after series compensation (related to 4.5 example)

№	Power of a capacitor bank, series compensation, kVAr	Name of variables	Voltage losses, kV, when line is loaded, %			
			100	75	50	25
1	Without compensation	$\Delta U_1 = U_a - U_b$	4,5	3,38	2,25	1,13
2	3150	$\Delta U_1 - \Delta U_2$ ΔU_2	4,2 0,5	3,15 0,23	2,1 0,15	1,05 0,08
3	2250	$\Delta U_1 - \Delta U_2$ ΔU_2	3,0 1,5	2,25 1,13	1,5 0,75	0,75 0,38

As mentioned above, voltage fluctuations as a result of series compensation will be lower than without compensation. Voltage fluctuations depend on compensation ratio.

4.3.3. A simplified method aimed at determining capacitors reactance of direct compensation plants **[5]**

The main parameter of a direct compensation plant is capacitors reactance X_C. Choice of capacitors reactance must be based on a value of voltage increase α. Vector diagram illustrating a direct compensation plant (Fig. 4.16) allows us to derive the following equation

$$\alpha = \frac{U_d}{U_b} = \sqrt{3}\frac{X_C \cdot I}{U_b}\sin\varphi_d + \sqrt{1 - 3\left(\frac{X_C \cdot I}{U_b}\right)^2 \cos^2\varphi_d} \quad (4.33)$$

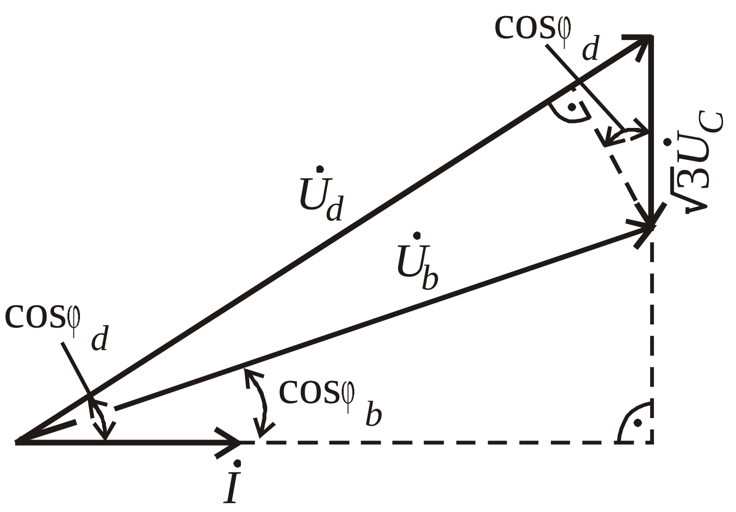


Fig. 4.16. Vector diagram illustrating a direct compensation plant

where U_d - output voltage; U_b – phase-to-phase input voltage; X_C - resistance; I - load current; φ_d – power-factor angle.

From the equation (4.33) we can define conditions for X_C, so that when φ_d, I and U_b are defined, voltage ratio α would have a maximum value. In order to do this we need to solve the equation

$$\frac{d\alpha}{dX_C} = \sqrt{3}\frac{I}{U_b}\sin\varphi_d - 3\frac{\frac{X_C \cdot I^2}{U_b^2}\cos^2\varphi_d}{\sqrt{1 - 3\left(\frac{X_C \cdot I}{U_b}\right)^2 \cos^2\varphi_d}} = 0$$

And we can find a required condition for the capacitance of a direct compensation plant

$$X_C = \frac{U_b}{\sqrt{3} \cdot I} \operatorname{tg} \varphi_d \quad (3.34)$$

When value is X_C, defined by (4.34), the maximum value of voltage ratio is acquired

$$\alpha_{\max} = \frac{1}{\cos \varphi_d} \quad (3.35)$$

The equation (4.33) proves that the direct compensation plant has some properties: relative voltage increase depends largely on the load type that is defined by current intensity and power factor load and their bilateral change over a time period. Relative voltage increase goes up along with current load and a decrease in power factor. With the increase in capacitance, increases α and under the condition (4.34) it can reach the maximum value. Meanwhile, the maximum value of a relative voltage increase depends on the load power factor; it increases while the value of load power factor decreases.

In order to find a solution to the equation (4.33) in Fig. 4.17 a nomograph nomogram is depicted. The nomograph nomogram considers an example of determining the resistance of the direct compensation plant with increasing voltage U_b = 10 kV at 10%, that is α = 1,1, with a power factor load cosφ = 0,8 and a current of I = 30 A. Resistance value is X_C = 35.8 Ohms.

Adjustment of the direct compensation plant to its maximum increase in voltage mode (the equation (4.34)) is not always possible as a result of induction motors and ferroresonance self-excitation.

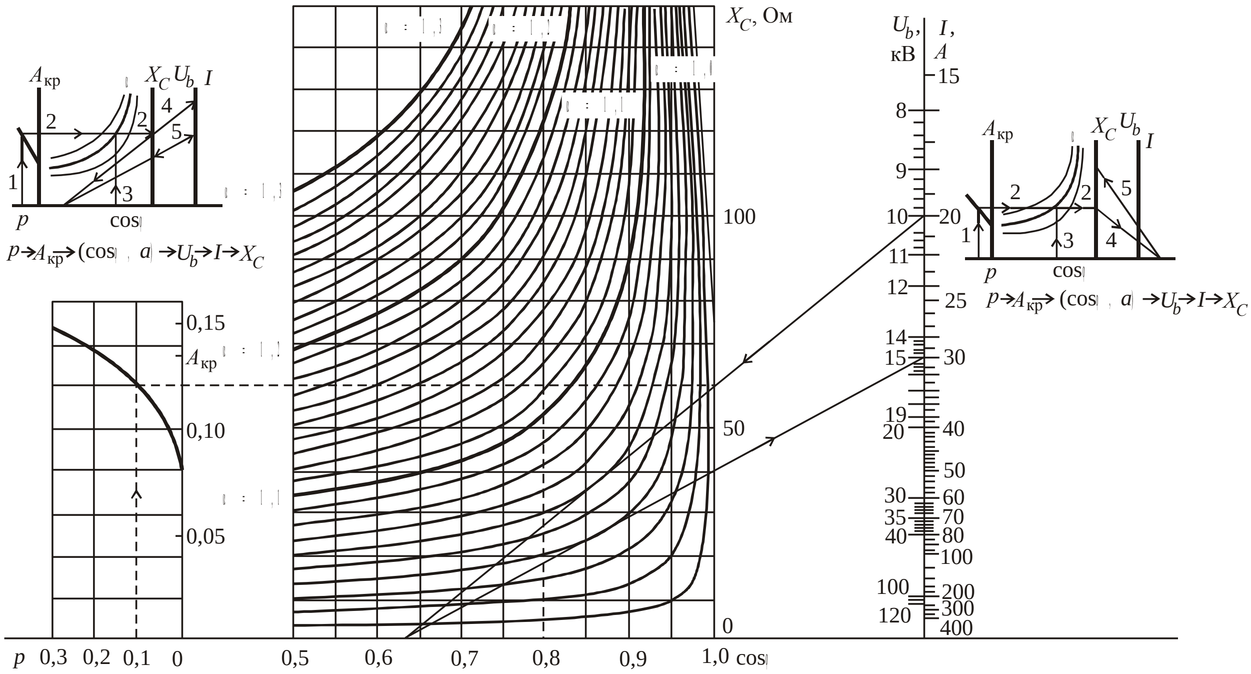


Fig. 4.17. Nomogram aimed at determining parameters of direct compensation plant: 1 - 5 - sequence of actions aimed at X_c assignment

Fig. 4.16 shows the connection between load power factor before and after the direct compensation plant, which is determined by the correspondence

$$\cos\varphi_b = \alpha \cos\varphi_d$$

The direct compensation plant improves the power factor if it increases the voltage.

To provide more accurate X_C definition it is necessary to consider the effect of unwanted modes, series and shunt components of voltage drop in the network and static characteristics of consumers.

4.3.4. Unwanted modes in power systems with direct compensation plants

Cost-effective and stable operation of a direct compensation plant in high voltage networks depends on the proper choice of capacity reactance. With an increase in this parameter increases the output voltage. Therefore, it is appropriate to increase capacity reactance at low network voltage.

Adjustment of a direct compensation plant to the maximum voltage mode (according to the equation (4.34)) is not always possible as a result of parametric resonance in induction motors. It seems to be also impossible as a result of ferromagnetic subharmonic oscillations.

Currents of induction motors containing lower harmonics, under parametric resonance conditions, cause a resonance between a direct compensation plant and circuit and motor inductance. It occurs at a frequency that is below the frequency of the power system. Under these conditions the motor rotates at low speed but in accordance with a resonance frequency. At the same time the motor operates as a converter, it consumes energy at the frequency of electric power system and gives it back to the network at a resonance frequency. This mode is accompanied by vibrations and high current in the motor and may have periodic voltage fluctuations.

Ferromagnetic phenomena of subharmonic oscillations are basically observed when an unloaded transformer is switched on or when a large increase in voltage occurs. If the series-connected capacitance has a sufficient value, the transformer core is saturated and there are considerable amplitude subharmonics with fractions (1:2, 1:3 and so on), the ratio of their frequencies to the principal one. This phenomenon is accompanied by an increase in current and voltage; it can lead to a line or transformer cut-off.

Shunt resistance, short-circuiting of capacitors, decrease in resistance can eliminate or limit unwanted modes.

Switching-on of shunt resistance. Active resistance is switched-on in series with capacitors. The main disadvantage of the method - energy losses in shunt resistance and decrease in the effect of voltage increase by a direct compensation plant .

In some cases *switching-on of resistance is enough* in order to eliminate unwanted modes. Such resistance is three times higher than capacitor resistance. Electricity losses in such plant will be notable. The method will be applicable if elimination of unwanted modes in the network can increase shunt resistance 10 – 20 times compared with X_C.

It is also possible to switch on a saturable reactor in series with a shunt resistor. A saturable reactor will be magnetized and open a way for an active resistance in case of subharmonic current components.

Capacitors shorting. Capacitors are automatically shunted by protection devices that react to subharmonic current components. After a while a device is automatically reclosed. It is assumed that during the pause motors will gain rated speed. This method is recommended for power supply systems with an essential service and large transfer capacity since it requires additional expenses for a switch and a special filter protection.

Decrease in resistance of a direct compensation plant. The method provides a reduction of X_C with a simultaneous decrease in breakdown voltage of an electric surge arrester. Reduction of breakdown voltage in electric surge arresters provides both capacitor shunting in case of unwanted modes with a significant voltage amplitude and thereby contributes to their elimination.

Unwanted modes are determined by load ratio share (lighting and power) that are in series with a motor. If there are other engines connected to the same direct compensation plant, the risk of parametric resonance is reduced. If there is a parallel light load, motors will not be affected by parametric resonance.

4.3.5. Selecting the main circuit and protection of a direct compensation plant.

The main circuit. The main circuit determines the method of activation and deactivation of capacitors in the network. A simplified circuit is used when a high voltage line is deactivated in order to check the capacitors. Basically, the lines are short distance dead-end feeders with capacitors which installed capacity is of a few hundred kVAr. A circuit with three disconnect switches is used when the line deactivation is unacceptable for *a direct compensation plant* maintenance. One of the disconnect switches is used to shunt capacitors. Two other capacitors are used to disconnect capacitors (Fig. 4.13). Such circuit fully meets operation conditions. It is more beneficial to choose a capacitor with a rated voltage that is calculated by the maximum current of normal operating conditions of a line. It is also beneficial to use surge protection from short circuit instead of installing capacitors without any protection and to choose capacitors in terms of their short circuit currents. Rated voltage of capacitors is selected according to expected load lines multiplied by a storage coefficient $\kappa_{зап}$ (approximately $\kappa_{зап}$ = 1.1), taking into account further load growth.

$$U_{ном\ C} \geq \kappa_{зап} \cdot I_{нагр} \cdot X_C \quad (4.37)$$

Terminal voltage may exceed proof voltage in case of short circuit of capacitors. Short-circuits can cause a breakdown or reduce service life of capacitors. High-speed protection is used to prevent such faults.

Protection devices of a direct compensation plant. Protection devices must meet the following requirements:

• must be easy for a setup and stable to voltage in $(1{,}5 - 3{,}5) \cdot U_{ном\ C}$ interval; setting and operation conditions must be easily checked and changed;
• quick operation time in case of short circuit currents and quick capacitors switching-on in case of short-circuit current decrease to a value of line operating current;
• resistance to short circuit currents taking into account their time of action;
• simplicity and convenience in operation;
• possibility of outdoor installations;
• low cost;
• plant switching-off in case of self-excitation and ferromagnetic subharmonic oscillations;
• protection from overloads;
• protection from voltage asymmetry of a capacitor bank;
• protection against short-circuits of the platform used for capacitors installation;
• capacitors protection in case of malfunctions in protective devices.

Protection devices can be divided into two groups depending on the application of a direct compensation plant. The first group consists of complex and expensive protection devices applied in large power plants, designed to enhance stability of power lines and to redistribute loads between parallel lines. The second group includes protection devices of low-power plants; these devises are used for voltage regulation in distribution networks and in case of short-circuit currents. Such protection devices are not expected to provide reliable operation.

The simplest protection of a direct compensation plant is the protection of the feed line and its switch (Figure 4.18a). In this case nominal voltage of a plant capacitors is chosen on the basis of maximum short-circuit current for capacitors. The choice is based their ability to overload voltage and load curve line. Such a solution may be the best in case of small short-circuit current rates compared to the maximum operating current of a line and low power of capacitors.

Protection circuit where nonlinear resistance is switched on in series with capacitors (Fig. 4.18b), for example, a saturable core reactor is not widely used since resonance phenomena can occur in a circuit.
With a power of several hundred kVAr a circuit with shunt arresters and damper resistance is applied (Fig. 4.18v). Low-power plants can do without damping resistance.
Fig. 4.18г shows a protection circuit with low rated voltage. Autotransformer 8 increases the voltage to a trip of the auxiliary arrester 6. At the same time capacitor 7 discharges through a saturable core reactor 5. If there is additional high-voltage, arrester breakdown can be observed 3. The arrester shunts the capacitor battery of a direct compensation plant. In this protection circuit the arrester 3 must withstand short-circuit currents up to the moment when protection of a feed line is off.

At average power plants (1-2 MVAr) a protection circuit with arresters is applied. The arrester is later shunted by a switch 9 or a contactor (Fig. 4.18д). An electric surge arrester and a shunting switch can be of lightweight construction. Voltage transformers 10 are switched on in series with capacitors. Voltage transformers can measure voltage, control capacitors by measuring the symmetry of their voltage and also voltage transformers can provide capacitors discharge when the plant is off.

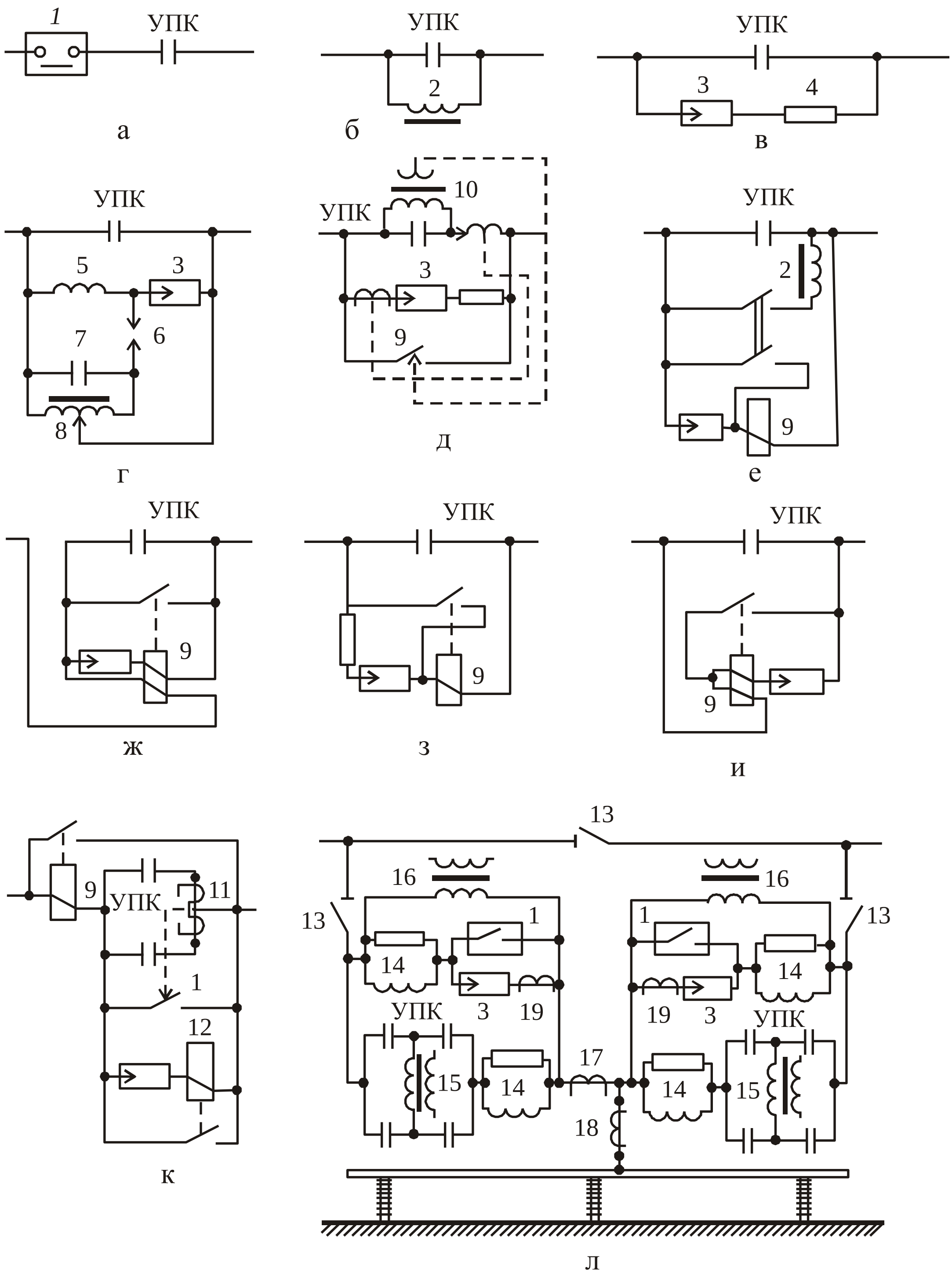


Fig. 4.18. Protection circuit of a direct compensation plant: 1 – switch 2 – saturable core reactor 3 - arrester, 4 - damper resistance; 5 - coil 6 - auxiliary arrester 7 - capacitor 8 - autotransformer 9 - contactor, 10 - voltage transformer, 11 – differential protection; 12 - contactor for overvoltage protection, 13 – disconnecting switch, 14 - damper circuit with a reactor, 15 – transformer for differential protection, 16 - transformer to protect against subharmonic oscillation and unbalance, 17 - transformer to switch on protection devices against overload

and battery charge; 18 - transformer for circuits control of insulation platforms 19 - transformer for circuits control of arrester operation.

Protection circuits of direct power plants in Fig. 4.18е-4.18и are a modification of the circuit in Fig. 4.18д. The peculiarity of the circuit in Fig. 4.18е – circuit with a choke 2 that shunt capacitors of a direct compensation plant, about 90% of short-circuit current flows through it and the winding of the contactor 9 can be reduced and with a decrease in short-circuit current to a value of the normal operating current line the contactor is switched off.

In Fig. 4.18ж choke coil is replaced by an extra one in the contactor, the coil is always connected to the line. Disadvantage of the circuit shown in Fig.4.18ж is that the contactor shunts the direct compensation plant in cases when short-circuit is eliminated before operation of protection devices. With the use of a disconnecting switch there should be a short line cut-off or a line shunt of a direct compensation plant to start up capacitors. This problem is eliminated in the circuit in Fig. 4.18и where the contactor winding 9 is composed of two parts. Only a part of winding is shunted when the contactor starts up. The winding is chosen so that the contactor is not constantly switched on, if the current does not reach dangerous values for capacitors.

In the protection circuit in Fig. 4.18к the contactor 9 is activated in case of overloads, the contactor 12 – in case of surge voltage, in addition it provides differential protection of capacitors. Switch 1 and contactor 12 are made with a special drive that work is based on the thermal effect of current. Short-circuit current heats a special mechanism where the pressure of the evaporated liquid increases as a result of temperature rise. After that the switch is activated and it shunts the capacitor bank of a direct compensation plant. After cooling off appeared vacuum turns off the switch. Time-current switch characteristic is consistent with the protective arrester time-current characteristic.

Fig. 4.18л shows one of the protection circuits of a high-power direct compensation plant. It designed to increase the capacity of transmission lines. Capacitor voltage is the main factor that determines the number of series-connected capacitor sections of a direct compensation plant. This circuit has two sections which are mounted on a common platform that has ground insulation against line voltage. Reactors provide a capacitor discharge during automatic reclosing. Platform power cut-off leads to a bridging of the plant. A direct compensation plant unsets automatically when the platform power is on again. Information about condition of the equipment platform, current and voltage levels is transmitted through the cables.

Thus, the following conclusion can be made:
• Protection of a direct compensation plant is based on the application of the arrester that starts up at a certain predetermined voltage and shunts capacitors; the arrester must withstand short-circuit current and capacitor discharge current for a period of time determined by a cut-off of a feed line or switching-on of a shunt switch;
• Protection includes capacitors and a special shunt switch that shunts automatically as an arrester; as a result arc in the arrester is extinguished and the arrester is no longer under the action of short-circuit current;
• Protection against subharmonic oscillations, differential protection of capacitors can be applied only to high power direct compensation plants.
Selection of a protection circuit for a direct compensation plant. It is necessary to take into account the above mentioned requirements while selecting a circuit for a direct compensation plant. Selection can be based only on the first six requirements taking into account that the capacity of distribution networks of a direct compensation plant is 1-2 MVAr. The seventh and the eighth requirements can be partially met if an appropriate set up of the arrester is provided and parameters of a direct compensation plant are followed.

Such requirements are satisfied by the protection circuit shown in Fig. 4.13. It fully meets the requirements of efficiency and reliability.
Arresters. Arresters with graphite and the ring-shaped electrodes, magnetic and air-blast and also caking dischargers are applied to protect devices of a direct compensation plant. The most widely used switches consist of ring electrodes with rotating arc stabilization (Fig. 4.19).
An arrester is made of copper. In the lower part there is a spark gap a_1; it is designed for voltage breakdown that is equal to 2-3.5-fold capacitor voltage at the maximum operating mode of a line. Set up of a spark gap takes place on schedule (see Figure 4.20). Arcing takes place if arrester voltage exceeds breakdown voltage of a spark gap. Due to electric field and thermal effect it rises to a ring-shaped electrode and rotates there until the line is tripped. The arc is extinguished after the line is tripped and the arrester is ready to operate.

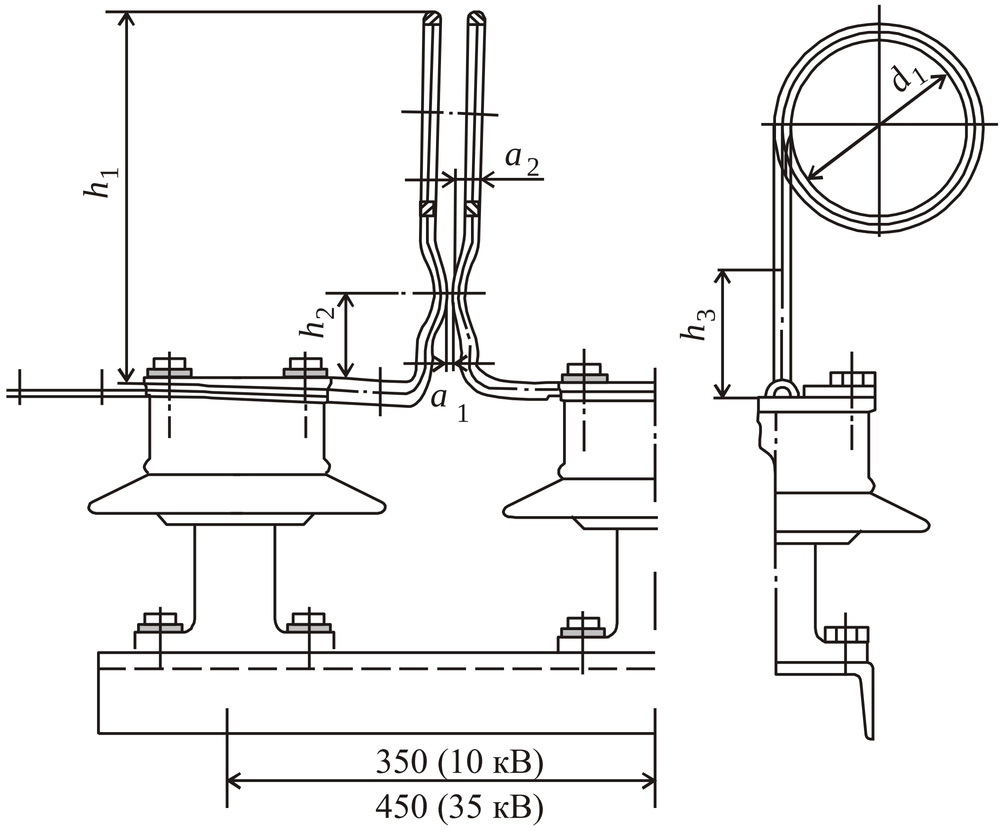


Fig. 4.19 Ring arrester

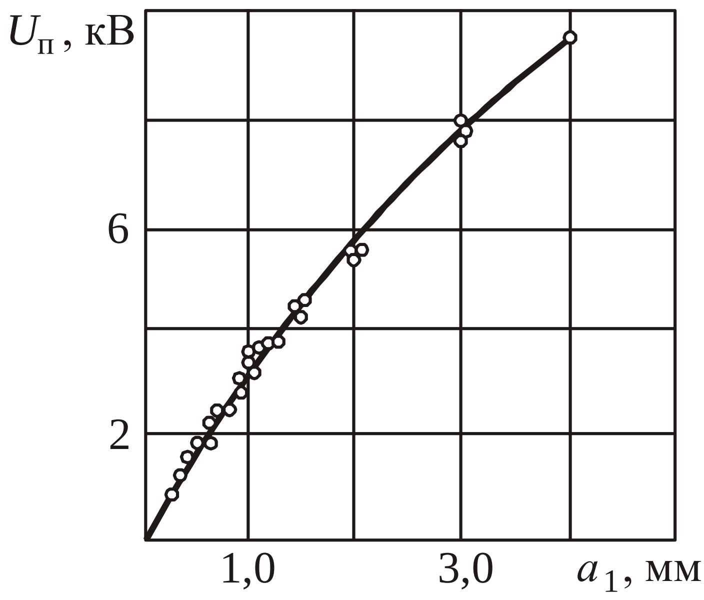


Fig. 4.20 Characteristic curve of breakdown voltage on the size of a spark gap

Electrodes with a sector shape cross-section are mounted with sharp edges facing each other. In this case arc is directed, accelerated and improved; burning and melting of electrodes are reduced. In case of short-circuit currents up to 6 kA electrodes are burned slightly since arc velocity reaches 125 m/sec. In case of short-circuit currents up to 6 kA electrodynamic force affects the arresters. It requires a firm attachment of electrodes to the support insulators.

4.4. Comparison of shunt and series compensations

Shunt compensation is widely spread and used to improve power factor of industrial enterprises. This was made possible due to the simplicity of the device, protection, control, maintenance and operation, power splitting of capacitor banks, their installation at any place of network devices where it is economically profitable due to technical and operational conditions.
Shunt compensation increases voltage level. However, when the load changes, voltage fluctuations remain the same as they were before the compensation. In the hours of minimum system load terminal voltage of capacitors can be higher than rated. Voltage deviation increases with the coincidence of a minimum load of the enterprise with a minimum load of the system. In such situations it is necessary to take measures for its reduction. One of the measures is to regulate the power of capacitors connected to the network automatically or by operating personnel, by total turning off of the capacitor bank or partially on a predetermined schedule.
Intermittent and shock loads cause voltage fluctuations on the buses of power supplies, and, consequently, the other receivers with a shock-free load are also

affected by voltage fluctuations. Power supply of such loads by separate lines and even by individual transformers is not always economically profitable.

Series compensation while increasing voltage at the receiving end provides voltage fluctuations at lower range. Series compensation should be used for short-and sharply changing loads. In the series compensation rated power of capacitors is not fully used as it is changes proportionally to the square of current passing through. Switching-on capacity in series decreases reactance circuit (network and the power transformer). It leads to an increase in short-circuit currents. In systems with voltage up to 1000 this circumstance is of particular importance since it is not always possible to find breaking equipment with sufficient stability to short circuit. As a result, sometimes there is a limitation of the power transformers.
Properties of shunt and series capacitive compensation differentiate their field of application in power systems. Series compensation is used as a way to regulate and stabilize voltage in electric circuits with sharp-changing loads. Shunt compensation is used to improve cosφ and for voltage regulation in power systems of industrial enterprises.

4.5. Compensation of reactive power load at industrial enterprises

Reactive power compensation is performed based on the balance of reactive power at a node of electrical network. The total generated reactive power for each mode of power is always equal to the total consumption of reactive power. Reactive power balance in the electrical network node is expressed by:

$$Q_{г} + Q_{ку} = Q_{п} + \Delta Q - Q_{лин} + Q_{р} \quad (4.38)$$

where $Q_{г}$ - reactive power which can be produced by generators at the node; $Q_{ку}$ - reactive power of compensating devices in the node, $Q_{п}$ - reactive power consumed by the load of the node; ΔQ - reactive power losses in the elements of the electrical network node; $Q_{лин}$ - reactive power generated by long-distance transmission lines related to the node; $Q_{р}$ - store of reactive power at the node.

For industrial enterprises $Q_{лин} = 0$, and store $Q_{р} = 1,1 \cdot Q_{п}$, then

$$Q_{ку} = 1,1 \cdot Q_{п} - (Q_{г} - \Delta Q). \quad (4.39)$$

The value $Q_{г} - \Delta Q = Q_{э}$ is determined by the grid and is given to the consumer. For low-power electric installations full compensation of reactive power is required, that is $Q_{ку} = Q_{п}$.

As it can be seen from the above relations, calculation of compensation reactive power must be made on the basis of the values of the reactive load in accordance with the schedule of reactive loads.

4.5.1. Consumers without synchronous motors

At most industrial enterprises most reactive load is concentrated on the side of 0.38 kV. Compensating devices can be connected:

• only to buses 6/10 kV;
• only part to buses 6/10 kV, and the part on the side of 0.38 kV;
• only on the side 0.38 kV.

Power of compensating devices is determined by the expression (4.39). Its distribution is carried out by techno-economic comparison of these options.
A traversal capacitor bank is installed for the purpose of reactive power compensation or voltage regulation. Cost of its installation should be fully considered in determining the estimated costs.
Calculations should take into account that the unit cost of installation of capacitor banks on the side 6/10 kV is lower than on the 0.4 kV side. Cell 6/10 kV connection of capacitor banks requires additional costs. $Q_{\text{ку}}$ power of 6/10 kV should be transmitted through transformers on the side of 0.4 kV. If transformers are fully loaded ($\beta = 1$), there is a problem of replacing transformers by higher power transformers or an increase in their number and profitability of such options.
The price of the capacitor bank includes a permanent part of $З_0$ which is independent of the power generated and the variable part is proportional to battery power:

$$З_{\text{БК}} = З_0 + З_1 \cdot Q_{\text{БК}} \quad (4.40)$$

where $З_1$ - unit cost per unit of generated power.
A constant component is determined by the value of the input device: switching and protective devices, transformers, ammeters, resistors, etc. The cost of this equipment does not depend (within limits) on the power of the capacitor bank. For a capacitor bank with an output regulation cost of the regulator should be considered.
For capacitor banks without control devices

$$З_0 = \text{Е} \cdot \text{К}_0 \qquad (4.41)$$

with control devices

$$З_0' = \text{Е} \cdot \text{К}_0 + \text{Е}_1 \cdot \text{К}_\text{р} \qquad (4.42)$$

where $К_0$ - cost of the input device; $К_р$ - cost of the control device, and Е = 0,223 – a coefficient taking into account the total annual allocations from the value of the input device; $Е_1$ = 0,27 – the same as the value of the regulating device.
The variable component of the value of capacitor banks is in proportion to their capacity. It is determined by the value of capacitors with fuses, material and installation of the cabinet where capacitors are installed. The value of a contactor or a switch that enables or disables sections of the battery while regulation of sections power is considered for regulated capacitor banks.
Power generated by the capacitor bank depends on the network voltage. Taking it into account and also power losses in capacitors

$$З_1 = Е \cdot З_{уд.\ БК}\left(\frac{U_{БК}}{U_{ном}}\right)^2 + C_0 \cdot \Delta P_{БК} \quad (4.43)$$

where $З_{уд.\ БК}$ - unit cost of installation of a capacitor bank, $U_{БК}$ - actual voltage on the capacitor bank; $\Delta P_{БК}$ - specific active power losses in the capacitor bank, $U_{ном}$ - nominal voltage; C_0 - unit cost of active power losses in the network and capacitor bank (defined by the grid) .
By dividing numerator and denominator in (4.43) on the value of the nominal voltage, we get

$$З_1 = Е \cdot З_{уд.\ БК}\left(\frac{\dot{U}_{БК}}{\dot{U}_{ном}}\right)^2 + C_0 \cdot \Delta P_{БК} \quad (4.44)$$

– where $\dot{U}$ is the relative magnitude of the supply voltage; $\dot{U}_{БК}$ – ratio of the rated voltage of capacitors to the nominal supply voltage.
Capacitors attached to the 0.38 kV network are constructed for a rated voltage equal to the rated voltage of the network. Capacitors attached to the network 6/10 kV are constructed for the voltage that is 5% greater than the rated voltage. The ratio of the rated voltage of capacitors and network voltage of 0.38 kV is $\dot{U}_{БК} = 1$, and for voltages 6/10 kV – $\dot{U}_{БК} = 1{,}05$.
Thus, the cost of installation of capacitor banks is determined by:

$$З_{БК} = З_0 + Е \cdot З_{уд.\ БК}\left(\frac{\dot{U}_{БК}}{\dot{U}_{ном}}\right)^2 \cdot Q_{БК} + C_0 \cdot \Delta P_{БК} \cdot Q_{БК} \quad (4.45)$$

Application of capacitor banks for reactive power compensation simplifies the calculation. In this case capital cost of acquisition and operational costs are taken into account.

Example 4.6.

A transformer of 6/0,4 kV with rated capacity $S_{ном}$ = 1000 kVA is connected to buses of a distribution point of an industrial enterprise. Active load on the side of 0.4 kV is 0.9 MW, reactive - 0.8 MVAr and full $S = \sqrt{P^2 + Q^2} = \sqrt{0,9^2 + 0,8^2} = 1,2$ MVA, that is, the transformer is overloaded.
Full reactive power compensation ($Q_э$ = 0) is defined by a power supply organization. There are no synchronous motors at the enterprise. Reactive power compensation can be accomplished by setting a capacitor bank:
a) 6 kV buses;
b) on the side of the 0.38 kV;
c) on the side of 6 kV and 0.38 kV side.
We need to choose the most cost-effective option.
Capacitor banks for 6 kV have a constant component of costs $З_{01}$ = 670 USD and the unit cost of 1 MVAr power generated $З_{11}$ = 1600 USD, and 0.38 kV bank $З_{00}$ = 0 (no need to replace the cell) and $З_{10}$ = 3000 USD/MVAr. If the capacitors will be installed only on the side of 6 kV, then transfer all of the compensating power (0.8 MVAr) to 0.38 kV side will require an increase in the nominal capacity of the transformer. The cost of the transformer with the equipment replacement by the other type (1600 kW) is 5,000 USD, in both cases transformer load is taken as β = 1.

Solution.
Determine the reactive power that can be transferred from 6 kV to 0.38 kV loads based on load transformer

$$Q = \sqrt{(S_{ном} \cdot \beta)^2 - P^2} = \sqrt{(1 \cdot 1)^2 - 0,9^2} = 0,44 \text{ MVAr.}$$

This is the maximum possible capacity of a capacitor bank of 6 kV, i.e. Q_1 = 0,44 MVAr.
Then the power of capacitor banks on 0.38 kV side will be:

$$Q_0 = Q_{потр} - Q_1 = 0,8 - 0,44 = 0,36 \text{ MVAr.}$$

The cost of banks installation will be:

$$З_1 = З_{01} + З_{11} \cdot Q_1 + З_{00} + З_{10} \cdot Q_0 = 670 + 1600 \cdot 0,44 + 0 + 3000 \cdot 0,36 = 2454 \text{ USD}$$

In this calculation the first two terms refer to a bank of 6 kV, the second - to the bank of 0.38 kV.
Replacement of a 1000 kVA transformer by a transformer of the other type with 1600 kVA power will allow passing through a transformer from 6 kV to 0.38 kV

$$Q_1 = \sqrt{(S'_{\text{ном}} \cdot \beta)^2 - P^2} = \sqrt{(1,6 \cdot 1)^2 - 0,9^2} = 1,4 \text{ MVAr},$$

that is more than required under the terms of compensation (0.8 MVAr). In this case installation of a bank on the side of 0.38 kV will not be required (Q_0 = 0), but on the 6 kV side the bank of Q'_1 = 0,8 MVAr is installed.

The cost of the second option will be:

$$З_2 = З_{01} + З_{11} \cdot Q'_1 + Е \cdot К_{\text{тр}} = 670 + 1600 \cdot 0,8 + 0,223 \cdot 5000 = 3065 \text{ USD}$$

If a capacitor bank is installed only on the 0.38 kV side the cost will be:

$$З_3 = З_{00} + З_{01} \cdot Q_0 = 0 + 3000 \cdot 0,8 = 2400 \text{ USD}$$

The last option is appropriate.

4.5.2. Power distribution of capacitor banks through network load nodes up to 1000 voltage

Distribution of capacitors power up to 1000 V defined earlier is considered for each workshop transformer substation. Profitability of such criterion of distribution - further reduction of the costs taking into account technical connectivity of individual cells. Technical data of capacitor banks are accepted in accordance with the manufacturer's data. The obtained value of the bank power is recommended to be rounded upward the nearest power of a standard capacitor unit.

Possible mounting location of capacitor banks is described in section 4.2.3. When one or two main busbars are powered from one transformer, each of the busbars is connected with only one bank up to 1000 V. Total estimated capacity of the banks is distributed between the busbars in proportion to their total reactive load. On a single busbar should be mounted no more than two capacitor units with similar power.

Distribution of total power of a capacitor bank is provided with consideration of reactive power transferred from the 6/10 kV, reactive loads of cabinets of 0.38 kV, network structure (radial or transmission) and resistances feeders.

Radial network. Radial lines with resistances r_1, r_2, …, r_n which feed cabinets with reactive loads calculated $Q_{\text{р}1}$, $Q_{\text{р}2}$, …, $Q_{\text{р}n}$,, while $Q_{\text{р}} = \sum_1^n Q_{\text{р}i}$ and $Q_{\text{БК}} \leq Q_{\text{р}}$ leave from the buses of 0.4 kV transformer substation.

Calculated values of power capacitor banks, mounted at $Q_{\text{БК}\,i}$ assemblies consistent with transmitted power from the 6/10 kV, are defined by:

$$Q_{\text{БК}\,i} = Q_{\text{р}\,i} - Q_i \quad (4.46)$$

where Q_i - power transmitted through the transformer in the i-тую radial line and rounded to the nearest standard value.

Distribution of power transmitted through the transformer along the lines of the radial network is made by the expression:

$$Q_i = \frac{Q \cdot r_{\text{эк}}}{r_i} \quad (4.47)$$

where Q_i - required power of i-ой line passed by the 6/10 kV; Q - total distributed power produced as a result of technical and economic calculations and transferred from the 6/10 kV side to the side 0,4 kV; r_i - radial line resistance of l_i length and s_i cross section, power supply unit of loads connection; $r_{\text{эк}}$ -equivalent resistance of the network voltage up to 1000V, defined by the formula:

$$r_{\text{эк}} = \frac{1}{\frac{1}{r_1} + \frac{1}{r_2} + \ldots + \frac{1}{r_n}}, \quad (4.48)$$

where r_1, r_2, …, r_n - resistance points of radial network.

Example 4.7.

Power circuit loads is shown in Fig. 4.21. Reactive loads $Q_{\text{р}1}$–$Q_{\text{р}4}$ of each distribution point and resistance feeders are indicated in the diagram. The total power of capacitor banks on the side of 0.38 kV is defined for the calculation and is 700 kVAr. Network of 6/10 kV transfers Q = 225 kVAr. We need to distribute capacitor banks among distribution points.

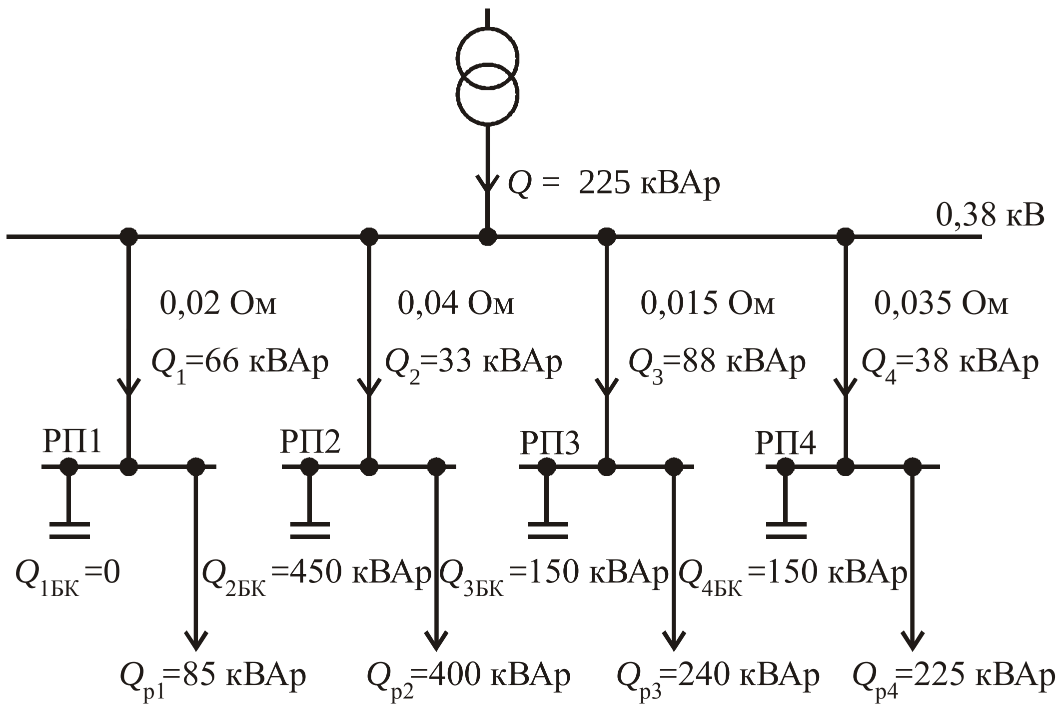


Fig. 4.21. Estimated layout of capacitor banks in networks of up to 1000V with radial power (example 4.7)

Solution.

1. Determine equivalent resistance of the network

$$r_{эк}=\left(\sum_{i=1}^{i=n}\frac{1}{r_i}\right)^{-1}=\frac{1}{\frac{1}{0,02}+\frac{1}{0,04}+\frac{1}{0,015}+\frac{1}{0,035}}=5,87\cdot10^{-3}\ \text{Ohms.}$$

2. All reactive power is transmitted from a network of 10 kV, that is Q = 225 kVAr are distributed among РП1РП4 in accordance with (4.47):

$$Q_1=\frac{Q\cdot r_{эк}}{r_1}=\frac{225\cdot5,87\cdot10^{-3}}{0,02}=66\ \text{kVAr;}$$

$$Q_2=\frac{Q\cdot r_{эк}}{r_2}=\frac{225\cdot5,87\cdot10^{-3}}{0,04}=33\ \text{kVAr;}$$

$$Q_3=\frac{Q\cdot r_{эк}}{r_3}=\frac{225\cdot5,87\cdot10^{-3}}{0,015}=88\ \text{kVAr;}$$

$$Q_4=\frac{Q\cdot r_{эк}}{r_4}=\frac{225\cdot5,87\cdot10^{-3}}{0,035}=38\ \text{kVAr.}$$

3. Design power of capacitor banks installed about distribution points РП1РП4 is determined by

$$Q_{1\,БК} = Q_{р1} - Q_1 = 85 - 66 = 19 \text{ kVAr};$$

$$Q_{2\,БК} = Q_{р2} - Q_2 = 400 - 33 = 367 \text{ kVAr };$$

$$Q_{3\,БК} = Q_{р3} - Q_3 = 240 - 88 = 152 \text{ kVAr};$$

$$Q_{4\,БК} = Q_{р4} - Q_4 = 225 - 38 = 187 \text{ kVAr}.$$

4. The scale of the nominal capacity of unregulated complete condensation of vector 0.38 kV bank with the lowest values (type УК̆0,38*Q*У3) is as follows: 75, 150, 225, 450 kVAr. Focusing on this scale, we choose: $Q_{1БК}$ = 0; $Q_{2БК}$ = 450 kVAr, $Q_{3БК}$ = 150 kVAr; $Q_{4БК}$ = 150 kVAr.

5. Total capacity of banks to be installed is as follows:

$$Q_{БК} = \sum_{i=1}^{i=4} Q_{БКi} = 0 + 450 + 150 + 150 = 750 \text{ kVAr},$$

that is higher than design value 700 kvar.

Let's consider the case where the total power of installed capacitor banks $Q_{БК}$ is greater than the sum of reactive loads of all distribution points $\sum_{i=1}^{i=n} Q_{рi}$ (i.e. $Q_{БК} > \sum_{i=1}^{i=n} Q_{рi}$) and 0.38 kV buses are also connected to the reactive load.

In this case, a capacitor bank should be connected to each distribution point; power of a capacitor bank is close or equal to the power of the reactive РП. In this case all the lines feeding the РП are discharged from the transfer of reactive power from the 6/10 kV. Excess bank power is connected directly to the buses 0.38 V.

Example 4.8.

In Fig. 4.22 a diagram of РП power supply ин radial lines indicating reactive loads is shown. Total power of capacitor bank is determined by calculation and $Q_{БК}$ = 900 kVAr. Total reactive load of РП1РП4 is $Q_{р1} + Q_{р2} + Q_{р3} + Q_{р4}$= 85 + 135 + 240 + 200 = 660 kVAr which is less $Q_{БК}$. Reactive load $Q_{р.ш}$ = 400 kVAr is connected to the 0.38 kV buses. Power Q =160 kVAr is transmitted from the network through the transformer. We need to distribute capacitor banks through the load nodes.

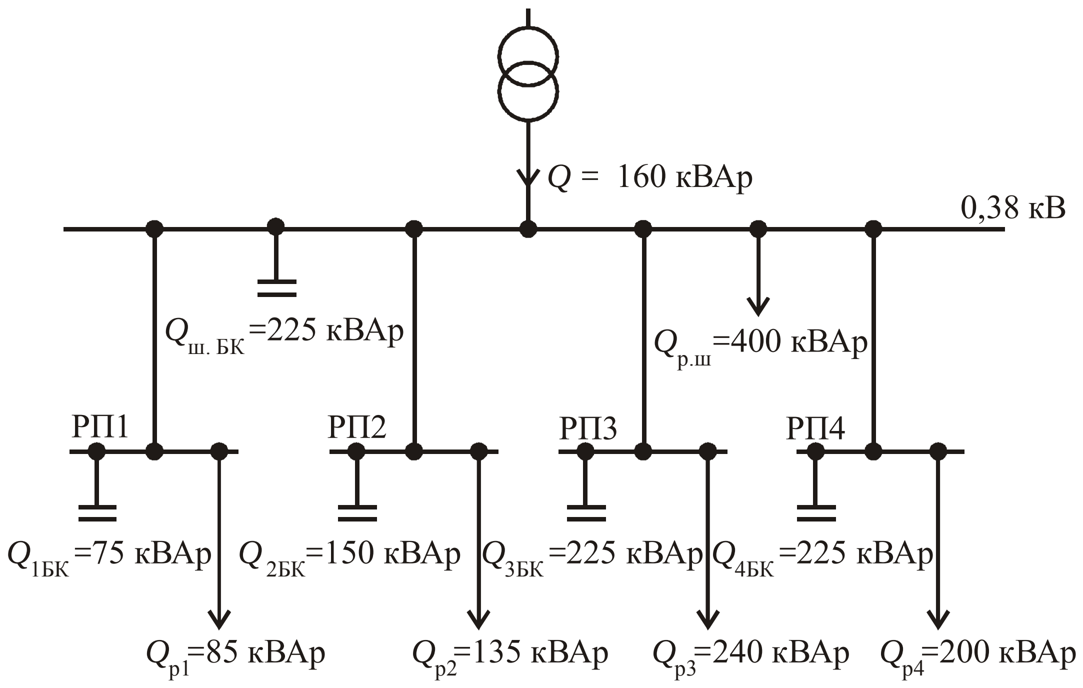


Fig. 4.22. Estimated layout of capacitor banks in the networks of up to 1000V with radial feed and load on buses (for example 4.8)

Solution.
Focusing on the scale of nominal power of capacitor bank (see Example 4.7), for each РП capacitor banks are selected: $Q_{1БК}$ = 75 kVAr; $Q_{2БК}$ = 150 kVAr; $Q_{3БК}$ = 225 kVAr; $Q_{4БК}$ = 225 kVAr. Then bank power connected to the buses will be:
$Q_{ш.\,БК} = Q_{БК} – Q_{1\,БК}\;\; Q_{2\,БК} – Q_{3\,БК} – Q_{4\,БК}$ = 900 – 75 – 150 – 225 – 225 = 225 kVAr.
Total power of all capacitor banks $Q_{БК}$ less than the amount of reactive loads ($Q_{р1} + Q_{р2} + Q_{р3} + Q_{р4} + Q_{р.ш}$ = 85 + 135 + 240 + 200 + 400 = 1060 kVAr) to a value of Q = 1060 - 900 = 160 kVAr, which is transmitted through the transformer.

Transmission network. Load and condenser units are attached to the taps from the main busbar 0.4 V. Taps are long. In this case, installation of capacitor banks is impossible without resistance taps. Equivalent resistance of the network for each tap point is determined by the formula of the parallel connection of resistance

$$r_{эк} = \frac{R_1 \cdot R_2}{R_1 + R_2} \;.$$

Power to the *i*-ому tap is distributed by the formula (4.47).

Example 4.9.
Power circuit loads connected to the busbar is shown in Fig. 4.23. Reactive load of

an assembly Q_{p1}–Q_{p4}, resistance busbar sections r_{12}–r_{34} and taps r_1–r_4 are indicated in the diagram. Total power of capacitor banks $Q_{1БК}$–$Q_{4БК}$ on the side of 0.38 kV is 600 kVAr. Compensating power Q = 200 kVAr is transmitted from 6 kV side. We need to find optimal value of the power capacitor banks connected to the assemblies.

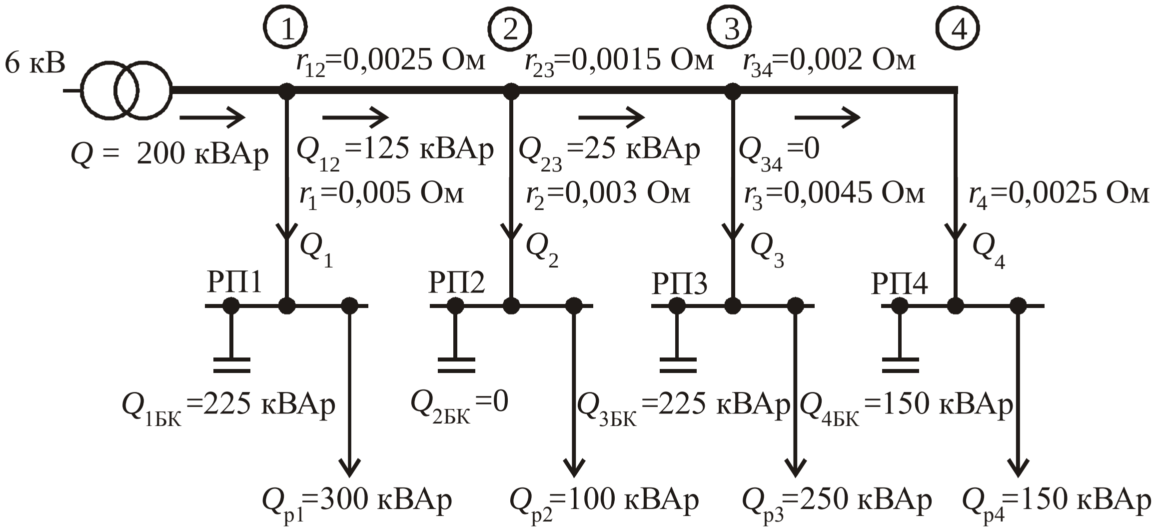


Fig. 4.23. Estimated layout of capacitor banks fed by burbuses with taps (for example 4.9)

Solution.

Starting from the end of the busbar we will determine the equivalent resistance of the network.

For a tap from point 3 where $R_1 = r_{34} + r_4$, a $R_2 = r_3$:

$$r_{эк\,3} = \frac{(r_{34} + r_4)\cdot r_3}{(r_{34} + r_4) + r_3} = \frac{(0{,}002 + 0{,}0025)\cdot 0{,}0045}{(0{,}002 + 0{,}0025) + 0{,}0045} = 0{,}00225 \text{ Ohms.}$$

For a tap from point 2 where $R_1 = r_{эк\,3} + r_{23}$, a $R_2 = r_2$::

$$r_{эк\,2} = \frac{(r_{эк\,3} + r_{23}) \cdot r_2}{(r_{эк\,3} + r_{23}) + r_2} = \frac{(0{,}00225 + 0{,}0015) \cdot 0{,}003}{(0{,}00225 + 0{,}0015) + 0{,}003} = 0{,}00167 \text{ Ohms.}$$

For a tap from point 1 where $R_1 = r_{эк\,2} + r_{12}$, a $R_2 = r_1$:

$$r_{эк\,1} = \frac{(r_{эк\,2} + r_{12}) \cdot r_1}{(r_{эк\,2} + r_{12}) + r_1} = \frac{(0{,}00167 + 0{,}0025) \cdot 0{,}005}{(0{,}00167 + 0{,}0025) + 0{,}005} = 0{,}00227 \text{ Ohms.}$$

Next, according to (4.47) we will determine reactive power transmitted from 6 kV to a tap of the 1 assembly *РП1*:

$$Q_{1\,расч} = \frac{Q \cdot r_{эк1}}{r_1} = \frac{200 \cdot 0{,}00227}{0{,}005} = 91 \text{ kVAr.}$$

Then, at full power compensation capacitor bank for this assembly will be: $Q_{1\,БК} = Q_{р1} - Q_{1\,расч} = 300 - 91 = 209$ kVAr.

According to the scale of nominal capacity of a capacitor bank (see example 4.7) we take $Q_{1БК}$ = 225 kVAr. Then, in tap *1* will be transferred power $Q_1 = Q_{р1}\ \ Q_{1БК}$ = 300 225 = 75 kVAr (not $Q_{1расч}$ = 91 kVAr) and at points 1 – 2 output will be:

$$Q_{12} = Q - Q_1 = 200 - 75 = 125 \text{ kVAr.}$$

Reactive power transferred to the branch 2, is:

$$Q_{2\,расч} = \frac{Q_{12} \cdot r_{эк2}}{r_2} = \frac{125 \cdot 0{,}00167}{0{,}003} = 70 \text{ kVAr.}$$

Power bank for *РП2:*

$$Q_{2\,БК} = Q_{р2} - Q_{2\,расч} = 100 - 70 = 30 \text{ kVAr,}$$

We define $Q_{2БК}$ = 0.

Then, in the tap 2 power will be transmitted

$Q_2 = Q_{р2}$ = 100 kVAr,

and in section 2 – 3 busbar power

$Q_{23} = Q_{12}\ \ Q_2$ = 125 100 = 25 kVAr.

Reactive power transferred to the branch 3 is:

$$Q_{3\,расч} = \frac{Q_{23} \cdot r_{эк3}}{r_3} = \frac{25 \cdot 0{,}00225}{0{,}0045} = 15 \text{ kVAr.}$$

Reactive power bank assembly *РП3*:

$$Q_{3\,БК} = Q_{р3} - Q_{3\,расч} = 250 - 15 = 235 \text{ kVAr.}$$

According to a scale of nominal capacity we accept $Q_{3БК}$ = 225 kVAr, in this case in tap 3 power will be transmitted

$Q_3 = Q_{р3}\ \ Q_{3БК} = 250\ \ 225 = 25$ kVAr

or

$Q_3 = Q_{3расч} + (Q_{3БК\ расч}\ \ Q_{3БК}) = 15 + (235\ \ 225) = 25$ kVAr.

Power on the busbar point 3 – 4 is:

$Q_{34} = Q_{23}\ \ Q_3 = 25\ \ 25 = 0$,

that is, capacitor bank for *РП4* is selected by $Q_{р4}$= 150 kVAr. Consequently, $Q_{4\ БК} = Q_{р4}$ == 150 kVAr (corresponds to the scale of nominal capacity).

Total capacity of all capacitor banks is:

$$Q_{БК} = \sum_{i=1}^{i=4} Q_{БКi} = 225 + 0 + 225 + 150 = 600 \text{ kVAr,}$$

thus, it is equal to a given power.

If taps to load from the transmission network are of short length and their losses can be neglected, capacitor banks should be chosen close to the power load on the taps and should be placed at the most remote distribution points.

Example 4.10.

Power circuit loads with their reactive power is shown in Fig. 4.24. We need to determine power of capacitor banks connected to the taps and total power of banks is $Q_{БК}$ = 770 kVAr and the network of 6 kV transmits power Q = 140 kVAr.

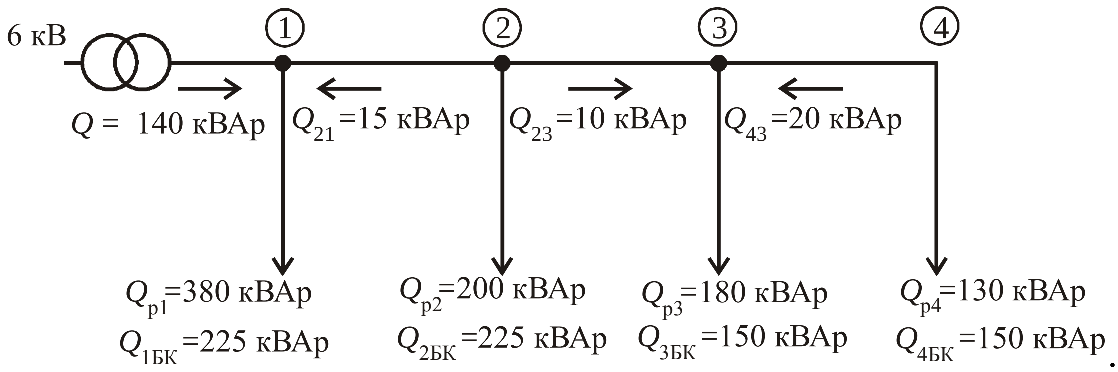


Fig. 4.24. Estimated layout of capacitor banks fed by busbar with short taps (for example 4.10)

Solution.

We install a bank 4 on the tap, bank's power is $Q_{4БК}$ = 150 kVAr. In this case at points 3 – 4 of a busbar, reactive power will be transferred in the direction to point *3*:

$$Q_{43} = Q_{4БК}\ \ Q_{р4} = 150\ \ 130 = 20 \text{ kVAr.}$$

On the tap *3* we install the bank $Q_{3БК}$ = 150 kVAr, while at points 2 – 3 power will be transmitted in the direction of point 3 equal to:

$$Q_{23} = Q_{р3}\ \ Q_{3БК}\ \ Q_{43} = 180\ \ 150\ \ 20 = 10 \text{ kVAr.}$$

On the tap 2 we install two banks $Q_{2БК}$ = 225 kVAr. While at points 1 – 2 power will be transmitted in the direction of point 1

$$Q_{21} = Q_{2БК}\ \ Q_{р2}\ \ Q_{23} = 225\ \ 200\ \ 10 = 15 \text{ kVAr.}$$

In addition, to the point 1 reactive power is transferred from 6 kV, its value is Q = 140 kVAr. Consequently, power of the bank should be:

$$Q_{1БК} = Q_{р1}\ \ Q\ \ Q_{21} = 380 - 140 - 15 = 225 \text{ kVAr.}$$

According to a scale of nominal capacity (see Example 4.7), we choose a bank with $Q_{1БК}$ = 225 kVAr.

Total power of capacitors installed in the taps, based on a scale of capacity, is equal to:

$Q_{БК} = Q_{1БК} + Q_{2БК} + Q_{3БК} + Q_{4БК}$ = 225 + 225 + 150 + 150 = 750 kVAr,

thus, it is close to a given power.

Power supply at a point between its ends. In this case, you must first determine equivalent resistance of each branch of the trunk main. Then, treating them as radial capacitors distributed between the branches, arrange capacitors between the branches, then install them at each branch the same as for a transmission line.

For a busbar with a uniformly distributed load (Fig. 4.25) capacitor bank is connected at one point of a busbar. The optimal distance of the attachment point to the bank busbar from the transformer is given by:

$$L_{опт} = L_0 + \left(1 - \frac{Q_{БК}}{2Q}\right) \cdot L \quad (4.49)$$

where $Q_{БК}$ - power of a capacitor bank; Q - total reactive load of a busbar; L_0 - length of a busbar without taps; L - length of distribution part of the busbar.

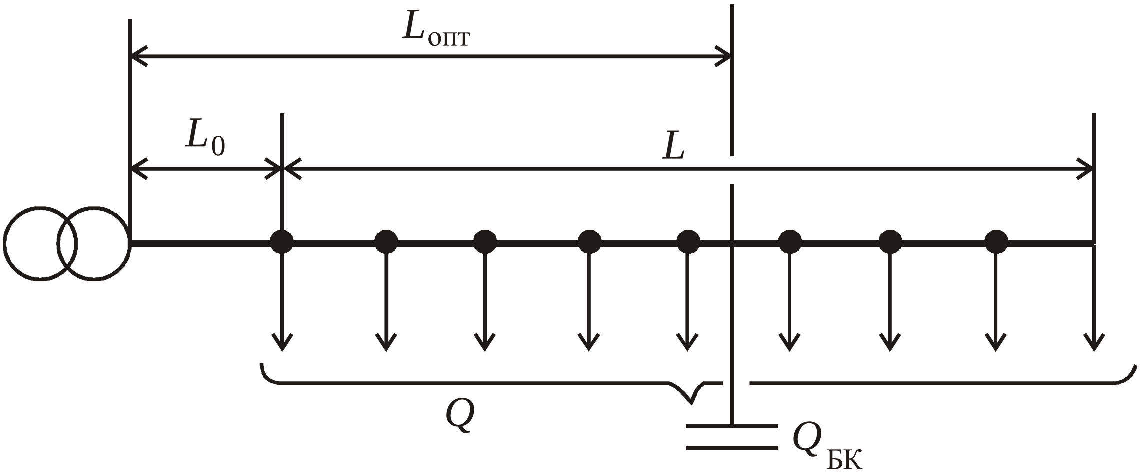


Fig. 4.25. Busbar with a uniformly distributed load

Example 4.11.

Workshop load of an industrial enterprise is connected to the busbar and uniformly distributed along its length L = 100 m. The busbar length before subbranching is L_0 = 130 m. Total reactive load Q = 500 kVAr. We need to determine distance from the substation to the installation point of a capacitor bank $Q_{БК}$ = 400 kVAr with minimum losses of active power in the busbar.

Solution.
Distance from the transformer substation to the capacitor connection point is determined by the ratio (4.49):

$$L_{опт} = L_0 + \left(1 - \frac{Q_{БК}}{2Q}\right) \cdot L = 130 + \left(1 - \frac{400}{2 \cdot 500}\right) \cdot 100 = 190 \text{ m.}$$

Single busbar transmission line requires installation of no more than two capacitor units similar in power. If the main reactive loads connected to the second half, only one bank with voltage of 1000V needs to be installed. The point of connection is determined by:

$$Q_h \geq \frac{Q_{БК}}{2} \geq Q_{h+1} \quad (4.50)$$

where Q_h, Q_{h+1}- the largest reactive load of a busbar node h before and after it (Fig. 4.26)

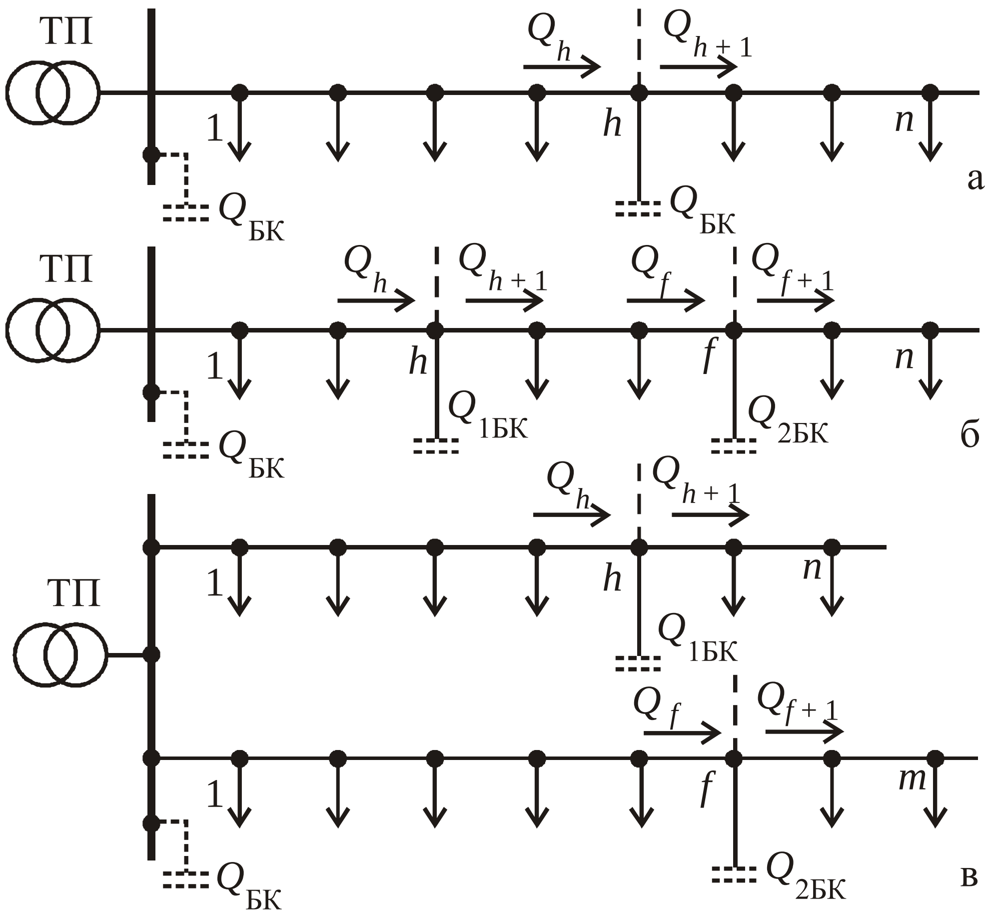


Fig. 4.26. Connection diagram of low-voltage capacitor banks connected to a main busbar: a - capacitor bank, b - two capacitor banks c - two main busbars with a capacitor bank

Two connection points of capacitor banks, upon their connection to a main busbar, are found by the following.

A connection point of a distant bank up to 1000V (Figure 4.26b):

$$Q_f \geq \frac{Q_{2\,БК}}{2} \geq Q_{f+1} \; . \quad (4.51)$$

A connection point of the closest to the transformer bank up to 1000V (Figure 4.26b):

$$Q_h - Q_{2\,БК} \geq \frac{Q_{1\,БК}}{2} \geq Q_{h+1} - Q_{2\,БК} \, . \quad (4.52)$$

Example 4.12.

We will need to determine a connection point of capacitor banks to a main busbur. Background information: reactive load is connected to a busbar ШМА 1600 as shown in Fig. 4.27. Reactive loads are given in kVAr. Calculated reactive load of a transformer constitutes 1430 kVAr. Total power of capacitors $Q_{БК}$ = 800 kVAr (there are three banks: two of 300 kVAr, one - 200 kVAr). Each busbar provides installation of a capacitor bank.

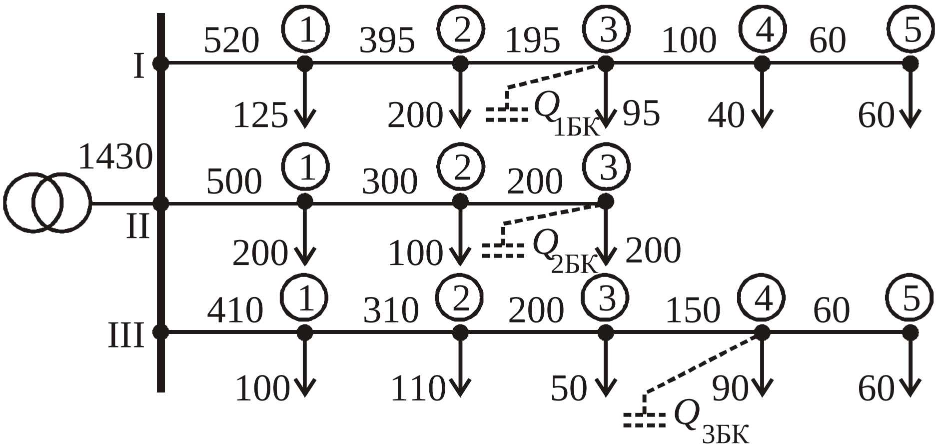


Fig. 4.27. Connection diagram of reactive loads connected to a busbar (related to example 4.12)

Solution.

Capacitor banks are installed in proportion to their reactive load between busbars, i.e. the first and the second busbars will have the banks of 300 kVAr, the third of 200 kVAr.

Let’s determine a connection point of the first capacitor bank to a busbar by (4.50):

Node 1 - $520 > \frac{300}{2} < 395$ - condition is not met;

Node 2 - $395 > \frac{300}{2} < 195$ - condition is not met;

Node 3 – $195 > \frac{300}{2} > 100$ - condition is met;

Node 4 - $100 < \frac{300}{2} > 60$ - condition is not met;

Node 5 - $60 < \frac{300}{2} > 0$ - condition is not met.

Therefore, the capacitor bank must be connected to the node 3. Similarly we define connection nodes of capacitor banks to the second and the third busbars (for 2 ШМА - node 3, for 3 ШМА - node 4).

Example 4.13.
We will need to define a connection point of two capacitor banks with voltage up to 1000V to a main busbar. Background information: before compensation reactive load (in kVAr) in busbar ШМА 1600 is allocated in accordance with Fig. 4.28. Eotal reactive load of the transformer is 920 kVAr. Estimated total capacity of capacitor units $Q_{БК}$ = 700 kVAr (300 kVAr the bank closest to the transformer and 400 kVAr - distant).

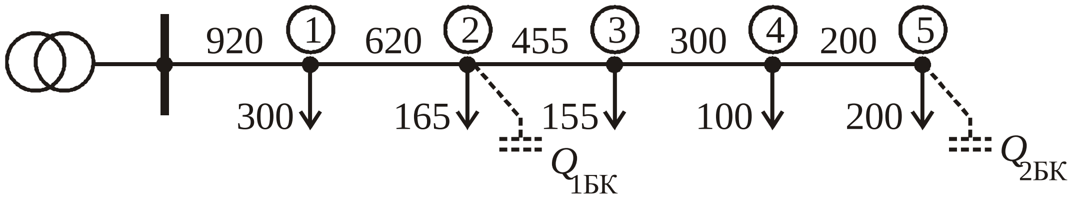


Fig. 4.28. Connection diagram of reactive loads connected to a busbar (related to example 4.13)

Solution.
1. We need to determine a connection point of a distant capacitor bank ($Q_{2БК}$ = 400 kVAr) according to the condition $Q_h \geq \frac{Q_{2\,БК}}{2} \geq Q_{h+1}$:

Node 4 – 300 > $\frac{400}{2}$ ≥ 200 – condition is met;

Node 5 – 200 ≥ $\frac{400}{2}$ > 0 – condition is met.

Therefore, the capacitor bank of 400 kVAr can be connected to the node 4 as well as to the node 5 (the technical solution is accepted due to construction).
2. We need to determine a connection point of a capacitor bank that is close to the transformer ($Q_{1БК}$ = 300 kVAr) according to the condition $Q_h - Q_{2\,БК} \geq \frac{Q_{1\,БК}}{2} \geq Q_{h+1} - Q_{2\,БК}$:

Node 1 – 920 – 400 > $\frac{300}{2}$ < 620 – 400 – condition is not met;

Node 2 – 620 – 400 > $\frac{300}{2}$ > 455 – 400 – condition is met;

Node 3 – 455 – 400 < $\frac{300}{2}$ > 300 – 400 – condition is not met.

Consequently, the second capacitor unit ($Q_{1БК}$ = 300 kVAr) can be connected to the node 2.

4.5.3. Consumers with synchronous motors (SM)

If an enterprise has at its disposal high power synchronous motors, they must be used for reactive power compensation in the first place. They generate reactive power that is consumed to compensate for reactive load on the buses 6/10 kV and transmitted to the side of 0.4 kV. If the installed transformers transmit reactive power generated by synchronous motors, then profitability of additional transformer installation can be doubted.
Commercially available synchronous motors are designed to work with advanced nominal rated $\cos\varphi_{НОМ}$ = 0.9. With rated resistive load $P_{НОМ}$, voltage (0,95-1,05) $\cdot U_{НОМ}$, nominal advance $\cos\varphi$ and nominal value of current excitation, synchronous motors can generate reactive power

$$Q_{НОМ} = \frac{P_{НОМ}}{\eta}\,\mathrm{tg}\varphi_{НОМ} \quad (4.53)$$

which is considered as nominal reactive power of a synchronous motor. Here η – nominal coefficient of efficiency, $\mathrm{tg}\varphi_{НОМ}$ = 0.484 which corresponds to $\cos\varphi_{НОМ}$ = 0.9.
For estimated calculations, taking the average η = 0,96, SD nominal reactive power of a SM can be determined by:

$$Q_{НОМ} \approx 0{,}5 \cdot P_{НОМ}. \quad (4.54)$$

When the motor is under loaded, active power is $\beta = P/P_{НОМ} < 1$, it is possible to overload the reactive $\alpha_{М} = Q/Q_{НОМ} > 1$ (Figure 4.29).

Maximum permissible reactive power overload also depends on voltage at the motor terminals: when voltage drops maximum reactive power increases, and decreases while an increase (Fig. 4.30). Average values of the load factor for the reactive power changes depending on the resistive load and voltage synchronous motors are given in Table 4.3.
Generation of reactive power if $\cos\varphi$ is advance is accompanied by additional losses of active power ΔP (Fig. 4.31), which with sufficient accuracy for practical calculations can be

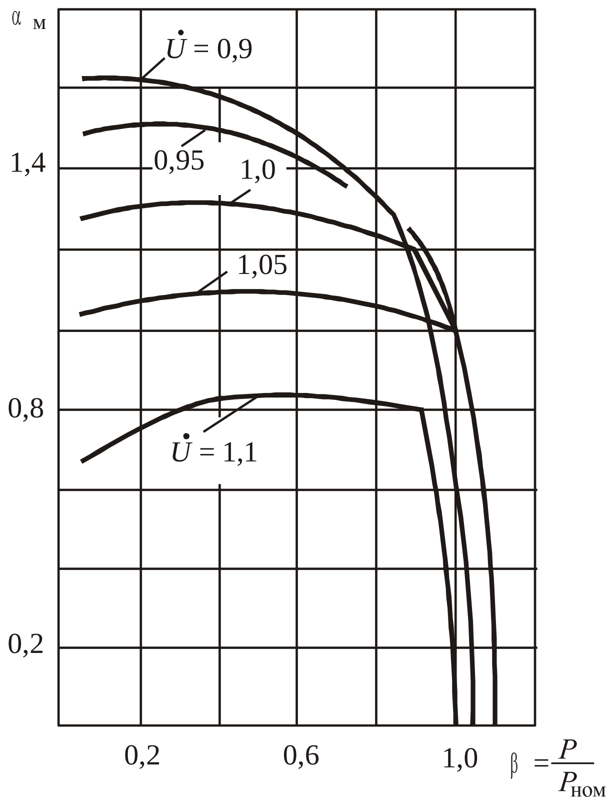


Fig. 4.29. Characteristic curve of available reactive power on the load factor for a synchronous motor СДН̃187112 with different values of voltage at its terminals

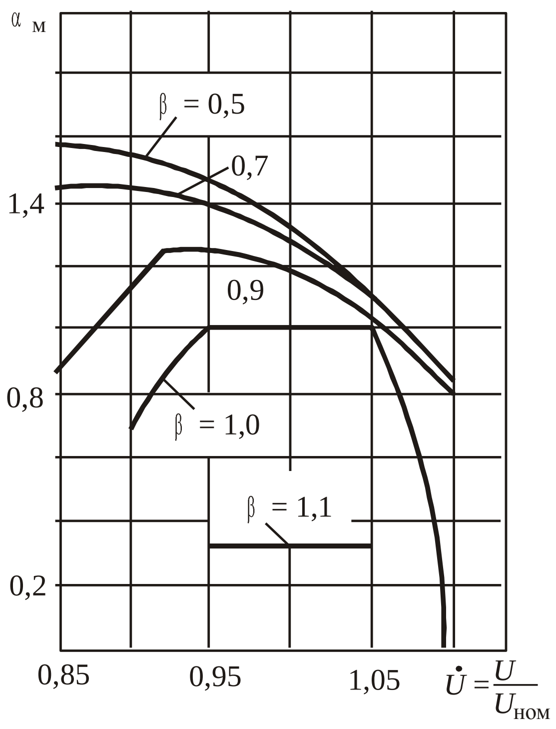


Рис. 4.30. Characteristic curve of available reactive power on voltage at terminals for a synchronous motor СДН̃187112 with different load factors

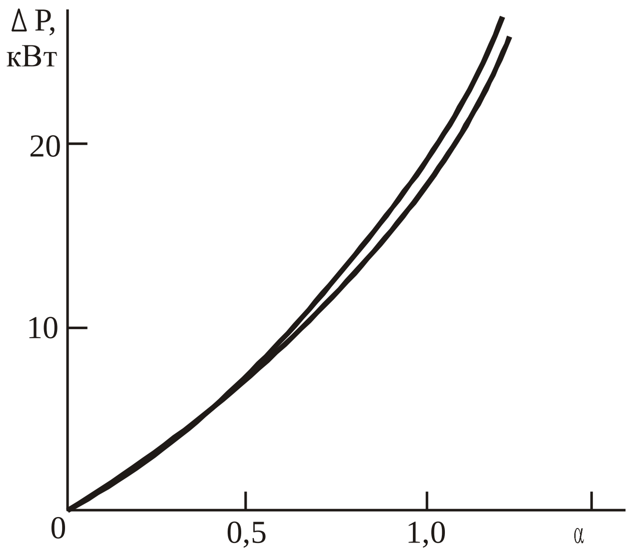


Fig. 4.31. Characteristic curve of active power losses in the generation of reactive power on the load factor α – for a motor *СДН̃15646*

Average values of relative terms of the available reactive power $\alpha_м$ for synchronous motors

Motor type	Voltage at terminals	Load factor		
		0,9	0,8	0,7
СДН 6 and 10 kV	0,95	1,31	1,39	1,45
	1,0	1,21	1,27	1,33
	1,05	0,96	1,12	1,17
СДН 6 kV				
600~1000 rpm	1,1	0,89	0,94	0,96
375~500 rpm	1,1	0,88	0,92	0,94
187~300 rpm	1,1	0,86	0,88	0,90
100~167 rpm	1,1	0,81	0,85	0,87
СДН 10 kV				
1000 rpm	1,1	0,9	0,98	1,0
250~750 rpm	1,1	0,86	0,90	0,92
СДН 6 and 10 kV	0,95	1,3	1,42	1,52
СТД	1,0	1,23	1,34	1,43
	1,05	1,12	1,23	1,31
	1,1	0,9	1,08	1,16
СД and СДЗ 380 V	0,95	1,16	1,26	1,35
	1,0	1,15	1,24	1,32
	1,05	1,1	1,18	1,25
	1,1	0,9	1,06	1,15

defined by

$$\Delta P = D_1\alpha + D_2\alpha^2 = D_1 \frac{Q}{Q_{\text{ном}}} + D_2 \frac{Q^2}{Q_{\text{ном}}^2}\,, \qquad (4.55)$$

where $\alpha = Q/Q_{\text{ном}}$ - load factor for reactive power; D_1 and D_2- parameters of a synchronous motor which term depends on a motor type, its power and revolutions per minute (reference [4]). These parameters remain practically unchanged when the motor load factor for active power in the range of 0,5 – 1,0 and changes in supply voltage from 0.95 to 1.1 nominal. For estimated calculations active power losses while generating $Q_{\text{ном}}$ can be calculated with the help of the motor coefficient of efficiency:

$$\Delta P \approx \frac{1}{6}\left(\frac{P_{\text{ном}}}{\eta} - P_{\text{ном}}\right)$$

The ratio of active power losses to the rated reactive power generated by an electric motor, that is specific losses, considers synchronous motor efficiency as a means of reactive power compensation. This ratio increases with a decrease in motor power and speed.
For a group of parallel, equally loaded and identical SM total active power losses due to the generation of reactive power is equal to:

$$\Delta P = N\left(\frac{D_1}{Q_{\text{ном}}}\cdot\frac{Q}{N} + \frac{D_2}{Q_{\text{ном}}^2}\cdot\left(\frac{Q}{N}\right)^2\right)$$

or

$$\Delta P = \frac{D_1}{Q_{\text{ном}}}\cdot Q + \frac{D_2}{Q_{\text{ном}}^2 N}\cdot Q^2 \qquad (4.56)$$

where N - number of motors; $Q_{\text{ном}}$ - rated motor power; Q - total reactive power generated by all motors.
Groups of SM can be used for designing a facility aimed at reactive power compensation. Groups of SM also generate power and transfer it through the

network. In this case, additional active power losses of SM due to the generation of reactive power for the planned facility will be:

$$\Delta P = \left[\frac{D_1}{Q_{\text{ном}}} \left(Q_{\text{пред}} + Q\right) + \frac{D_2}{Q_{\text{ном}}^2 N} \left(Q_{\text{пред}} + Q\right)^2 \right] - \left(\frac{D_1}{Q_{\text{ном}}} \cdot Q_{\text{пред}} + \frac{D_2}{Q_{\text{ном}}^2 N} \cdot Q_{\text{пред}}^2 \right)$$

or

$$\Delta P = \frac{D_1}{Q_{\text{ном}}} \cdot Q + \frac{2D_2 \cdot Q_{\text{пред}}}{Q_{\text{ном}}^2 N} \cdot Q + \frac{D_2}{Q_{\text{ном}}^2 N} \cdot Q^2 \qquad (4.57)$$

where Q - reactive power generated by the SM for the transfer to the projected facility; $Q_{\text{пред}}$ - reactive power generated by the SM before its connection to a network project (preload).

Theoretically, the unit cost of each of the three equation components (4.57) will be different. It is determined by the graph of the power generation Q and $Q_{\text{пред}}$. It is virtually impossible to take into account the difference in the cost of losses by choosing a means of compensation. In addition, the cost of losses depends on the mode of synchronous motors. If excitation is not controlled by motors, generated power remains unchanged and the number of losses hours will be equal to the number of operation hours. If the reactive power generated by SM is regulated according to voltage changes or reactive power consumption, the number of losses hours will be determined by the schedule changes in generated power.

The cost of losses in the generation of reactive power for a group of similar motors in the same mode, is calculated as follows:

$$C = C_0 \left(\frac{D_1}{Q_{\text{ном}}} + \frac{2D_2 \cdot Q_{\text{пред}}}{Q_{\text{ном}}^2 N} \right) \cdot Q + C_0 \frac{D_2}{Q_{\text{ном}}^2 N} \cdot Q^2 \quad (4.58)$$

where C_0 - unit cost of active power losses.

In general, the cost of using the same type of SM as a controlled source of reactive power will be determined by:

$$\text{З} = \text{З}_0 + \text{З}_1 \cdot Q + \text{З}_2 \cdot Q^2. \quad (4.59)$$

Constant component of costs:

$$\text{З}_0 = E_{\text{р}} \cdot N \cdot \text{К}_{\text{р}} \quad (4.60)$$

where $K_р$ - cost of a regulator; $E_р$ - total annual allocations from the value of the regulator; N - the number of motors.
Unit costs for 1 MVAr generated by motors:

$$З_1 = C_0\left(\frac{D_1}{Q_{ном}} + \frac{2D_2 \cdot Q_{пред}}{Q_{ном}^2 N}\right) \quad (4.61)$$

and unit costs for MVAr² generated power:

$$З_2 = C_0 \frac{D_2}{Q_{ном}^2 N}. \quad (4.62)$$

For newly commissioned synchronous motors $Q_{пред} = 0$

$$З_1 = C_0 \frac{D_1}{Q_{ном}}.$$

Power of capacitor banks on 0.38 kV side will be determined by the difference between a given total compensating capacity and power transferred from the 6/10 kV. The cost of reactive power compensation in this case is defined as the sum of generation cost of reactive power on the side 6/10 kV (cost of active power losses in synchronous motors), and installation costs for capacitor banks on the side of 0.38 kV.
Maximum reactive power that can be transferred from the 6/10 kV to 0.38 kV network with N identical power transformers, is calculated by the relation:

$$Q_1 = \sqrt{(N \cdot \beta \cdot S_{ном})^2 - P} \quad (4.63)$$

where P - total active load on the side of 0.38 kV, $S_{ном}$ - nominal capacity of transformers; N and β - number of transformers and their load factor.

If reactive power $Q_э$ is transferred from the electric power system, compensating power $Q_к$ must be not less than

$$Q_к \geq Q_А + Q_Б - Q_э \quad (4.64)$$

where $Q_А$ - reactive load on the buses 6/10 kV, $Q_Б$ - reactive load on the side of 0.38 kV.
Maximum reactive power generated by synchronous motors is determined by the expression:

$$Q_м = \frac{\alpha_м \cdot P_{ном} \cdot \mathrm{tg}\varphi_{ном}}{\eta_{ном}} \quad (4.65)$$

$\alpha_м$ – a coefficient taking into account the permissible overload of synchronous motors for reactive power depending on voltage and the load factor for active power (see Table 4.3).

Example 4.14.

Fig. 4.32 shows a diagram of one section of the distribution point. Two SM of 2500 kW each and rotation 1000 r/min are attached to the buses of 10 kV. The load factor of each motor is $\beta = 1$, and the power factor is $\cos\varphi = 0{,}9$. Synchronous motors are commissioned once again, that is, pre-load is $Q_{пред} = 0$. Consumption of reactive power in networks of 10 kV by power consumers at other industrial enterprises reaches $Q_A = 1900$ kVAr. At 0.38 kV network design loads for the most loaded shifts are: $P_р = 4.5$ MW, $Q_р = 3.2$MVAr, $S_р = 5.5$ MVA. The feed system is in the area where the cost of losses is equal to 64 USD/kW, and may transfer maximum reactive power $Q_{э1} = 1.2$ MVAr during peak hours.

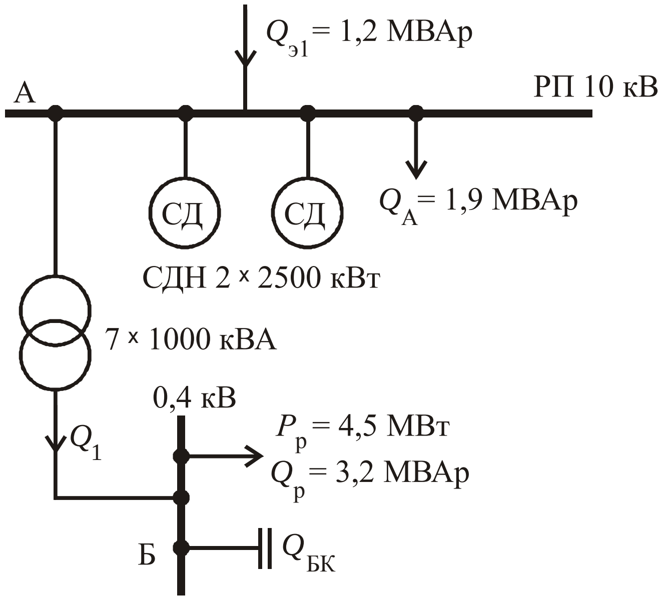


Fig. 4.32. A calculation scheme of reactive power compensation with synchronous motors in the network (related to example 4.14)

The load factor of transformers $\beta_{тр} = 0.7$ with bus ties in the network of 0.4 kV. Area of a workshop $F_ц = 40000$ m2. The cost of substations with transformers of 1000 kVA and the required equipment $К_т = 17\,000$ USD. The enterprise operates in two shifts.

We need to determine the best option for reactive power compensation. Constant component of costs is zero and standard coefficient of efficiency of capital investments - 0.193.

Solution.
According to specific loads of a workshop

$$\sigma = \frac{S_р}{F_ц} = \frac{5500}{40000} = 0{,}138\,\frac{кВА}{м^2}$$

we accept transformers with a rated capacity of $S_{ном}$ = 1000 kVA. Minimum required number

$$N = \frac{S_р}{\beta \cdot S_{ном}} = \frac{5500}{0{,}7 \cdot 1000} = 7{,}8,$$

according to the first option for further calculations we take N_1 = 7.
Reactive power generated by two SM is determined by the reference data [4] and is equal to

$$Q_{ном.\,СД} = n \cdot Q_{ном} = 2 \cdot 1{,}265 = 2{,}53 \text{ MVAr.}$$

Reactive power which can be transferred from the system and synchronous motors to the side 0.4 kW:

$$Q_{0{,}4\,кВ} = Q_{ном.\,СД} + Q_{э1} - Q_А = 2{,}53 + 1{,}2 - 1{,}9 = 1{,}83 \text{ MVAr.}$$

According to (4.63) the maximum power can be transferred through the transformers

$$Q_{ВН7} = \sqrt{(N_1 \cdot \beta_{тр} \cdot S_{ном})^2 - P_р^2} = \sqrt{(7 \cdot 0{,}7 \cdot 1)^2 - (4{,}5)^2} = 1{,}21 \text{ MVAr.}$$

The remaining uncompensated power (total power of banks below 1000V) on the side of 0.4 kV in the transmission of reactive power from 10 kV network is equal to 1.21 MVAr:

$$Q_{БК\,I} = Q_р - Q_{ВН\,7} = 3{,}2 - 1{,}21 = 1{,}99 \text{ MVAr.}$$

According to [6] we accept 13 capacitor banks УКБ – 0,38 – 150У3 with a total power of $Q_{БК\,I} = 1950$ MVAr.

The second option. We increase the number of transformers by one, that is, N_2 = 8, then the maximum power that can be transmitted through the transformer, will be

$$Q_{ВН7} = \sqrt{(N_2 \cdot \beta_{тр} \cdot S_{ном})^2 - P_р^2} = \sqrt{(8 \cdot 0{,}7 \cdot 1)^2 - (4{,}5)^2} = 3{,}4 \text{ MVAr,}$$

that is, required reactive power on the side of 0.4 kV ($Q_р$ = 3.2 MVAr) can be transferred from the 10 kV by means of eight transformers. In this case, installation of capacitor banks on the side of 0.4 kW is required. However, available power of 10 kV network, which can be transferred over to the 0.4 kW, is equal to $Q_{0{,}4\,кВ}$ = 1.83 MVAr. Consequently, on the side of 0.4 kV capacitor are needed, their total power will be

$$Q_{БК\,II} = Q_р - Q_{0{,}4\,кВ} = 3{,}2 - 1{,}83 = 1{,}37 \text{ MVAr.}$$

According to [4] we take nine capacitor units УКБ̃0,38150У3 with a total power of

$Q_{БК\,II} = 1350$ MVAr.

Techno-economic comparison of options. The first option: 7 transformers with a nominal power of 1000 kVA each and 13 capacitor banks УКБ̃0,38150У3 with a total power of $Q_{БК\,I} = 1950$ MVAr.

The second option: 8 transformers with a rated power of 1,000 kW each, and 9 capacitor banks УКБ̃0,38150У3 with a total power of $Q_{БК\,II} = 1350$ MVAr.

We need to determine the value of calculated unit costs for SM used as sources of reactive power. They are determined by the value of active power losses due to reactive power generation and transmission of power in the 0.4 kV network:

$$З_{СД} = З_0 + З_1 \cdot Q + З_2 \cdot Q^2,$$

where a constant component of the costs according to the condition of the example is zero and $З_1$ and $З_2$ according to (4.61) and (4.62) are:

$$З_1 = C_0\left(\frac{D_1}{Q_{ном}} + \frac{2D_2 \cdot Q_{пред}}{Q_{ном}^2 N}\right) = C_0 \frac{D_1}{Q_{ном}} = 64\frac{9{,}2}{1{,}265} = 469\frac{у.е}{МВАр};$$

$$З_2 = C_0 \frac{D_2}{Q_{ном}^2 N} = 64\frac{8{,}93}{1{,}265^2 \cdot 2} = 175\frac{у.е}{МВАр}.$$

Costs of installation of capacitor banks are defined by (4.45):

$$З_{БК} = З_0 + E \cdot З_{уд.БК}\left(\frac{\dot{U}_{БК}}{\dot{U}_{ном}}\right)^2 \cdot Q_{БК} + C_0 \cdot \Delta P_{БК} \cdot Q_{БК}$$

and are: for the first option

$$З_{БК\,I} = 0{,}223 \cdot 6{,}2 \cdot \left(\frac{1}{1}\right)^2 \cdot 1950 + 64 \cdot 4{,}5 \cdot 10^{-3} \cdot 1950 = 3676\,\text{USD};$$

for the second option

$$З_{БК\,II} = 0{,}223 \cdot 6{,}2 \cdot \left(\frac{1}{1}\right)^2 \cdot 1350 + 64 \cdot 4{,}5 \cdot 10^{-3} \cdot 1350 = 2380\,\text{USD}$$

where $З_{уд.\,БК}$ = 6.2 USD/kVAr taken from [4] for УКБ̃0,38150У3 and $\Delta P_{БК}$ = 4.5 kW/MVAr = $4{,}5 \cdot 10^3$ kW / kvar; $\dot{U}_{БК}/\dot{U} = 1/1$

For the first option costs are comprised of active power losses in SM and the cost of installation of capacitor banks on the side of 0.4 kW:

$$З_I = З_1 \cdot Q_{ВН\,7} + З_2 \cdot Q_{ВН\,7}^2 + З_{БК\,I} = 469 \cdot 1{,}21 + 175 \cdot 1{,}21^2 + 3676 = 4500\,\text{USD}$$

For the second option we must consider the cost of a substation:

$$З_{II} = З_1 \cdot Q_{0,4\,кВ} + З_2 \cdot Q^2_{0,4\,кВ} + З_{БК\,II} + Е_Н \cdot К_т =$$
$$= 469 \cdot 1{,}83 + 175 \cdot 1{,}83^2 + 2380 + 0{,}193 \cdot 17000 = 7105 \text{ у.е.}$$

$$З_{II} = 7105 > З_I = 4500 \text{ USD}$$

Therefore, the best option for reactive power compensation is the first option.

4.5.4. Comparative efficiency of capacitor banks and synchronous motors

Despite the fact that we apply SM to generate reactive power, we don't need to spend money on additional equipment. For some SM types it is less profitable than to install an extra capacitor bank due to active power losses in the motor.
In Fig. 4.33 characteristic curves of unit cost of reactive power generation from nominal power of different types of compensating devices are shown. For synchronous motors costs correspond to the full use of their reactive power. From the figure it follows that compensating possibilities of low-voltage and high voltage SM with a frequency of 250 rev/min is less profitable than installation of an additional capacitor bank. The same can be applied to a synchronous motor with a rotation frequency of 500 rev/min and available power of less than 2 MVAr, as well as SM with a speed of 750 rev/min and power of less than 0.7 MVAr for $U_{ном}$ = 6 kW and power of less than 1,5 MVAr for $U_{ном}$ = 10 kV.

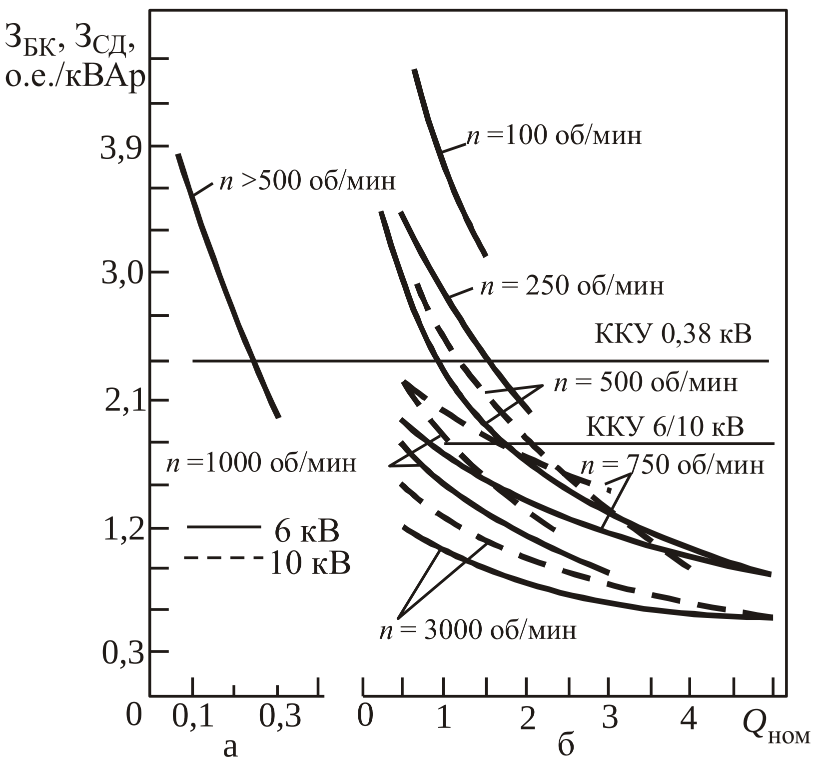


Fig. 4.33. Unit costs for reactive power generation of synchronous motors and capacitor banks

However, it does not mean that SM should not be used for reactive power compensation. Production costs of reactive power for these synchronous motors 6/10 kV are smaller than for capacitor banks. If we use their available power by not more than 70-80%, and for synchronous motors 0.38 kW - 40-60%. Taking into account specific conditions (circuit network, SM type, operation mode) we can select SM we need for reactive power compensation.

In case of shared use, control rules of capacitor banks and synchronous motors in operation must be followed. Sequence control of reactive power should be set up so that in case of an increase in total generated power, SM reactive power will decrease in the first place since specific losses in capacitor banks are less than in synchronous motors.

A power control of capacitor banks must go off when a permissible limit of SM reactive power is reached. Such operation sequence is achieved by installation of capacitor banks with longer time delay operation, compared to control SM time delay, for sections switching off.

If we set up a dead zone for reactive current, it will allow us to carry out control within the range of the power section that corresponds to the bank. Therefore, SM provides an opportunity to choose cheaper capacitor bank - with less control possibilities.

4.5.5. Power boost for capacitor banks

Power of a capacitor bank, regardless a connection diagram, is proportional to the sum of capacities of all phases and voltage square in the network (see equations (4.16) and (4.17)). Such dependence of the bank on line voltage is unfavorable since the needs of electrical power systems and power supply systems of industrial enterprises in reactive power increase in case of voltage decrease and decrease in case of its increase. This drawback is particularly relevant in case of accidents when there are short voltage drops and reduction of reactive power. Such reduction has a negative affect on system stability (Figure 4.2).

Power boost of capacitor banks eliminates this drawback by automatic switching. In Fig. 4.34 basic circuits of power boost providing a parallel-series connection of capacitor banks at higher than nominal voltage are shown. In these schemes power control of the capacitor bank is made by variation of the circuit connection of capacitors in each phase. As a result, capacitances as well as voltage of each individual capacitor are changed.

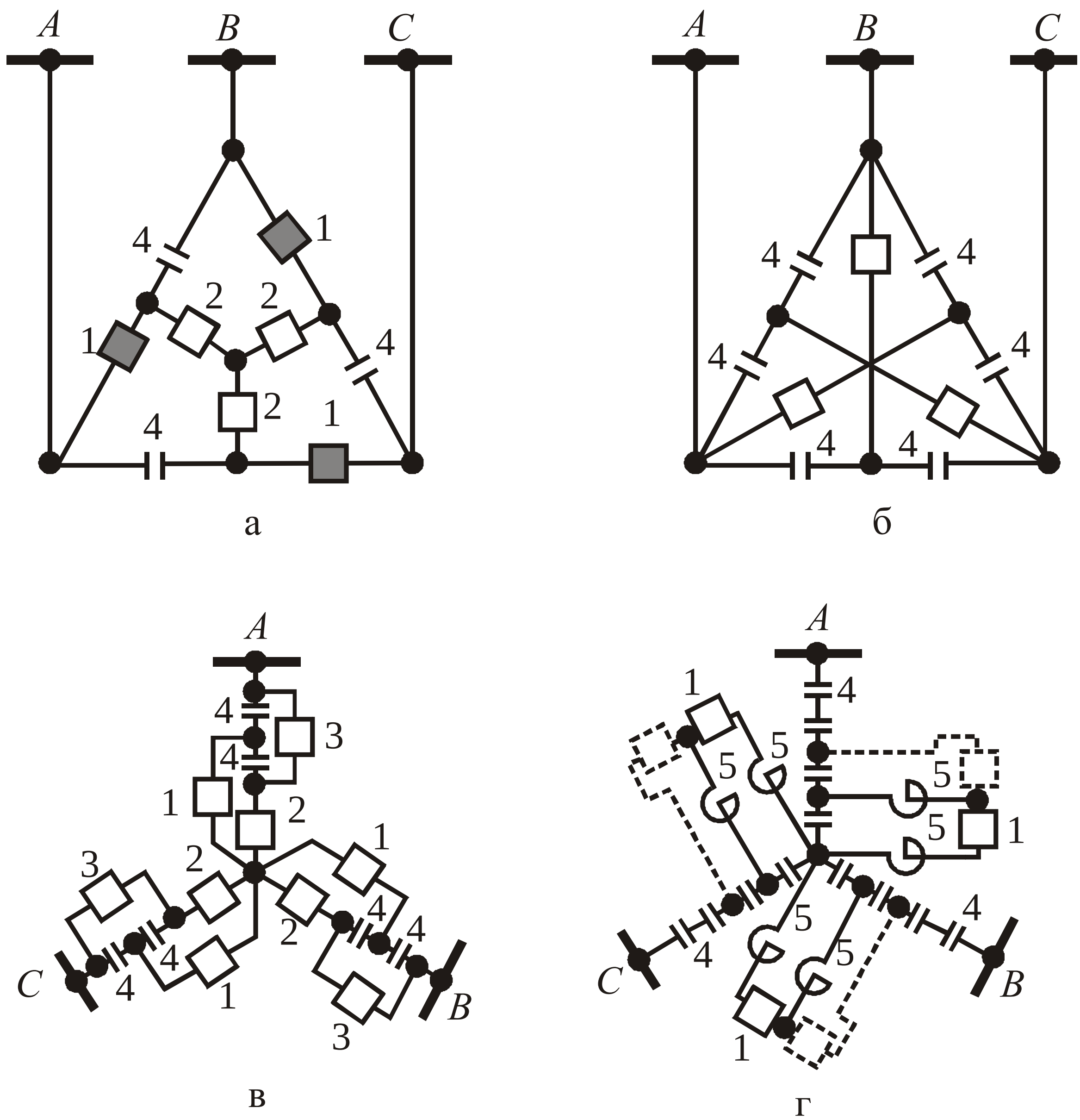


Fig. 4.34.Power boost circuit of capacitor banks: a - with periodic switchover from star to delta network, b - capacitors with switching in phases, c, d - shunting of series of capacitors, 1, 2, 3 – power circuit breakers, 4 - capacitor banks 5 – current-limiting reactors

Bank switch from spider to delta (Fig. 4.34a) provides a three-fold power boost:

$$\frac{Q_{\text{БК }\Delta}}{Q_{\text{БК Y}}} = \frac{\omega \cdot C \cdot U^2}{\frac{1}{3}\omega \cdot C \cdot U^2} = 3 .$$

Sequence of switches operation: 2 – turns off, 1 - turns on.
Bank commutation from a delta network to a double delta network (Figure 4.34b) is provided by bridging the peak with opposite sides of a delta network. It provides a four-fold power boost:

$$\frac{Q_{\text{БК }2\Delta}}{Q_{\text{БК }\Delta}} \le 4 .$$

Commutation of capacitor groups in each phase of the star from series connection to parallel (Figure 4.34v) provides a four-fold power boost:

$$\frac{Q_{\text{БК паралл}}}{Q_{\text{БК посл}}} = 4 .$$

Sequence of circuit breakers operation: 1 – turns on 2 – turns off 3 – turns on.
Electrical bridging of capacitors connected to the star (Fig. 4.34g) provides a four-fold power boost for capacitor banks that still operate:

$$\frac{Q_{\text{БК шунт}}}{Q_{\text{БК}}} \le 2 - 4 .$$

In this circuit capacitors bridging is provided by high-voltage circuit breakers through current limiting reactors.
Application of the circuits can be considered appropriate for a short power boost of the capacitors under emergency conditions when it is required to maintain system stability. However, the circuits of power boost provide significant short-term transition voltage on the capacitors that make up the bank, and they require special cosine capacitors that can withstand long-alive voltage rise at its terminals.
The above mentioned circuits are used in electric power systems and capacitor units of industrial enterprises. In order to implement these circuits stability of the system or the angle of the load should be assessed. It is recommended to use fast-operating thyristor switches in order to control the mode of power boost of capacitor banks.

4.5.6. Control of reactive power in the networks of electric power systems

Balance optimization of reactive power in power supply of industrial enterprises, selection of type and power, mounting location of capacitor banks should be solved at minimum costs. Reactive power compensation and improvement of the power

quality is one of the ways to reduce losses and improve efficiency of electrical installations.
If reactive power compensation is partial, not full, the electrical network will be overloaded with reactive and inductive current. If the reactive power compensation is full and designed for a maximum reactive load mode and capacitor banks will be switched on permanently, in this case in the periods of reactive power decrease, overcompensation of reactive power will be observed. In this case reactive power of a capacitor bank will be transferred to the electrical network, and it will be overloaded with reactive current of capacitive type. The line voltage rises and can reach unaccepted values. To avoid such phenomena capacitor banks must be equipped with control devices of their reactive power.
In electrical devices, where for compensation of reactive power synchronous compensators and synchronous motors are used, a smooth change of reactive power is provided by change of their excitation current. In capacitor banks control of reactive power is provided in steps, therefore capacitor banks are divided into sections. The number of capacitor sections is chosen according to a consumption schedule of reactive power. 3- 4 sections are usually applied. When the schedule of electric loads is irregular, 5-6 sections can be applied.
Reactive power control of a capacitor bank can be produced by:
• manually by operating personnel;
• automatically due to effects of different electrical parameters and non-electric sensors.
Depending on selected control parameters, automatic control of capacitor banks regimes is provided by an open-circuit or a close-circuit (Fig. 4.35).
If the control parameter does not change significantly with changes of capacitor power or does not depend on it, the block control diagram can be open (Fig. 4.35a).

An adjustor ЗО reacts to an input control parameter *x* and when it reaches a reference value $x_{оп}$

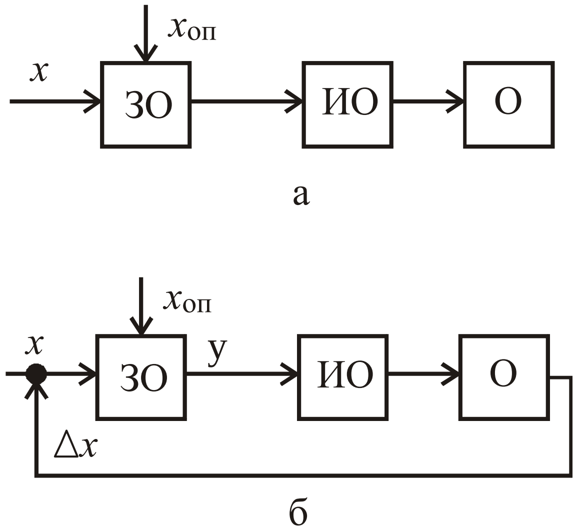


Fig. 4.35. Block diagram of reactive power control modes: a - with an open-circuit, b – with a close-circuit; ЗО – an adjustor; ИО – an executive device, О - control object, and *x* – control parameter; x_{on} – reference value of the control parameter; Δx - value of parameter control, *y* - value of regulatory impact

acts through the executive device and influences a control object – a capacitor bank. Such control regime is used for single-or two-section capacitor banks operating in “on-off” mode.

If a parameter or combination of control parameters essentially depend on the mode of a capacitor unit, a block diagram of control can be as shown in Fig. 4.35b - with a close-circuit. An adjustor, along with the input of parameters x, receives a deviation of the control parameter x from a defined $x_{оп}$ which should be taken into account in the control process. Such control is for synchronous motors and multi-sectional capacitor banks. To restore the control parameter, a control action *y* gets to an executive device which is a switching device of section of the capacitor bank or automatic excitation controller of a synchronous motor. Change of a capacitor bank power involves a change in control parameter on the Δx value.

For more efficient use of reactive power of a capacitor bank it is recommended to use automatic control. Automatic control can be performed according to:

• time of a day;

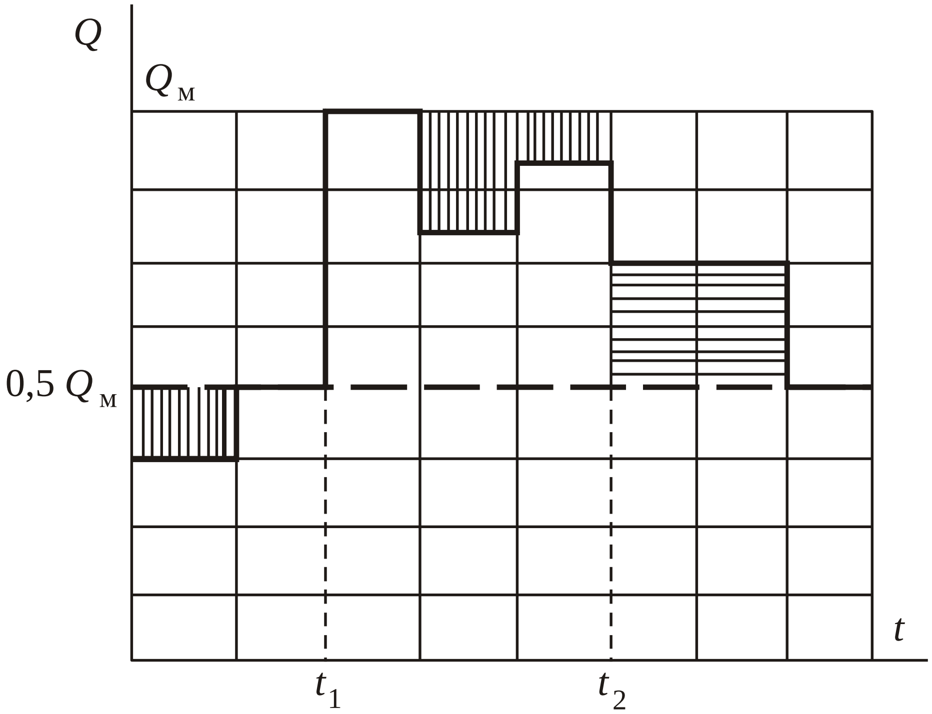


Fig. 4.36. Graph of reactive load which is used to regulate active power according to time of a day: $Q_м$ - maximum reactive load; t_1 - time of maximum load; t_2 - end of maximum load; - overcompensation; - undercompensation

• voltage at a load node;
• load current;
• value and nature of reactive power;
• nonelectric sensors.

Reactive power control according to time of a day is provided by a particular program in accordance with the requirements of production technology. Reactive load chart is basis of regulation (Figure 4.36), if the chart is stable.

Reactive load $Q_н$ can be fully compensated for reactive power $Q_к$ of a capacitor bank. Let's assume that the capacitor unit has two sections of equal power. One of the sections is on all the time; the second is on only during peak hours at the time $t_1 t_2$. With one-step automatic control electric clock ЭВЧС̆24 is used. The clock can control up to several capacitor banks of one enterprise not far from each other.

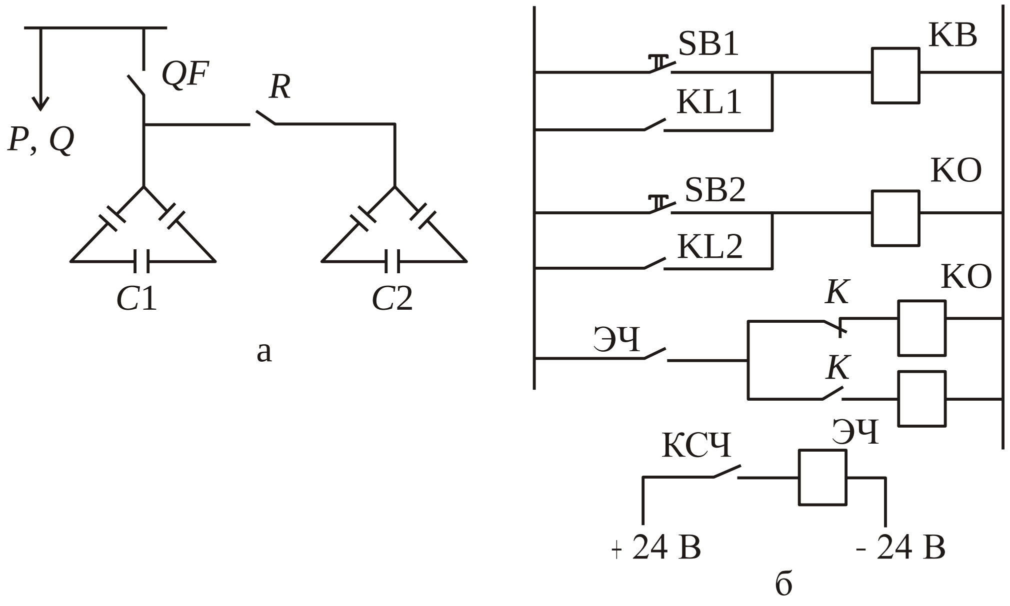


Fig. 4.37. The circuit of automatic control of the second section of a capacitor bank according to time of a day: a - circuit of primary connections, b – control circuit; *P, Q* - active-inductive load; *QF* – circuit breaker in the circuit of a capacitor bank; *C1*, *C2* - section of a capacitor bank; *K* - contactor contacts; *KB, KO* – switching-on , -off coils of a contactor; *KL1, KL2* – slave relays; *SB1, SB2* – push-button switches; *ЭЧ* - electric clock; *КСЧ* - impulse contact of master clock system

In Fig. 4.37 a circuit of automatic control of reactive power with application of electric clocks ЭВЧС-24 with one terminal and two intermediate relays is shown. An electric clock ЭЧ is switched on by the impulse contact КСЧ of the master clock system. When the contact ЭЧ is closed, time t_1 (e.g. 07:00), an intermediate relay *KL1* is actuated and it closes the circuit of capacitors bank coil. Contacts *K* of a contactor switch on the second section of the capacitor bank. Simultaneously, auxiliary contacts *K* in the circuits of intermediate relays *KL1* and *KL2* change their position. The contactor after switching-on is on the latch, coil contactor is disconnected from the power source. Voltage is also disconnected from the electric clock winding. During t_2 after disconnection of the maximum reactive load *Q*, ЭЧ contact is closed, intermediate relay *KL2* is actuated and switches on a trip coil of the KO. The contactor will be switched off and the second section of the capacitor bank will be switched-off too. Auxiliary contacts *K* of the contactor change their position again. The circuit enables or disables the second section of the capacitor bank manually using push-button switches *SB1* and *SB2*.

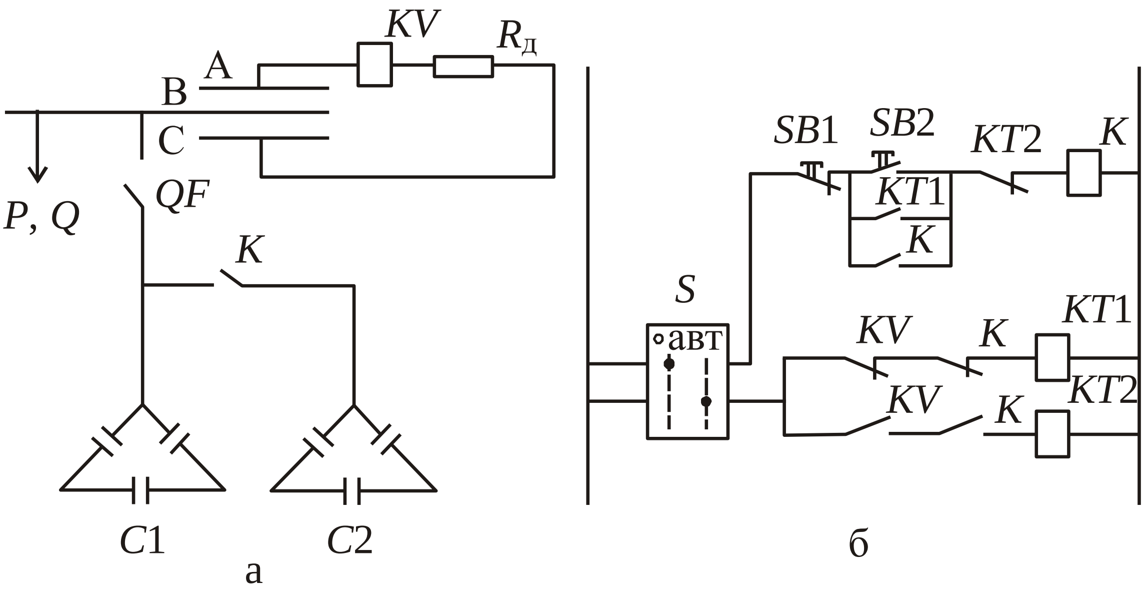


Fig. 4.38. The circuit of automatic control of reactive power in voltage function: a – a circuit of primary connections, b - control circuit; *P, Q* - active-inductive load; *QF* - circuit breaker in the capacitor bank; *C1, C2* - section of a capacitor bank; *KV* - voltage relay; $R_{д}$ - additional resistance; *K* - contacts, *KT1, KT2* - time relay; *SB1, SB2* - push-button switches; *S* – control key.

Control of reactive power according to voltage at a load node. It is used in a case when the network voltage is determined by reactive loads. In this case, a simultaneous control of reactive power and voltage is required. The voltage at connection point of a capacitor bank depends not only on the load fed from this item, but also loads of other power consumers, as well as measures of voltage regulation in the power system or in the main substation of an enterprise. When power of a capacitor bank is regulated, it must be taken into account that at a constant reactive load power of a capacitor bank is increased-voltage increases too, with a decrease – it is reduced. In Fig. 4.38 a capacitor bank in the circuit control of reactive power is shown.

Undervoltage relay is used as an adjustor connected to the buses of a load node or through a voltage transformer. If necessary, the relay can be actuated through an additional resistor $R_{д}$. By reducing the voltage in the network below a predetermined limit voltage relay *KV* is actuated, and closes its normally closed contact in the circuit of *KV*-coils of relays KT1, which was open. Time relay KT1 with a predetermined time delay (2-3 min.) makes contact KT1 in the circuit of contactor winding and automatically switches on an additional section of the capacitor. Generated reactive power is increased, network voltage is increased too. When reactive load is reset, voltage can be increased and may reach values higher than the set limit. KV voltage relay is activated and closes its contact in KV circuit of time relay coil *KT2* which with time delay of 2-3 min. makes its contact of the contactor coil K, and automatically disables an additional section of the КУ from network. Time delay is required for an offset of occasional short-term high and low voltage. The circuit makes it possible to carry out manual control mode of reactive power by means of push-button switches SB1 and SB2. The choice of manual or automatic control mode is provided by the control key S.

Multistage regulation of reactive power can be achieved by automatic control of capacitor banks АРКОН type. A controller operates as a voltage function or voltage with current correction and phase shift angle between them. It consists of a command unit (Fig. 4.39), and controlled program unit which consists of several attachments according to the number of regulation stages.

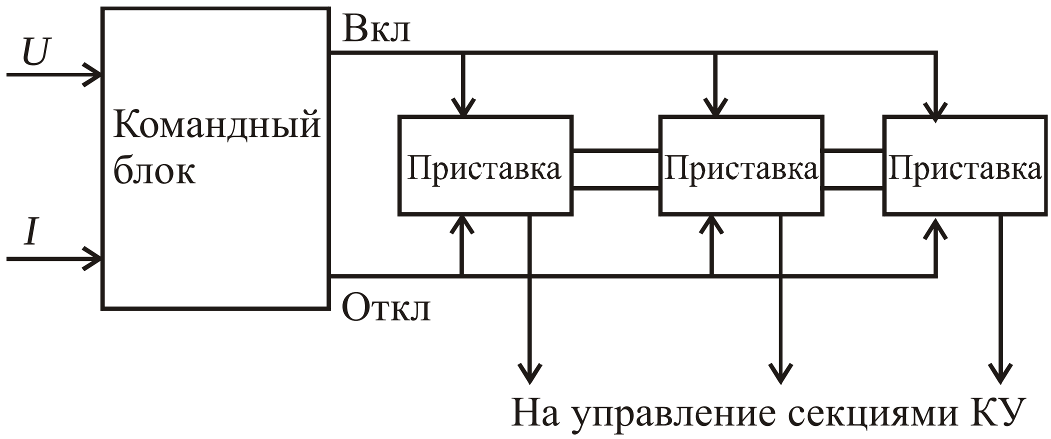


Fig. 4.39. Structural circuit of АРКОН automatic regulator

command unit – командный блок

program unit – программный блок

attachment – приставка

capacitor unit sections control – управление секциями конденсаторной батареи

on –вкл

off – откл

The command unit, depending on the size of the input signal, generates a command to the program unit that enables and disables sections of a capacitor unit. For example, three attachments with a logical decision of enabling or disabling sections of a capacitor unit with a ratio of capacity 1: 2: 4 allow us to get seven stages of regulation.

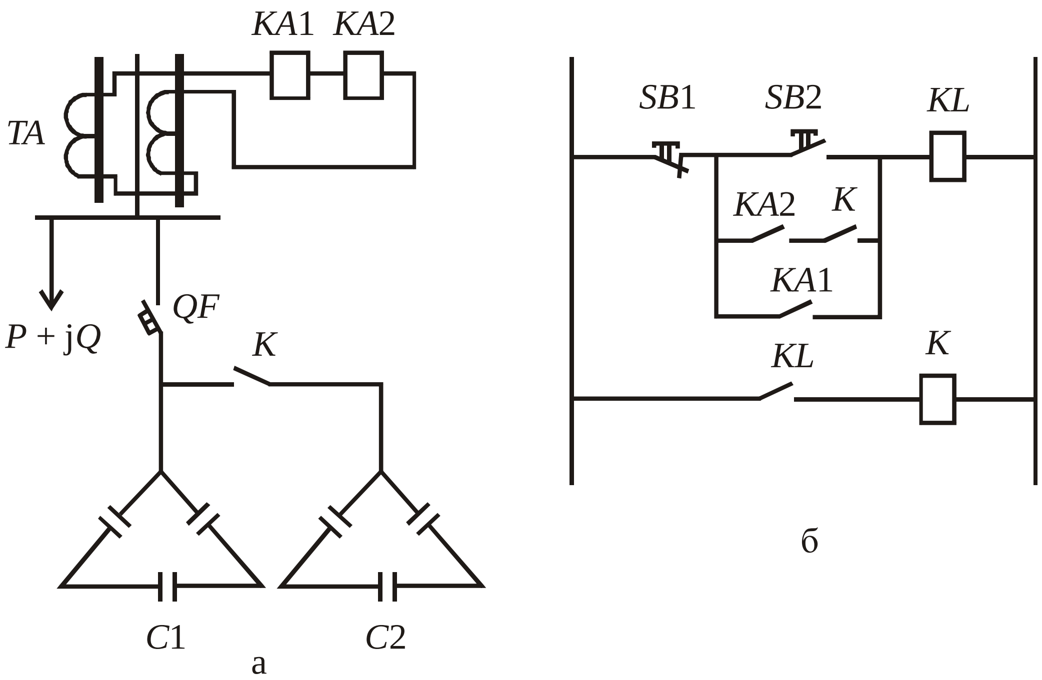


Fig. 4.40. The circuit of automatic control of reactive power according to the load current: a - circuit of primary connections, b - control circuit; *P + jQ* - active-inductive load; QF - circuit breaker in a capacitor bank; *C1*, *C2* - sections of a capacitor bank; *KA1*, *KA2* - current relay; *K* - contactor; *SB1*, *SB2* – push-button switches

Power sections of a capacitor bank are
1: 2 (1 + 2) 4 (1 + 4): (2 + 4) (1 + 2 + 4).

Voltage of a regulated part of the network is applied to the input of a command unit when reactive power is adjusted. If applicable, it is necessary to take into account a phase angle between current and voltage. A controlled current is supplied to the input of a command unit.
Regulation of reactive power according to the load current. If the load is dramatically changed during the day, power of a capacitor bank needs to be changed in the function of consumed current. Single-step automatic control of load current can be applied with two electromagnetic current relays *KA1* and *KA2*,

mounted on the input node to load buses (Fig. 4.40). One of them enables a switch-on function during load increase, the second – a switch-off function during load decrease.

Regulating points of current relays are set for different currents values. For example, *KA1* – 5 A, *KA2* – 3 A. In case of low load, an additional section is off, although current relay *KA2* has actuated, its front contacts are made, front contacts of a contactor *K* are broken.

In case of load current increase and when current reaches 5 A current, a relay *KA1* is actuated. A slave relay *KL* enables a contactor *K* and the second section of a capacitor bank.

In case of current decrease a relay *KA1* is actuated in the first place, its contactors are broken, but a relay *KL* is not disabled as the contacts *KA2* and *K* are made. If current is lower than 3A, a current relay *KA2* breaks the circuit of *KL* and disables the contactor *K*. The second section of a capacitor unit is disabled.

The circuit provides manual control mode of a capacitor bank.

Regulation of reactive power according to a change of reactive load. Load in an electrical network is constantly changing and its reactive component is changing in the first place. An automatic control device of reactive power Б2201 is applied for mode control of a capacitor bank (Figure 4.41).

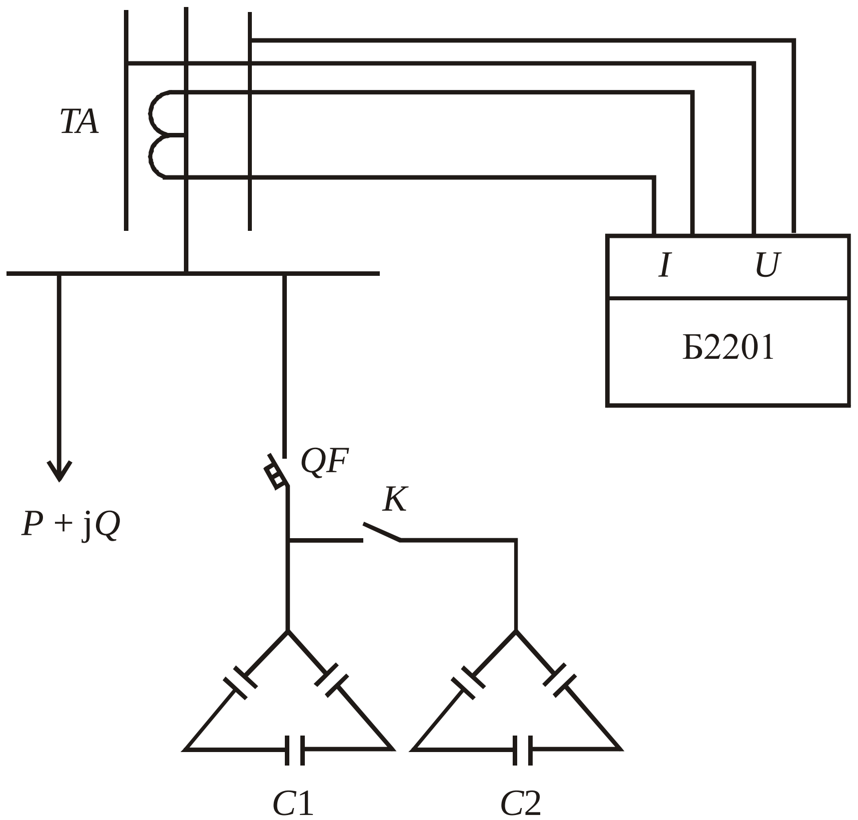


Fig. 4.41. Control circuit of reactive power by means of an automatic control device Б2201: *P + jQ* - active-inductive load; *C1, C2* – sections of a capacitor bank; *QF* – circuit breaker; *K* – a contact of a contactor ; *TA* - current transformer; *I, U* - current from a current transformer and line voltage.

The controller has two inputs. The first input is supplied with one phase current (e.g. B), the second – phase-to-phase voltage of the other two phases. Regulated reactive power

$$Q_{\text{ф}} = I_{\text{B}} U_{\text{AC}} \cos(90 - \varphi) = I_{\text{B}} U_{\text{AC}} \sin \varphi, \quad (4.66)$$

where $Q_{\text{ф}}$- reactive power of a phase; I_{B} - current of one phase; U_{AC} – phase-to-phase voltage of the other two phases; φ – angle of phase shift between current and line voltage.

The controller is supplied with an indicator of a regulating point of a dead band so that to avoid frequent switches of capacitor bank steps.

Time delay of the controller depends on difference between actual and set reactive power consumption. The greater this difference, the faster the controller is activated, and the faster maintenance of reactive power.

In electric installations with unbalanced electrical load a controller of reactive power can be applied. It ensures initial load balancing and afterwards reactive power compensation in electric installations. The controller of reactive power has three sets of inputs; each is supplied with a linear current of a corresponding phase and phase-to-phase voltage of the other two phases. It makes it possible to regulate the change of reactive power in each phase of an electrical network with an unbalanced load. The capacitor unit has two single-phase sections in each phase and up to six three phase sections. The controller has a power allocation phase, the most heavily loaded by reactive power, a single-phase section of a capacitor bank is connected to this phase. If voltage symmetry is not restored, the second-phase section is enabled. In case of reactive load decrease, sections are off. With an increase in reactive load in three phases of the network, three-phase alternating sections of a capacitor bank are on. In case of reactive power decrease, they are automatically disabled.

REFERENCES

1. Yu.K. Rozanov Fundamentals of Power Electronics. - Moscow: Energoatomizdat, 1992. - 384.

2. Kabyshev A.V. Electric power facilities. P.2. Calculation of short circuit currents in electrical systems up to 1000 VA - Tomsk: Publishing house of Tomsk Polytechnic University, 2009. - 168.
3. Kochkin V.I. Nechaev O. The use of static reactive power compensators in electric power networks and enterprises. - Moscow: Publishing House of the NC ENAS, 2000. - 248.
4. Kabyshev A.V., Obukhov S.G. Calculation and design of electro-trosnabzheniya facilities and installations. - Tomsk: Publishing house of Tomsk Polytechnic University, 2006. - 248.
5. Pobul G.H. Increasing the capacity of distribution networks with high-voltage capacitive compensation longitudinally. - Moscow: Energiya, 1977. - 63.
6. Klimova, G.N., A.V. Kabyshev Elements of energy in an electric industry. - Tomsk Polytechnic University, 2008. - 187.
7. Kudrin B.I. History of reactive power compensation / / Elec-trick. - 2001. - № 6. - P.26-29.
8. Zhelezko Y.S. Reactive power compensation and power quality improvement. - M. Energoatomizdat, 1985. - 224.
9. Reference design of electrical networks / edited by DL Faibisovich. -M. Univ of NC ENAS, 2006. - 320.
10. On the validity of applying the provisions of the Instruction on the order of payments for electricity and heat, and approved by the State Committee Energy Ministry of Russia November 30, 1993 (№ 01 - 17/1443-11, VK-7539). - Newsletter of the Federal Energy Commission of Russia. - 2000. - June 13, № 11.
11. Poniatowski V. Power factor, and factors affecting its value of industrial enterprises in power and ports. -M.: Traslit, 2009. - 54.
12. Zhelezko Y.S. Loss of electricity. Reactive power. Power quality: a guide for practical calculations. -M. Univ of NC ENAS, 2009. – 459 p.