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POWER QUALITY IN POWER SUPPLY SYSTEMS

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The textbook covers questions on the power quality (PQ) in the power supply systems studied within the course “Power quality in power supply systems". There are given: the analysis of main causes and sources of interference worsening the power quality indices (PQI) and leading to the normal functioning disruption of power supply systems; the examples of consequences when the current-consuming devices operate with PQI deviations from the standard ones; the information on improving the quality indices to the level of electromagnetic compatibility of power supply facilities.

It is intended for students studying in the direction 13.04.02 – ″Power engineering and electrical engineering″.

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INTRODUCTION

Electrical energy, as a special type of product, has certain characteristics that give evidence of its suitability in various industrial processes.

The set of characteristics, at which the current-using equipment is capable of performing the desired functions, are united by a common term **electric power quality** or **power quality** (PQ). The power quality is evaluated with technical and economical indices, which take into account the ***technological*** (defects and deteriorations of the product quality, a reduced productivity, a technological process irregularity) and ***electromagnetic*** (an increase in energy losses, a damage to the electrical equipment, disruptions in automation, telemetry, communications) ***damage*** to the national economy.

The desire to improve the productivity in up to date industrial enterprises, and also the more complex technological processes has led to a widespread usage of controlled powerful valve electric drives and converting installations, as well as powerful electric arc furnaces and welding systems. A key feature of such consumers is a significant impact on the power quality of the power supply networks. In turn, the normal operation of electrical equipment strongly depends on the power quality in the power supply system.

The power quality together with the reliability, safety and efficiency is one of the mandatory requirements for the power supply systems. The power quality is characterized by a set of properties and **power quality indices** (PQI), which are generally regulated in every country by the national standards. For example, in the Russian Federation, PQI are regulated by the Russian government technical requirements GOST 32144-13 "***Electrical energy. Electromagnetic compatibility of technical equipment. Power quality limits in the public power supply systems***". This standard can be considered as a variation of international standard IEC-61000 (IEC – International Electrotechnical Commission), which includes a family of standards providing the information about the limits and features of measurement for different PQI. The PQ standards are the levels of electromagnetic compatibility between the power supply systems and the electrical equipment. The electromagnetic compatibility is the ability of electrical equipment, automation and remote control units to function steadily in terms of an exposure to electric and electromagnetic fields and does not cause a harmful interference to other objects.

In addition to the electromagnetic compatibility requirements, due to the release of the Russian Federation Government Decree № 1013 dated on 14.08.1997 about the inclusion of electrical energy in the list of goods, which must be certified, the power quality should be observed also in terms of the RF Law "On Consumers' Rights Protection". It means that electrical energy supplied to the consumer must have the stated quality.

To ensure the proper technical and economic indices for the power supply systems the PQI must be maintained according to the requirements of the GOST 32144-13, which are presented in the table B.1

TABLE B.1 The power quality indices and their standards according to the GOST 32144-13.

Item No	Name of the PQI, its designation and measuring units	Limits
Continuous changes in voltage characteristics		
1	**Frequency deviation Δf** (Hz)	**- must not exceed ± 0.2 Hz for 95%** of the time interval of one week; **- must not exceed ± 0.4 Hz for 100%** of the time interval of one week.
2	**Voltage deviation (%)** - Positive voltage deviation $\delta U_{(+)}$ - Negative voltage deviation $\delta U_{(-)}$	**must not exceed 10%** of the nominal or agreed voltage value U_{nom} for 100% of the time interval of one week.
3	**Flicker indicators**: – Short-term P_{st} (a.u.) – Long-term P_{lt} (a.u.)	**- P_{st} should not exceed 1.38;** **- P_{lt} should not exceed 1.0** within 100% of the time interval of one week.
4	**Voltage THD (Total Harmonic Distortion) factor** K_u (%)	in table 3.1
5	***n-th*** **harmonic distortion factor** $K_u(n)$ (%)	in table 3.2
6	**Negative sequence voltage unbalance factor** K_{2u} (%)	**Must not exceed 2% for 95**% of the time interval of one week; **Must not exceed 4% for 100%** of the time interval of one week;
7	**Zero sequence voltage unbalance factor** K_{0u} (%)	**Must not exceed 2% for 95%** of the time interval of one week; **Must not exceed 4% for 100%** of the time interval of one week;
Random events		
8	Voltage interruption	------------
9	Voltage dip	------------
10	Voltage swell	------------
11	Surge voltage	------------

Continuous changes in the supply voltage characteristics are long-term deviations of the voltage characteristics from the nominal (rated) values and are mainly caused by load changes or the influence of non-linear loads. Random events are sudden and significant changes in the voltage shape, leading to a deviation of its parameters from the nominal ones. These voltage changes are usually caused by unpredictable events (for example, a damage to the user's equipment on the electrical network) or external influences (for example, weather conditions or actions of a party other than the user of the electrical network).

The requirements of this standard (GOST 32144-13) are applied when establishing PQ standards in electrical networks of:

- general purpose power supply systems connected to the Unified Energy System;
- isolated power supply systems of general purposes.

The requirements of this standard apply in all operation modes of power supply systems of general purpose, except for modes caused by:

- force majeure circumstances: earthquakes, floods, hurricanes, fires, civil unrest, military action.

To maintain the PQI within the rated limits, the PQ should be constantly monitored to analyze and to take measures in order to improve the PQI. The objectives of the PQ control are as follows:

- to check compliance of the PQI with the requirements of standard GOST 32144-13;
- to determine the reasons for the PQI non-compliances;
- to determine the damages caused by the non-compliance to the PQ requirements;
- to identify the violators of requirements for each separate PQI and impose the economic penalties.

According to GOST 32144-13 when controlling the PQI there are following basic rules:

- a control duration of most PQI must not be less than one week;
- There are two types of PQI limits: normally allowed and maximum allowed.

The PQI meets the GOST standard if its averaged (integrated) assessments do not exceed the maximum allowed limits for 100% of the time interval of one week and normally allowed limits for at least 95% of the time interval of one week.

In this textbook, the main power quality indices, their deviations from standard requirements and influence on the production process, operation of various electrical equipment and the power supply networks are studied. We also consider the causes that lead to poor the power quality, methods and tools to maintain the PQI in the given limits.

The textbook does not claim to address all of the issues, so the text contains references to the publications, which you can use to expand the knowledge on relevant topics.

1. VOLTAGE DEVIATIONS

1.1. The concept and essence of the issue

One of the most important power quality indices is the root-mean-square (rms) voltage, which can be phase (phase-to-ground) or linear (phase-to-phase) according to the consumer connection diagram.

Within a single transformation stage, the supply voltage value varies in relatively small limits, so in order to simplify the calculations, and to make it clear, we use the term «voltage deviation».

Voltage deviation δU is the difference between the actual (rms) U and the nominal U_{nom} voltage values for the given network:

$$\left.\begin{aligned} \delta U &= U - U_{nom} \ \ (V, kV); \\ \delta U_{(+)} &= \frac{U_{(+)} - U_{nom}}{U_{nom}} \cdot 100\ \%; \\ \delta U_{(-)} &= \frac{U_{nom} - U_{(-)}}{U_{nom}} \cdot 100\ \%; \end{aligned}\right) \quad (1.1)$$

The actual (or rms) voltage U value in the single-phase electrical networks is defined as the root-mean-square voltage of the fundamental frequency $U_{(1)}$ averaged over a time interval of 10 minutes without taking into account the harmonic components. In the three-phase networks, it is defined as the root-mean-square voltage of the fundamental frequency in direct sequence $U_{1(1)}$ also averaged at the same time interval.

According to the GOST 32144-13 during normal operation modes of the current-using equipment, the voltage deviations from the nominal value **must not exceed 10%** of the nominal or agreed voltage value U_{nom} for 100% of the time interval of one week. To fulfill the mentioned requirement, first of all, it is necessary to perform the voltage deviation control and measurement, do calculations and determine its indices and take measures to stabilize them. These issues are discussed in detail in [1,2]. Also, other PQI are considered in these works.

To understand the essence of the voltage deviation occurrence let`s consider the voltage and current vector diagram of the simplest electrical network with an impedance Z = $R + jx$. Such diagram is presented in fig. 1.1.

The characteristic equations for this network will have the following form:

$$\overline{U}_n = \overline{U}_c + \delta\overline{U}; \quad (1.2)$$

$$\begin{aligned} \delta\overline{U} &= IZ = (I_a - jI_r)(R + jx) = \\ &= I_a R + I_r X - j(I_a X - I_r R) = \Delta\overline{U} - j\Delta\overline{U}, \end{aligned} \quad (1.3)$$

where $\overline{U}_n$ is the voltage vector of the supply network; $\overline{U}_c$ is the voltage vector at the terminals of consumer; $\delta\overline{U}$ is the voltage drop in a line with impedance Z = $R + jx$; $\Delta\overline{U}$ and $j\Delta\overline{U}$ are the longitudinal and transverse components of the voltage drop.

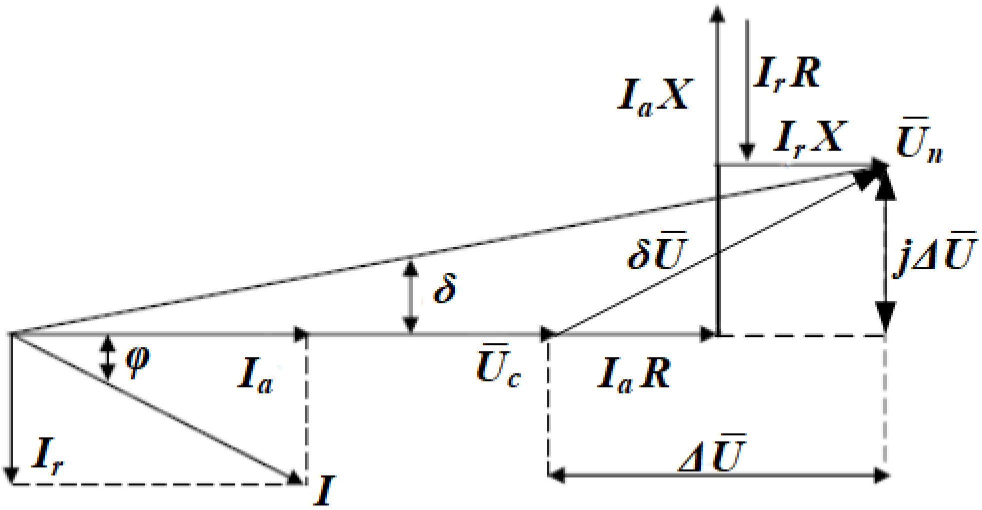


Fig. 1.1. Voltage and current vector diagram of a simple electrical network

The transverse component of the voltage drop in the case of an active-inductive load is relatively small. Angles δ between the voltages in the nodes of the power supply system are also not sufficient (in practice, the total angle between the voltages at various levels of transformation does not exceed 10°). That is why, for the practical calculations of the voltage deviations and fluctuations in industrial networks, the difference between the voltage drop and the voltage losses may be considered as negligible and the voltage losses can be calculated according to the equation:

$$\Delta U = I_a R + I_r X \approx |\delta \bar{U}|. \tag{1.4}$$

Taking into account that in the industrial electric networks $R / X = 0.03 ... 0.1$, the expression (1.4) can be written in per-unit values in the following way:

$$\Delta U_{p.u.} = \frac{\Delta U}{U_{nom}} = \frac{I_a R + I_r X}{U_{nom}} = \frac{PR + QX}{\sqrt{3} U_{nom}^2} = \frac{P\frac{R}{X} + Q}{\sqrt{3} U_{nom} \frac{U_{nom}}{X}} \approx \frac{Q}{S_{sc}}, \tag{1.5}$$

Where S_{SC} - short-circuit power, P - active power at the considered part of the network; Q – reactive power at the considered part of the network.

The equation (1.5) implies that mostly the voltage condition in the electric networks is determined by the reactive power mode.

For the multi-level power networks, we obtain the similar results. This can be seen in an example of voltage deviation calculation in the two-level power supply system [4].

An important aspect in determining the parameters of voltage deviation is a building of a voltage deviations histogram, which is read from special devices, or built according to the statistical observing data. The histogram shows the probability of PQI values to fall in the range of allowed values over the measurement period.

According to the histogram, we calculate the probable PQI numerical characteristics: mathematical expectation (M), dispersion (D), mean square deviation (σ). Knowledge of these parameters is necessary to improve the voltage quality.

The graphical representation of a steady-state voltage deviation histogram may have a form shown in Fig. 1.2:

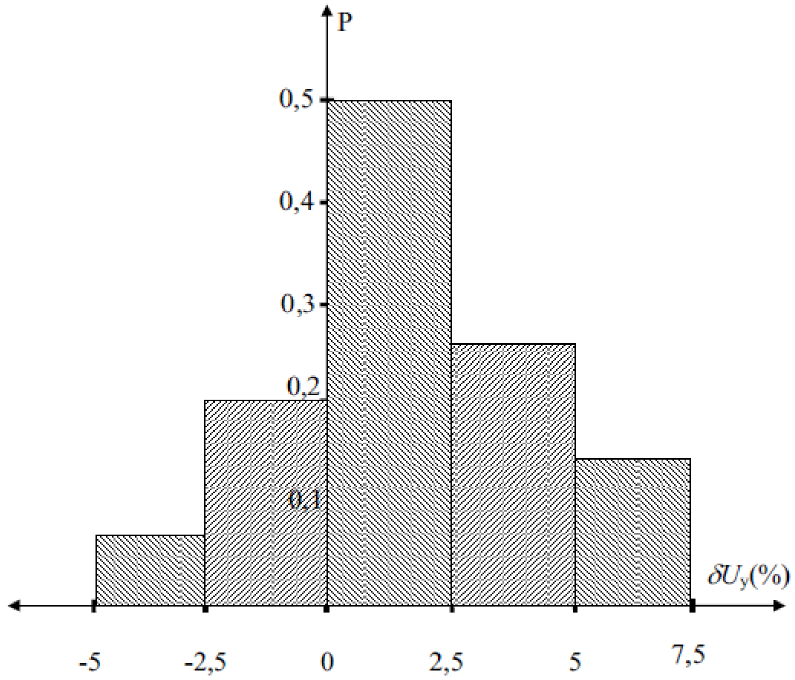


Fig.1.2. *An approximate histogram of the voltage deviation*

The mathematical expectation of a steady-state voltage deviation $M(\delta U_y)$ characterizes the average voltage level in the given electrical network point during the controlled time period. It can be defined from the histogram by the formula:

$$M(\delta U_y) = \sum_{i=1}^{k} \delta \bar{U}_{yi} \cdot P_i \ (\%), \tag{1.6}$$

where k = number of digits in the histogram; $\delta \bar{U}_{yi}$ - the middle value of *i-th* interval; P_i - the probability of the voltage deviation fall in the *i-th* interval.

Scattering the voltage deviation with respect to the mathematical expectation is characterized by the dispersion. It is equal to the squared mathematical expectation of a random variable deviation from its mean value. Using the histogram, the dispersion is calculated according to the equation:

$$D(\delta U_y) = \sigma^2(\delta U_y) = \sum_{i=1}^{k} \left[(\delta \bar{U}_{yi})^2 \cdot P_i \right] - \left[M(\delta U_y) \right]^2 =$$

$$= \sum_{i=1}^{k} \left[\delta \bar{U}_{yi} - M(\delta U_y) \right]^2 P_i \ \%, \tag{1.7}$$

Where $\sigma(\delta U_y)$ – the mean square or standard deviation.

1.2. Influence of voltage deviations on the performance of electrical equipment and the production technological process

The main factors that cause voltage deviations in power supply systems are the changes in working modes of the current-using equipment and power sources, and an improper connection of single and shock loads to the elements of the power supply system.

The PQI deviation from the standard or optimal values can cause the economic losses to the energy consumer, who has electromagnetic and technological components. The electromagnetic component can cause mainly additional losses of the active power and energy and reduce the electric equipment lifespan due to the accelerated electrical insulation aging. The technological component is associated with an increase in the production process duration, with a decrease in the electrical equipment productivity that leads to a growth of the specific power consumption per each economic output unit.

The analysis of dependences of the power supply system energy characteristics should be carried out by studying the influence of the voltage quality on the basic types of electrical equipment: motors, lighting installations and production equipment. Let's consider the work of typical current-using equipment under different PQ deviations.

Induction motors. The vast majority of motors in industrial power plants are the induction motors. The research [5] has shown that the voltage deviation significantly affects the energy performance of induction motors. For example, Fig. 1.3 shows the relationships of the additional active power losses $\delta(\Delta P_{nom})$ and reactive power losses $\delta(\Delta Q_{nom})$ in respect to the nominal (ΔP_{nom}, ΔQ_{nom}) ones depending on the voltage deviations.

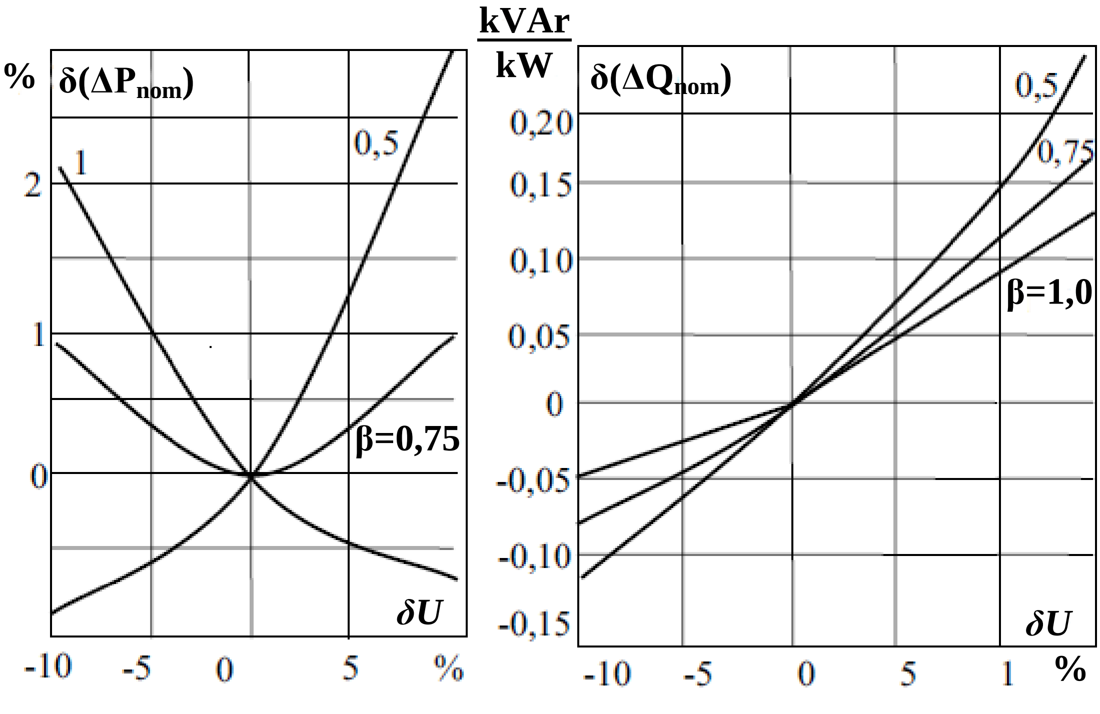


Fig 1.3. *The power loss changes in dependence on the voltage deviations at different load factors **β**: a - active power; b - reactive power*

As you can see from the figures, the change in the active losses in the induction motors with voltage deviations within ±10 % U_{nom} are relatively small (not more than 0,03 ΔP_{nom}), but they become the same order as the losses in the power supply networks.

In practice, it is considered that for the line A induction motors with power of 20 ... 100 kW within acceptable range of voltage deviations, a 1% voltage change leads to a 3% increase in the reactive power consumption.

The changes in the energy characteristics of an induction motor, in dependence on the voltage magnitude and frequency deviation relatively to the nominal values, can be easily analyzed by the equivalent circuit diagram shown in Fig. 1.4. The change in the network voltage U causes a corresponding variation in the magnetizing current I_o:

$$I_0 = \frac{\dot{U}_1 - (r_1 + jx_1)\dot{I}_1}{r_0 + jx_0} \tag{1.8}$$

and, respectively, the motor magnetic flux Φ.

Neglecting the voltage losses in the primary (stator) winding at low slips $S<S_{cr}$, we can approximately assume that the relative changes in the motor magnetic flux directly connects with the relative changes in voltage and frequency values by the following formulae:

$$\frac{\Phi}{\Phi_{nom}} = \frac{U}{U_{nom}} = K_U,$$

$$\frac{\Phi}{\Phi_{nom}} = \frac{f_{nom}}{f} = K_f, \tag{1.9}$$

where U_{nom}, f_{nom} - nominal voltage and frequency values; K_U, K_f – relative values of voltage and frequency.

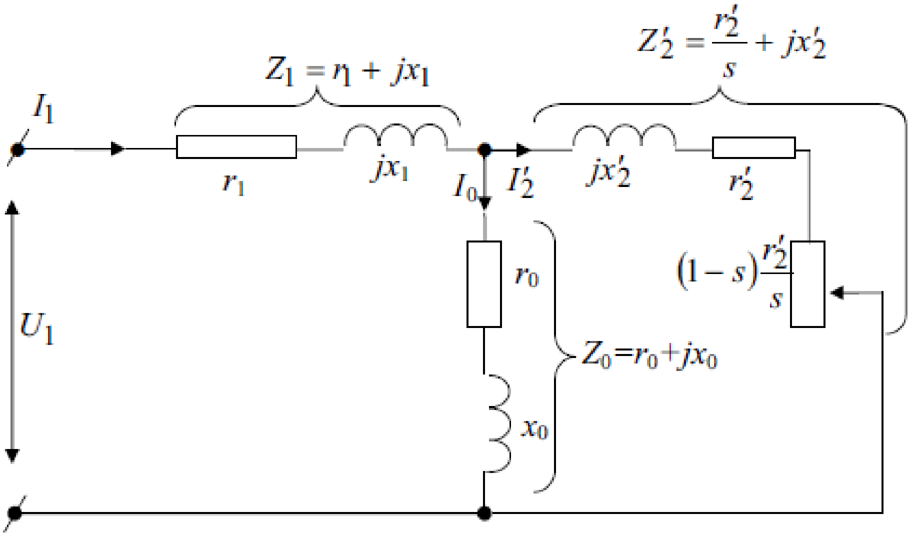


Fig. 1.4. *An equivalent circuit diagram of the induction motor*

The relative magnitude of the torque M at the rated (nominal) frequency (K_f=1) as a function of the supply voltage is defined as:

$$M = \frac{2b_{nom}\left(\frac{U}{U_{nom}}\right)^2}{\frac{S_{cr}}{S} + \frac{S}{S_{cr}}}, \quad (1.10)$$

where $b_{nom} = \frac{(M_{max})_{nom}}{M_{nom}}$; $(M_{max})_{nom}$, M_{nom} - the maximum nominal value and the nominal value of torque; S_{cr} - critical slip, at which the motor develops its maximum torque (S_{cr} = 5…15 %). Therefore, when the voltage U changes, the motor speed-torque characteristic will also change. If maintain the load characteristics constant M_c= const, it will lead to a slip variation approximately inversely as the voltage square:

$$\frac{S}{S_{nom}} \approx \frac{M_c U_{nom}^2}{M_{nom} U^2}, \quad (1.11)$$

under the assumptions that $S_{nom} \approx \frac{S_{cr}}{2b_{nom}}$, $b_{nom} > 1.6$.

The graphical dependences of the slip on the voltage at the nominal frequency and different values b_{nom} are shown in fig. 1.5.

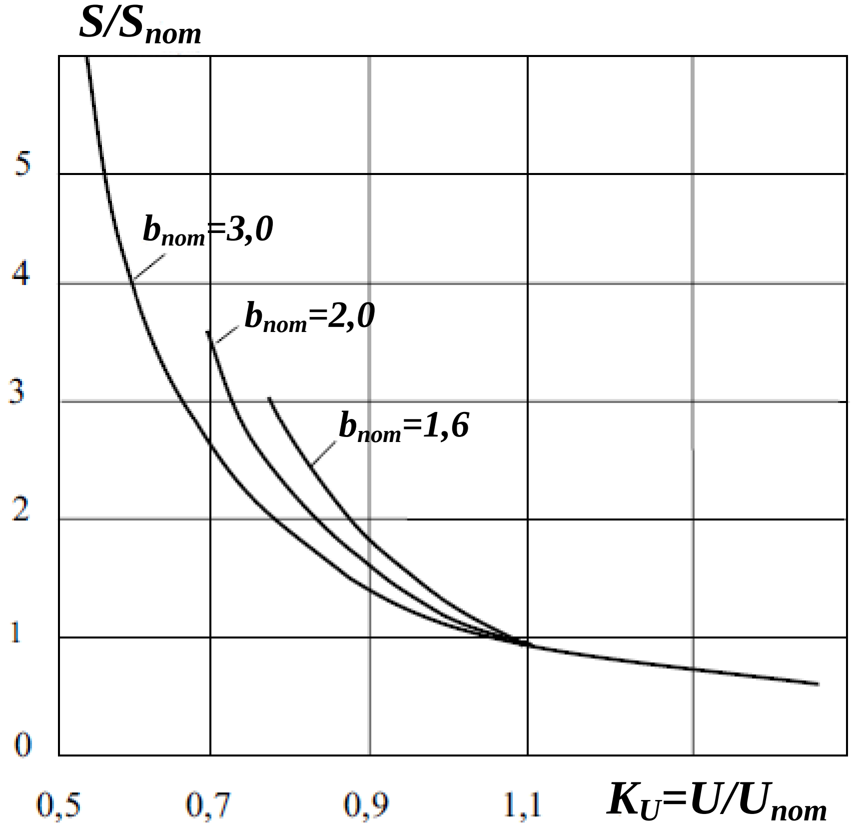


Fig. 1.5. *The slip change in dependence on the voltage*

The induction motor torque is related to the slip value at different supply voltage values by a graphical dependence shown in Fig. 1.6.

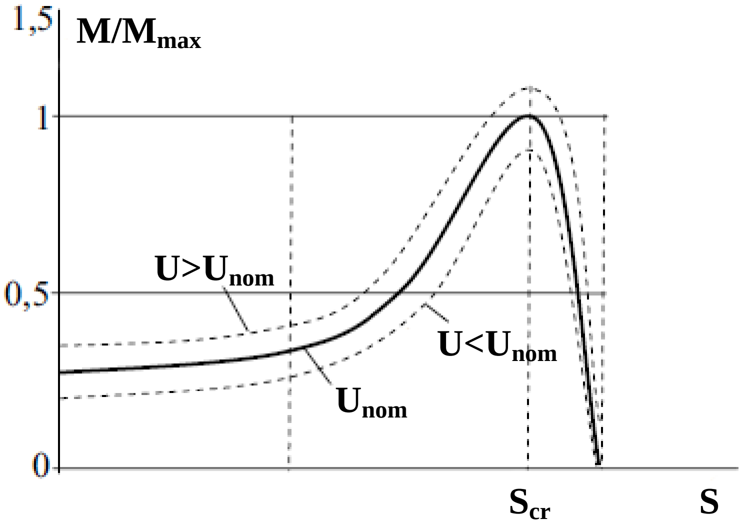


Fig. 1.6. *Torque characteristics of the induction motor at various supply voltages*

The rotor current at voltage deviations changes inversely proportional to the voltage:

$$I'_2 \approx \frac{M_s I'_{2nom} U_{nom}}{M_{nom} U}. \qquad (1.12)$$

The stator current of an induction motor without the active open-circuit losses ($\sin\varphi_0$ = 1.0) is determined by the geometric sum of the active and reactive components:

$$I_1 = \sqrt{(I_0 + I'_2 sin\varphi')^2 + (I'_2 cos\varphi')^2}, \qquad (1.13)$$

where $cos\varphi' = \sqrt{\frac{b_c + \sqrt{b_c^2 - 1}}{2b_c}}$, $sin\varphi' = \frac{1}{2b_c\left(b_c + \sqrt{b_c^2 - 1}\right)}$, $b_c = b_{nom}\frac{M_{nom}}{M_s}\left(\frac{U}{U_{nom}}\right)^2$

The stator current change as a function of the voltage at the nominal values of frequency and load (K_f = 1, $M_c = M_{nom}$) and b_{nom} = 2 is shown in Fig. 1.7.

The stator current phase can be approximately defined as:

$$\varphi = arctg\frac{I_0 + I'_2 sin\varphi'}{I'_2 cos\varphi'}. \qquad (1.14)$$

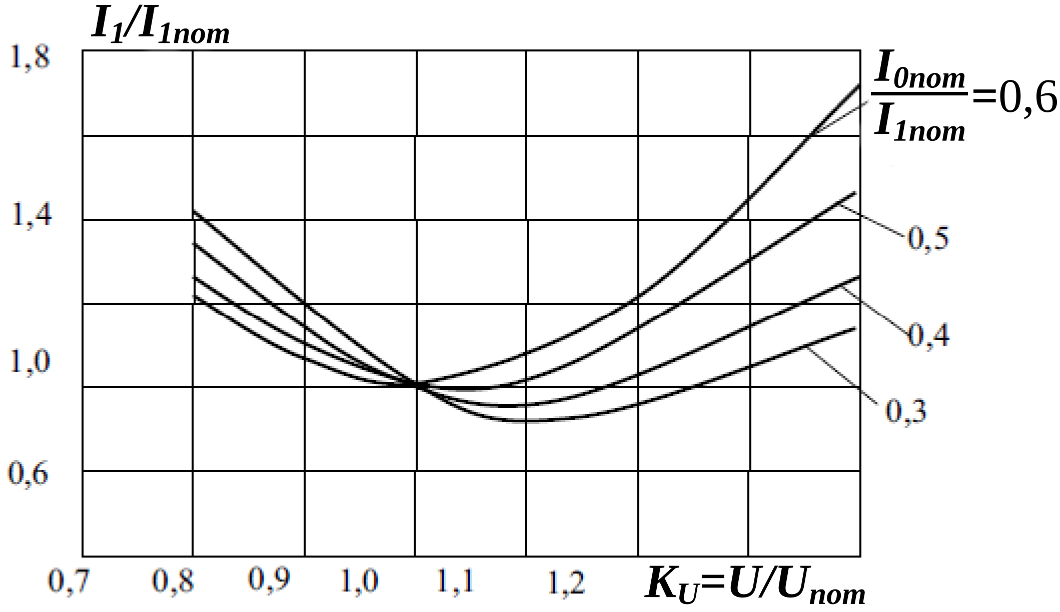


Fig. 1.7. *Changes in the motor stator current depending on the voltage for different multiplicity of the open-circuit current*

Thus, when the voltage decreases, the magnetizing current is going down, and the stator current, which is equal to the geometric sum of the reduced rotor current and open-circuit current, can increase or decrease according to the induction motor load and the relation between I_2 and I_0. The rotor current always increases.

Working with voltage reduced by more than 5% from nominal is only acceptable on the condition of the motor underload. Otherwise, the rotor winding overheating is possible.

When the voltage is risen up, the magnetic flux increases, but the slip and the rotor current decreases. The magnetizing current increases, while the stator current can increase or decrease according to the induction motor load and the ratio between I_0 and I_2.

The power developed by the motor will remain virtually unchanged, as the rotor speed is slightly changed.

The undervoltage has a significant impact on the lifespan of induction motor. This is connected with the accelerated insulation aging, when the motor current increases. So, at 10% of voltage deviation and the nominal motor load its lifespan is reduced by half.

The pro forma data on the supply voltage deviation effect on the characteristics of induction motors are listed in Table 1.1.

The active power consumed by the motor from the network at a fixed frequency (K_f = 1) under voltage deviations can be determined by the formula:

$$P = \sqrt{3}U\left(I_0 cos\varphi_0 + \frac{I'_{2nom}M_c U_{nom}}{M_{nom}U}\right)\cdot\sqrt{\frac{b_{nom}+\sqrt{b_{nom}^2-1}}{2b_{nom}}}, \quad (1.15)$$

where U, U_{nom} – actual and nominal phase-to-phase voltages in the supply network.

The reactive power consumed by the motor at a nominal frequency (K_f = 1) and voltage deviations are equal to:

$$Q \approx Q_{nom}\left[C\left(\frac{U}{U_{nom}}\right)^2 + (1-C)\left(\frac{M_s U_{nom}}{M_{nom} U}\right)^2\right], \quad (1.16)$$

where $C \cong 1 - \frac{1}{\left(b_{nom}+\sqrt{b_{nom}^2-1}\right) tg\varphi_{nom}}$.

Table 1.1. *Changes in the characteristics of induction motors under the positive and negative voltage deviations*

Motor characteristics	The change in the characteristics at voltage change	
	-10 %	**+10 %**
- Starting and maximum torque	-19 %	21 %
- The synchronous speed	const	const
- Slip	23 %	-17 %
- Speed at rated load	-1.5 %	1 %
- The efficiency at the load:		
- nominal	-2 %	+1 %
- 75 %	const	const
- 50 %	-1…-2 %	1…2 %
Power factor at the load:		
- nominal	1 %	-3 %
- 75 %	2…3 %	-4 %
- 50 %	4…5 %	-5…-6 %
-Rotor current at the nominal load	14 %	11 %
-Stator current at the nominal load	10 %	-7 %
-Starting current	-10…-12 %	10…12 %
-Winding temperature increase at nominal load	5…6°	virtually unchanged

The diagram of a dependence of the reactive power, which is consumed by the induction motor, on the voltage is shown in Fig. 1.8.

The change in the voltage frequency causes a variation in the inductive resistance of an induction motor that affects its energy characteristics. In particular, the decrease in the frequency at a constant voltage and constant torque resistance will increase the magnetizing current I_0 and, consequently, the motor magnetic flux Φ, according to the dependence:

$$\frac{\Phi}{\Phi_{nom}} = \frac{f_{nom}}{f}. \quad (1.17)$$

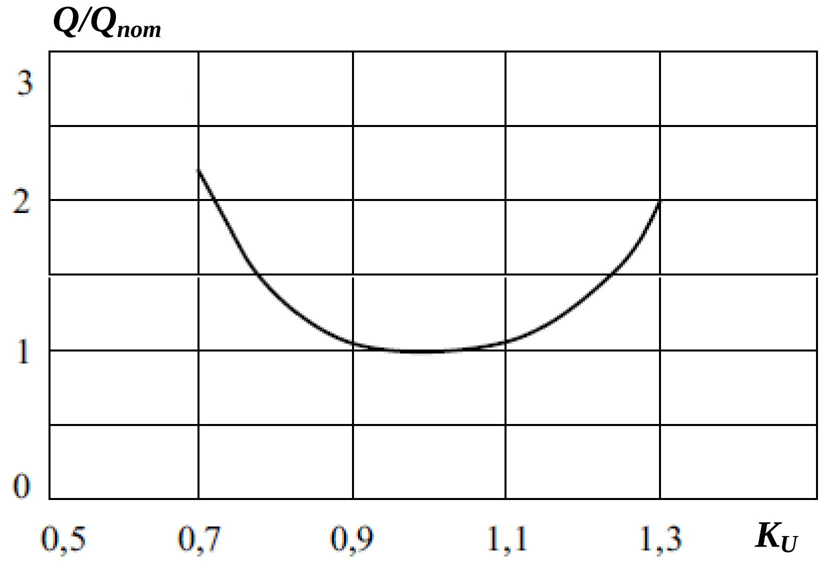


Fig. 1.8. *Change in the motor reactive power depending on voltage*

The larger magnetic flux will increase the torque inversely as the square of the frequency. To maintain a balance between the load resistant torque and motor torque, the slip decreases in accordance with the equation:

$$S = \frac{f_{nom} S_{cr}}{f\left(b_c + \sqrt{b_c^2 - 1}\right)}. \tag{1.18}$$

The decrease in the slip leads to the rotor current reduction. The stator current, in this case, may grow or fall in the same manner as in the case of the voltage increase. In Fig. 1.9, you can see dependences of the slip on the frequency, when working at a nominal voltage and torque.

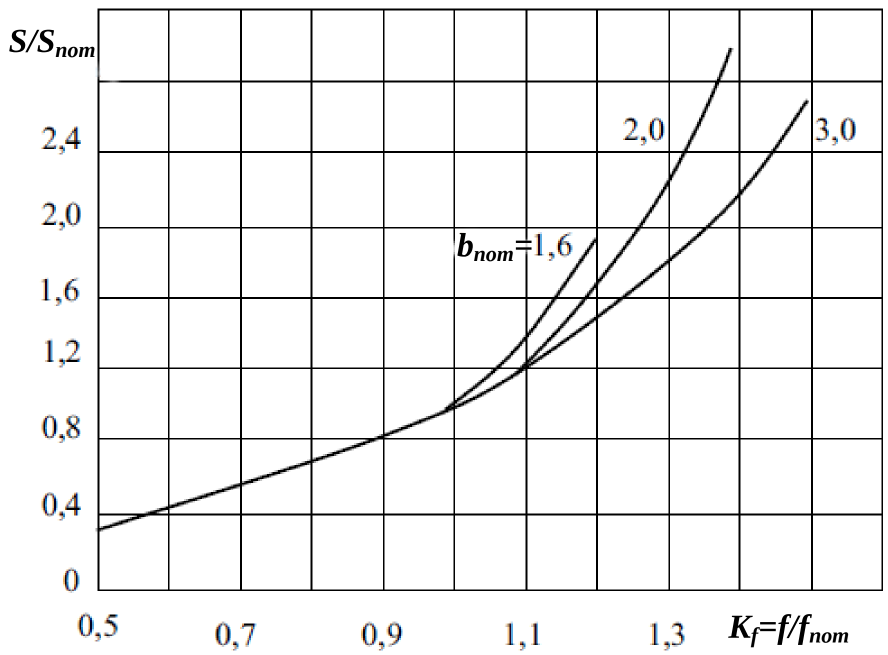


Fig. 1.9. *The dependence of slip on the frequency at nominal voltage and torque*

As can be seen from the Fig. 1.9, the slip is proportional to the frequency change, when the frequency is decreased at constant load, and varies to a greater extent with frequency growth.

The Fig. 1.10 shows the dependence of the stator current on the frequency, when operating at a nominal (rated) torque and voltage.

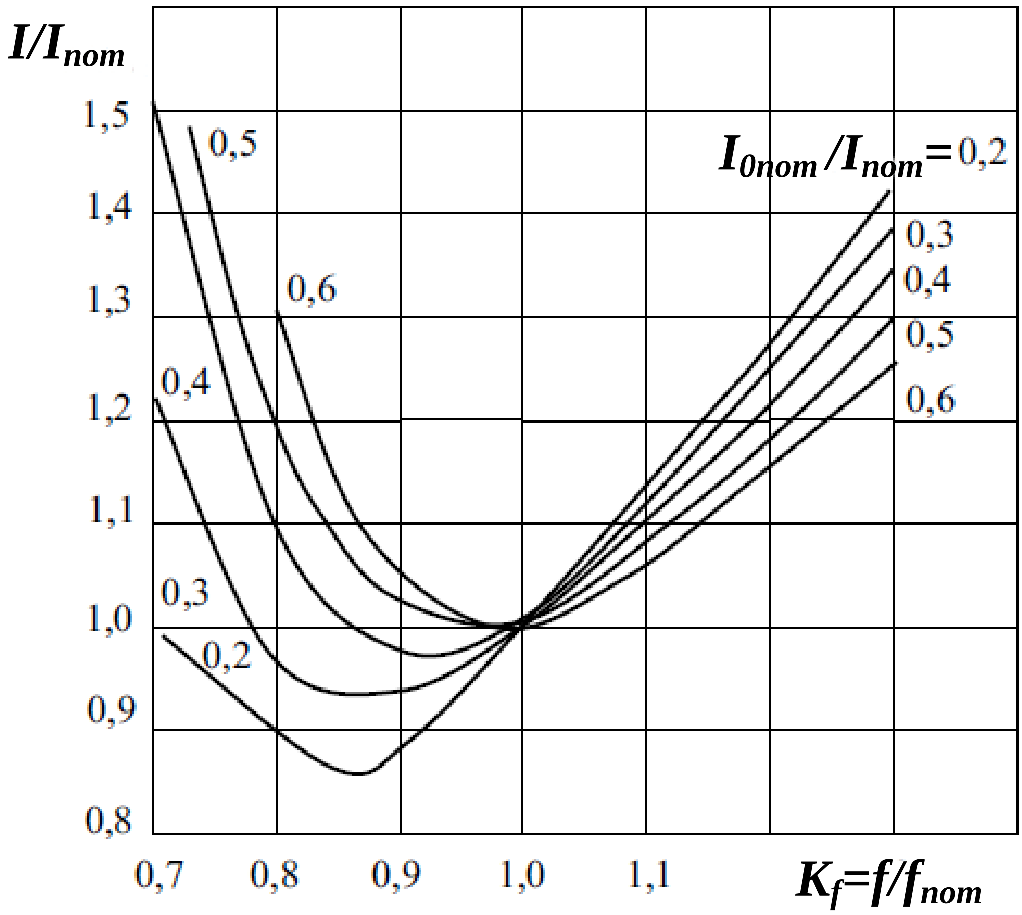


Fig. 1.9. *The dependence of stator current on the frequency at rated torque for motor having b_{nom}=2.*

Under the frequency enhancing at a nominal voltage and torque, the stator current increases (Fig. 1.10), and this increase is greater, the smaller the open-circuit current is. With frequency decreasing, the stator current at small values of the open-circuit current at first goes down and then starts growing, while for large values of the open-circuit current it increases all the time because of a sharp increase in the magnetizing current.

Thus, the frequency decreasing is almost equivalent to the voltage raising. Consequently, if ***f*** decreases and we reduce the voltage accordingly, then the magnetic flux, and therefore, the open-circuit current of the rotor and stator remain the same as at a nominal operation. Some changes in the steel losses and, consequently, in the active component of open-circuit current have practically no impact on the stator current.

The motor speed varies almost proportionally to the frequency of the network. For example, for an induction motor having a multiplicity of the maximum torque b_{nom} = 2.0, the critical slip S_{cr} = 0.1, and working at a constant resistance torque, which is equal to the nominal one, a 10% frequency deviation leads to a 9.8 % rotor speed change.

Production equipment. In systems of production lines, automated machine tools, etc., voltage deviations can significantly affect the production equipment performance. Let's consider several examples [8].

Experimental studies [8] carried out on the rolling machines of a Hardware Metallurgical Plant showed that the average minute performance of these machines is 0.275 kg, when the voltage at the motor terminals is equal to $U = 1,05 \cdot U_{nom}$ and 0.236 kg for $U = 0,9 \cdot U_{nom}$.

With the three shifts on a plant, the underproduction at one machine at $U = 0,9 \cdot U_{nom}$ is about 5000 kg per year. Increasing the voltage over the $1,05 \cdot U_{nom}$ leads to a product quality reduction.

In the distribution network of above 1000 V, the voltage change of 1%, when smelting 45% of ferrosilicon, leads to a drop in the productivity of ore-thermal furnace to 1.717 tons per day.

Lowering the voltage to 1% for the transfer pumps at a paper mill leads to a 0.1% underproduction.

The research on weaving machines revealed that for each percent of voltage decrease the mechanisms reduce performance by 0.2%, while the voltage deviations above 5% leads to the enhanced decrease in the productivity per each percent of deviation. When the voltage is increased, the equipment productivity is negligible.

The equipment productivity reduction and increase in power losses leads to an increase in the energy consumption per output unit up to 0.3% for each percentage of voltage deviation. With positive voltage deviations, the specific power consumption is reduced to 0.2% to every deviation percent, respectively.

Voltage deviations have significant affected the technological processes in electrothermics. When the voltage decreases, the duration of the process becomes longer, and in some cases, there may be a complete process failure. Thus, when the voltage drops to 8 ... 10%, the technological process in resistance furnaces and induction furnaces cannot be completed. For example, in one of the plants during annealing the workpieces made of nonferrous metal in resistance furnaces with total a capacity of 675 kVA, when the voltage dropped to 7%, the process was 5 hours instead of 3 hours at a nominal voltage. When the voltage dropped to 7% or more the technological process was impossible. Annealing delay in electric furnaces leads to the process lengthening, increased electrical energy consumption and increase in production costs.

Lighting Installations. The power of lighting installations at enterprises is characterized by the load density of 10 ... 100 W/m^2 and higher, depending on the production requirements.

The common light sources, which are used in lighting installations, are now incandescent lamps (light bulbs) and gas-discharge lamps such as low-pressure fluorescent mercury lamps, high-pressure mercury lamps, high pressure sodium lamps, arc xenon tube lamps.

The characteristic features of light bulbs are as follows: a simple connection scheme, they are uncritical to changes of environmental conditions, the power factor is practically equal to 1. The majority of incandescent lamps has a light output in the range 7 ... 19 lumens/watt (lm/W). A lifespan of such lamp type does not exceed 1,000 hours. The low light output and a relatively short lifespan make the usage of incandescent lamps in the industrial enterprises limited.

The gas-discharge lamps have a significantly better performance in the light output. For example, the high-pressure mercury lamps are characterized by the light output of about 40 ... 60 lm/W, while the high pressure sodium lamps have 140 lm/W. The lifespan of gas-discharge lamps is times superior to the lifespan of incandescent lamps. This determines the almost universal application of gas-discharge lamps to illuminate the production facilities and the outdoor areas.

The disadvantages of the gas-discharge lamps are as follows: the need for run-regulating equipment, which should include compensating capacitors to improve the power factor up to 0.9 - 0.95; significant fluctuations of the light flux; long, up to 5-7 minutes process of a lamp buildup.

An important light source characteristic is the dependence of the light output on the supply voltage value and lamp power consumption, respectively. The relative performance of incandescent lamps and gas-discharge lamps, on the example of high-pressure mercury lamp, are shown in Fig. 1.11 and 1.12. The figure shows the dependence of the relative values of the light output B/B_{nom} (curve 1), the power consumption P/P_{nom} (curve 2), the lifespan of T/T_{nom} (curve 3) as a function of the relative voltage U/U_{nom} [7].

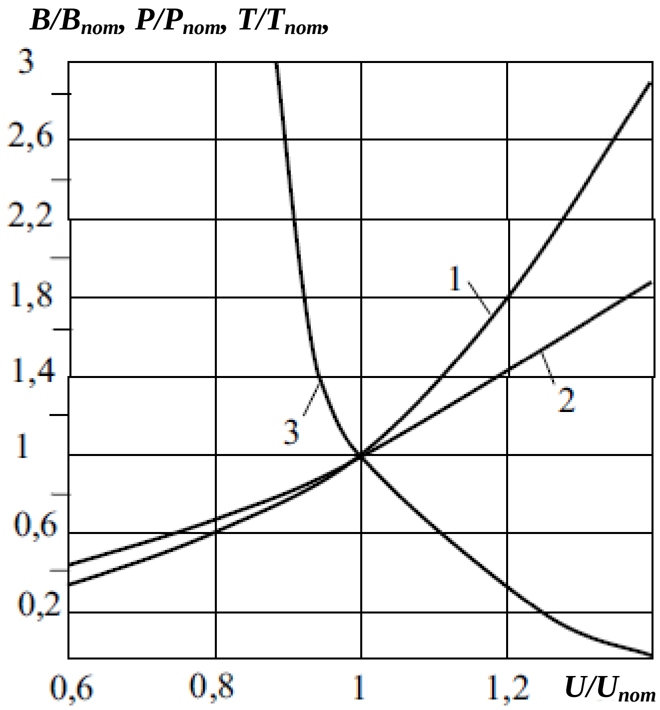


Fig. 1.11. *The relative performance of incandescent lamps*

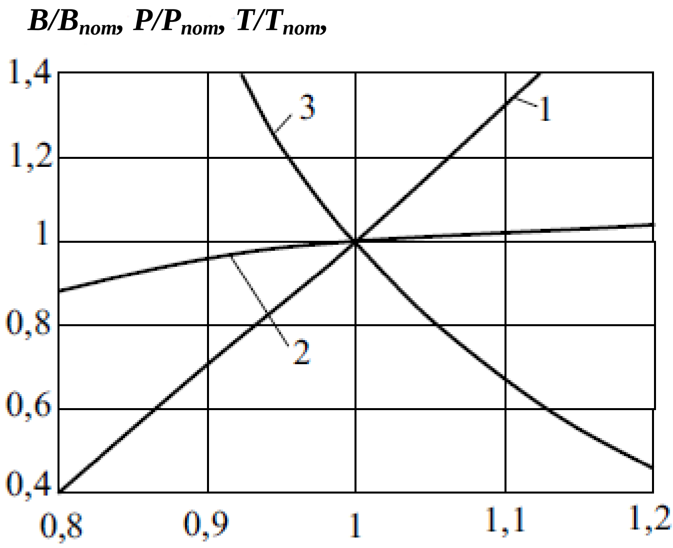


Fig. 1.12. *The relative performance of high-pressure mercury lamps*

The curves in Fig. 1.11 and Fig. 1.12 clearly reflect the dependence of the energy and lighting lamp parameters on the supplied voltage, which in turn, significantly changes their lifespan. For example, the incandescent lamps are the most sensitive to changes in the supply voltage. The voltage reduction even within 2.5% leads to a loss of the luminous flux. The voltage increase by 5% leads to a double reduction of the lamp lifespan. The gas-discharge lamps are less sensitive to the level of the supply voltage in accordance with a lighting performance. However, the power consumed by a lamp increases significantly, when the supply voltage increases. The increase in the power consumed by lamps of different types as a percentage of the nominal power consumption is given in Table 1.2.

Table 1.2. *Lamps power consumption growth*

Lamp type	**overvoltage, %**					
	1	2	3	5	6	10
Incandescent lamps	1.6	3.2	4.7	8.1	11.5	16.4
High-pressure mercury lamps	2.4	4.9	7.2	12.2	17	24.3
High pressure sodium lamps	2	8	11	18	23	34

In addition to a substantial increase in the power consumption for lighting, a supply voltage growth leads to the necessity to increase the number of lamps required for lighting installation operation and to additional operating costs. The relations between the supply voltage excess and the relative lifespan and the number of lamps of various types necessary for the operation are shown in Table 1.3 [13].

These data clearly show that it is necessary to effectively stabilize the voltage at the terminals of the light sources to use rationally the electrical energy for lighting and reduce the operating costs.

Table 1.3. *Number of necessary lamps*

Parameter	**Overvoltage, %**						
	0	1	2	3	4	5	6
Relative lifespan of lamps, %:							
incandescent	100	87.1	75.8	66.2	50.5	38.7	7.8
gas-discharge	100	95	93	90	85	80	73
Number of necessary lamps for the operation							
incandescent	100	114	132	151	198	258	1284
gas-discharge	100	105	108	111	118	125	137

1.3. Methods and means of voltage deviation reduction

The main factors affecting the voltage deviation magnitude in the power supply systems are the maintenance of the reactive power load balance at the nodes, the optimum voltage regulation at the main substation, the usage of a local voltage control, the rational phase distribution of shock and single-phase loads.

One of the main conditions to reduce the power losses and improve its quality is to increase the nominal voltage level. Typically, the excess of voltage deviations above the allowed limits indicate the irrational voltage level at the given power supply stage.

Voltage regulation at the main substation. The most effective method to reduce the voltage deviations is the voltage control. When saying the voltage control, we mean a set of activities using different equipment to limit the voltage deviations at the power consumer side within acceptable limits. The voltage control at enterprises can be carried out in the following ways [4]:

- boosting the additional voltage U_{add} by including in-series regulating transformers or by changing the transformer turn ratio;
- change in the longitudinal and transverse components of the voltage drop (change in the reactive component of the full current load and in the inductive reactance of the network) by regulating the reactive power flux in the supply and distribution networks by means of compensating devices (capacitor banks, synchronous machines and synchronous compensators);
- changing the voltage in the power system networks by varying the generators excitation current;
- change in the power system diagram and others.

The change in the boost voltage by including an in-series regulating transformer (boosting transformers or linear regulators) is really expensive, that is why they are mainly used at the power substations. At the enterprises, this method is used only in high-power converting installations.

Changing the voltage at the buses of the power supply sources (centralized control) is carried out by the "counter-regulating law": during the peak load modes, the voltage is increased up to no less than 5% of nominal voltage, and during the minimum load modes the nominal voltage is maintained.

The on-load tap-changing transformers have a large adjustment scale, which is from ± 10 to ± 16%. The number of tapping steps depends on the voltage of one step, which can be 1.25% to 2.5% with an automatic or manual voltage control.

The tapped or SWE transformers (switching without excitation - SWE), have a control range of ± 5 (10)% from the nominal voltage. Such control is used mainly during seasonal load changes (transition to winter or summer schedules).

The on-load tap-changing transformers are much more expensive than the SWE transformers, so basically only the high voltage (above 35 kV) transformers are equipped with the on-load tap-changing devices. The use of on-load tap-changing transformers at the 6 ... 10 kV voltage level is determined by the feasibility study (for example, in the electrolysis and electro-thermal installations).

The simultaneous voltage control at the terminals of all current-using equipment may be rational, if they are homogeneous (pump station motors, electrolysis shop). In other cases, the analysis of load graphs is carried out and the current-using equipment is combined in peer groups, which are connected to a single on-load tap-changing transformer. If it is impossible to combine the current-using equipment into peer groups, the control is made under the law determined by the prevailing load.

The voltage deviation decrease can be obtained by reducing the active R (increasing the cross-section of wires and number of cores in the network) and the reactive X components of the power supply system. The X reduction is achieved by splitting the wireway phases and by using an in-series capacitive compensation. In the latter case, there is a decrease in the line reactance ($X = X_L - X_c$) and voltage losses decrease, respectively. The negative effects of an in-series compensation are as follows: an increase in the short-circuit currents in the feeders, an overvoltage occurrence in the capacitor banks, when there is a short-circuit above the capacitors in the circuit, and the possibility of low-frequency oscillations in an in-series circuit "inductance-capacitance".

The voltage losses reduction can also be achieved by adjusting the reactive power flux in the supply and distribution networks of an enterprise using compensating devices.

The expression for determining the voltage U_1 at the buses of the main step-down substation (MSDS), taking into account the above-mentioned control methods, can be represented by the formula:

$$U_1 = U_n \pm U_{add} - \frac{P_e R + (Q_e - Q_{CD})(X_L - X_C)}{U_{1nom}}, \tag{1.20}$$

where U_n – the voltage of the supply network feeding the main step-down substation (reduced to U_1); U_1 and U_{1nom} – actual and nominal values of the voltage in the distribution network of 6-10 kV at enterprise; R, X_L, X_c – the equivalent resistances of supply network from the system to the load node, including X_L and X_c

from the installations of an in-series compensation, if they are; U_{add} – additional voltage increase provided by the transformer winding taps switch or by the in-series regulating transformer; Q_{cd} - adjustable power of compensating devices; P_e and Q_e - calculated active and reactive loads of enterprise including losses.

The U_1 voltage control, according to (1.20), can be achieved by adjusting the voltage supplied from the power system (network) U_n. It is possible to do, for example, by changing the generator excitation in the operational management of the system supervisor. This method of the centralized area control does not always correspond to the duty of a particular enterprise.

The most effective way is considered to be the complex control, when together with the change in the transformer turn ratio the power of the enterprise compensating devices are consistently changed. In electrical networks of industrial enterprises, the reactive resistance is in 10...30 times more than the active one [4], hence the voltage at the load buses U_1 (Figure 1.13) significantly depends on the reactive power Q, derived from the system, which is the product of $Q \cdot X$. Curve I represents the nonlinear dependence of $U_1 = f(Q)$, since an increase in the reactive power consumption of the system increases nonlinearly X_L (reactive power is taken from more distant power plants). Using the on-load tap-changer of the transformer T, we can vary the voltage U_1 (Curves II, III), without changing the reactive power Q, derived from the system.

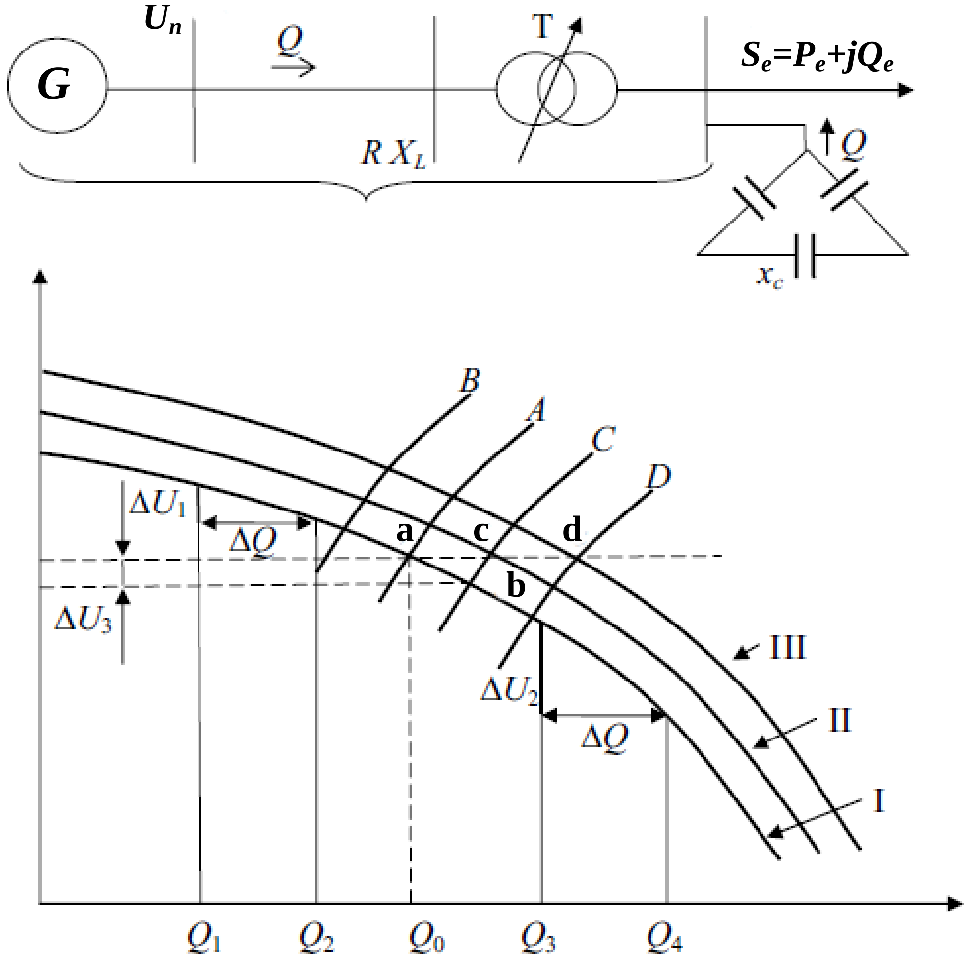


Fig. 1.13 *Dependences of voltage and reactive power flux in the load node*

When changing the reactive load, the ratio, which is called the slope coefficient K_c, will be different in different parts of the curve $U_1 = f(Q)$, i.e. if $(Q_2-Q_1)/\Delta U_1 = 10$, then $(Q_4-Q_3)/\Delta U_2$ will have $K_c >> 1$. This fact must be taken into account for the on-load tap-changer automatics, because with the same change in the reactive power, the voltage correction can be different.

The reactive power Q_e (load) consumption is varied in accordance with the static characteristics $Q_e = f(U_1)$. For example, curve A represents the static load characteristic for a given value Q_0.

With a decrease in Q (capacitor bank (CB) enabled) the characteristic curve will take the position B, with an increase in Q (CB partially disabled) - the position of C, D, etc.

Suppose the initial consumption balance and reactive power generation is set in the point *a* of the curves I and A intersection. If load Q_e increases (curve C), the intersection of characteristics occurs in the point *b*, the voltage will drop to the value ΔU_3. The on-load tap-changing transformer T can transfer the characteristic I to the position II, while the intersection point will transfer to the point *c*. The voltage, in this case, will increase according to the transformation T step change. The transition to the point *d* is similar.

Thus, by adjusting Q_e simultaneously with the transformer voltage change U_{add} an enterprise can achieve the constant voltage U_1 with an optimal value of power flow from the system to the considered load node.

Local voltage control in distribution networks. Certain energy consumers have different distances from the main step-down substation, different load demand curves that leads to the different requirements for the voltage control. Therefore, the individual voltage control, which is applied in the certain network points or directly to the consumer terminals, is known as the local voltage control. For this purpose, controlled reactive power sources (SM - synchronous motor and CB – capacitor banks) and devices, creating a boost voltage U_{add} (linear controllers and constant-voltage regulators) are used. Let`s consider the relation between the reactive power and the voltage at the load node, which allows to locally control the voltage [9].

When you turn on or turn off the compensating devices, the voltage at the terminals will vary according to (1.20) and multiplied by the value (by the step):

$$V = \frac{Q_{CD}X}{U}, \tag{1.21}$$

where Q_{cd} - compensating devices power; X – reactance of the circuit “system - the terminals of the compensating device”; U – the voltage at the terminals.

If we assume that the voltage U at the connection point of the compensating devise is equal to U_{nom}, then the overvoltage is V,%:

$$V = \frac{Q_{CD}X}{U_{nom}^2}100 = \frac{Q_{CD}}{S_{sc}}100. \tag{1.22}$$

The reactive power of the compensating device is needed to boost the voltage to the desired level $V_{reg.}$, can be found from (1.21):

$$Q_{reg} = \frac{V_{reg} U}{X}. \quad (1.23)$$

If the voltage and V_{reg} is given in per-unit values V_{p*}, then

$$Q_{reg} = \frac{V_{p*} U_{nom*} U_{nom}^2}{X}. \quad (1.24)$$

When connecting 380 V capacitor banks to the buses of the substation transformer, the voltage rise is defined as

$$V_{reg} = \frac{Q_{CD} U_{sc}}{S_{nom.tr}}, \quad (1.25)$$

Where $S_{nom.tr.}$ – nominal transformer power; U_{sc} – transformer short-circuit voltage, %, which in the per-unit values is equal to the transformer resistance and the short-circuit resistance after the transformer (not including X_{syst}).

In the enterprise distribution networks, the 6-10 kV networks are usually short and have a low resistance. Therefore, varying the capacitor bank power does not allow providing an effective local voltage regulation. That is why, the centralized on-load tap-changer control at the main step-down substation is required. The local regulation is required for the networks up to 1000V, where a rational combination of automatic and fixed capacitor banks can provide a required power level and its control.

The next important means of voltage quality improvement is a change in the transformer turn ratio for the plant transformers (PT). PT are at different distances from the main step-down substation and, therefore, the voltage losses will be different. To keep the voltage deviations at the equipment terminals in the required limits, it is necessary to choose the PT transformation ratio according to the voltage deviation at the higher side of the transformer and its load.

Usually, the plant transformers have no devices for switching taps on-load. Such transformers are called transformers - SWE - switch without excitation. Since the switching of the transformer taps with SWE is done, when it is disconnected from the network (they are rarely produced, only in seasonal load changes), it is important to choose the plant transformer turns ratio so that the voltage deviation at the terminals of the power consumers at the time of minimum and peak loads do not exceed the allowed limits.

The local voltage regulation through the additional e.m.f. is done by installing boosting transformers at the required network points, but it is really expensive [9].

The local voltage control is used only when other methods of regulation have no the desired effect.

Normalization of voltage deviations in lighting networks. In general, the requirements for the quality of lighting power sources are more stringent than the requirements for other electrical consumers. This is due to the rated illumination intensity and the lamp lifespan.

The power of lighting installations is usually supplied from 380/220 V transformers, which are generally the same for lighting and power loads and have a variable load graph. The lighting networks are characterized by the large branching and length. Therefore, an essential requirement for the calculation of lighting network is the choice of such wire cross-sections, in which the voltage deviation at the terminals of the light sources would be within the allowable limits.

The recommended voltage level in the most remote light sources shall be not less than 97.5% of the nominal value. The voltage drop to more than 10% from the nominal value does not guarantee even a reliable ignition and combustion of gas-discharge lamps.

The voltage losses are determined taking into account the transformer losses:

$$\Delta U_\delta = U_{OC} - \Delta U_{tr} - U_l, \tag{1.26}$$

where U_{oc} – transformer open-circuit voltage, corresponding to the nominal voltage at the terminals of the transformer secondary winding and is equal to 105% of lamp rated voltage; ΔU_{tr} - voltage losses in the transformer, %; U_l - the minimum allowable lamp voltage as a percentage of nominal voltage.

Assuming that $U_{oc} = 105\%\ U_{nom}$, $U_l = 97{,}5\%\ U_{nom}$:

$$\Delta U_\delta\ \% = 105 - \Delta U_{tr} - 97{,}5 = 7{,}5 - \Delta U_{tr}, \tag{1.27}$$

The voltage losses in the secondary transformer winding depends on its load and parameters, as well as the network power coefficient:

$$\Delta U_{tr} = \beta cos\varphi (U_a + U_r tg\varphi) \tag{1.28}$$

where $\beta = S/S_{nom}$ - the power coefficient of the transformer with a nominal power S_{nom} (kVA) and estimated network power S (kVA); $U_a = (\frac{\Delta P_{sc}}{Snom}) \cdot 100$ - the active component of the short-circuit voltage, %; ΔP_{sc} – power losses in the short-circuit mode, kW; $U_r = \sqrt{U_{sc}^2 - U_a^2}$ - the reactive component of the short-circuit voltage, %; U_{sc} - short-circuit voltage, %; $cos\varphi$ - power factor in the secondary voltage network and the corresponding $tg\varphi$.

When choosing a cross-section of the lighting network neutral wires, it is necessary to take into account the load imbalance on the supply network phases, arising during simultaneous switching on of lamps in a group network.

In the three-phase networks with gas-discharge lamps, even with the even phase load, the circulating current is flowing through the neutral wire. Its appearance is associated with the current curve non-sinusoidality and higher harmonics, which are the causes of non-linearity of the fluorescent lamps volt-ampere characteristics and the inductance coil presence in the circuit with steel and capacitors.

Therefore, for the lighting networks with incandescent lamps the cross-section of the neutral wire in the supply network should be a half of the phase wire, and for feed lines with the gas-discharge lamps should be equal to the phase wire. For the two-wire lines, the cross-sections of the neutral and phase wires should be the same.

In production conditions, it is sometimes not possible to acquire a satisfactory voltage quality at the terminals of the lighting installations using the methods mentioned above. In this case, it is recommended to use boosting transformers (BT), which are single or three phase transformers 220/12V or 220/24V.

The boosting transformer allows creating an additional e.m.f., which is summed with the main network voltage vector. Such transformer has two windings: one of them (secondary winding) is connected in-series with the load line, where the voltage is regulated, and the primary winding is connected to the power source. The additional e.m.f. produced by BT depends on the voltage of the primary winding and the transformer ratio. The additional voltage can be altered by changing:
a) BT transformation ratio (Fig. 1.14 a);
b) voltage supplied to the BT primary winding with an auxiliary transformer control or autotransformer (AT) (Fig. 1.14 b);
c) phase voltage in the BT primary winding.

Depending on the connection scheme of the primary winding, BT can provide a bootstrap phase-coinciding or phase-shifted relatively to the main voltage. Connecting the primary winding of the regulating transformer or AT to different phases (Fig. 1.15, b), it is possible to obtain different values of the BT output voltage, i.e., voltage at the lighting installation terminals.

The BT power depends on the voltage boost value U_{boost} produced by BT, and the power transferred to consumers through the line S_c:

$$S_{bt} = \frac{U_{boost}}{100} \cdot S_c, \qquad (1.29)$$

Typically, the BT power is 10 ... 15% of the load power, where the BT is installed. This method can substantially correct the voltage deviation at the terminals of lighting installations.

For facilities with special lighting and stability requirements, special devices to limit and regulate voltage at the U_{nom} level are used. The most widely spread are the thyristor voltage limiters (TVL), in which, depending on the input voltage, the thyristor control angle α changes so as to maintain the voltage at a given level.

Self-test questions

1. Which power quality indices do you know?
2. How can you test the power quality indices in their compliance with the GOST 32144-13?
3. What is meant by the electromagnetic compatibility of the power supply systems and electrical equipment?

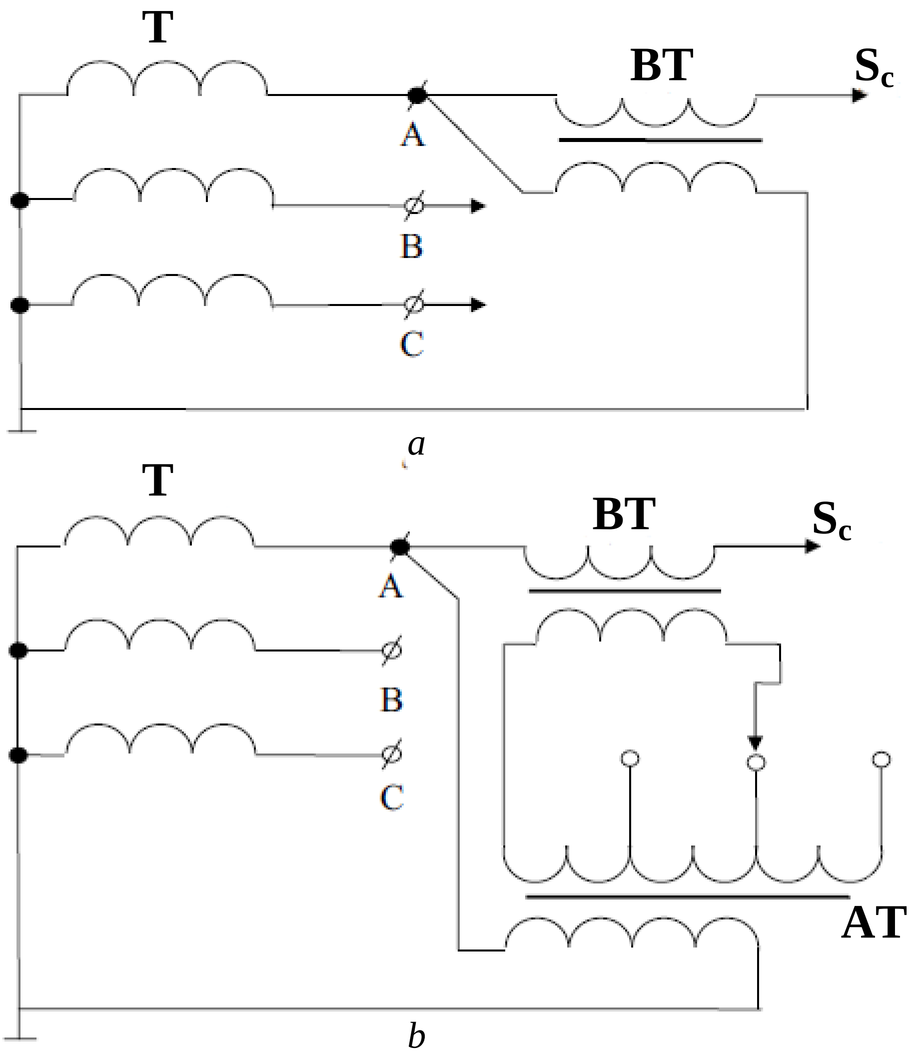


Fig. 1.15. *Connection schemes for boosting transformers: a) directly to the network; b) to the network through the autotransformer*.

4. What causes the change in voltage deviations?
5. How is it possible to determine the voltage deviation at the current-using equipment terminals?
6. What is the effect of voltage deviations on the induction motor energy characteristics?
7. What is the influence of the power quality on the production installations?
8. What are the characteristics of lighting installation in comparison to other enterprise electric-using equipment?
9. What methods of voltage control are applied at the enterprise networks?
10. When is the local and individual voltage control applied?
11. How are the taps of a SWE transformer chosen?
12. Explain the physical process of reducing the voltage deviations by means of longitudinal and reactive shunt compensation.
13. How is the normalization of voltage deviations by means of boosting transformer achieved?

2. VOLTAGE FLUCTUATIONS

Voltage fluctuations are short-term changes in the voltage caused by inclusions of high-power abruptly variable loads: electric arc furnaces, welding machines, valve inverters, etc. GOST 32144-13 limits the value of the voltage fluctuations frequency only at the terminals of lighting installations and radio equipment, but they also affect the work of other current-using equipment.

2.1 Determination of voltage fluctuation indices

Voltage fluctuations are characterized by the following indices: peak-to-peak voltage (voltage swing), voltage fluctuations frequency, the interval between successive voltage changes, including the flicker indicator.

The peak-to-peak voltage (voltage swing) δU_t can be found:

$$\delta U_t = \frac{|U_i - U_{i+1}|}{U_{nom}} \cdot 100\,\%\,, \tag{2.1}$$

where U_i, U_{i+1} - successive extremums values or extremum and horizontal section of the root-mean-square voltage envelope of the fundamental frequency, determined at each fundamental frequency half-cycle (Fig. 2.1).

When the voltage THD (total harmonic distortion) factor does not exceed 5%, it is allowed to determine δU_t by the formula:

$$\delta U_t = \frac{|U_{Ai} - U_{Ai+1}|}{\sqrt{2}U_{nom}} \cdot 100\,\%\,, \tag{2.2}$$

where U_{Ai} and U_{Ai+1} - successive extremums values or extremum and horizontal section of the voltages amplitude envelope values at each half-cycle of the fundamental frequency.

The voltage change repetition frequency at periodic voltage fluctuations is calculated by the formula:

$$F_{\delta U_t} = \frac{m}{T} \quad (s^{-1}, min.^{-1}) \tag{2.3}$$

where m - number of voltage changes over a time period T; T - measurement time interval, which is equal to 10 min.

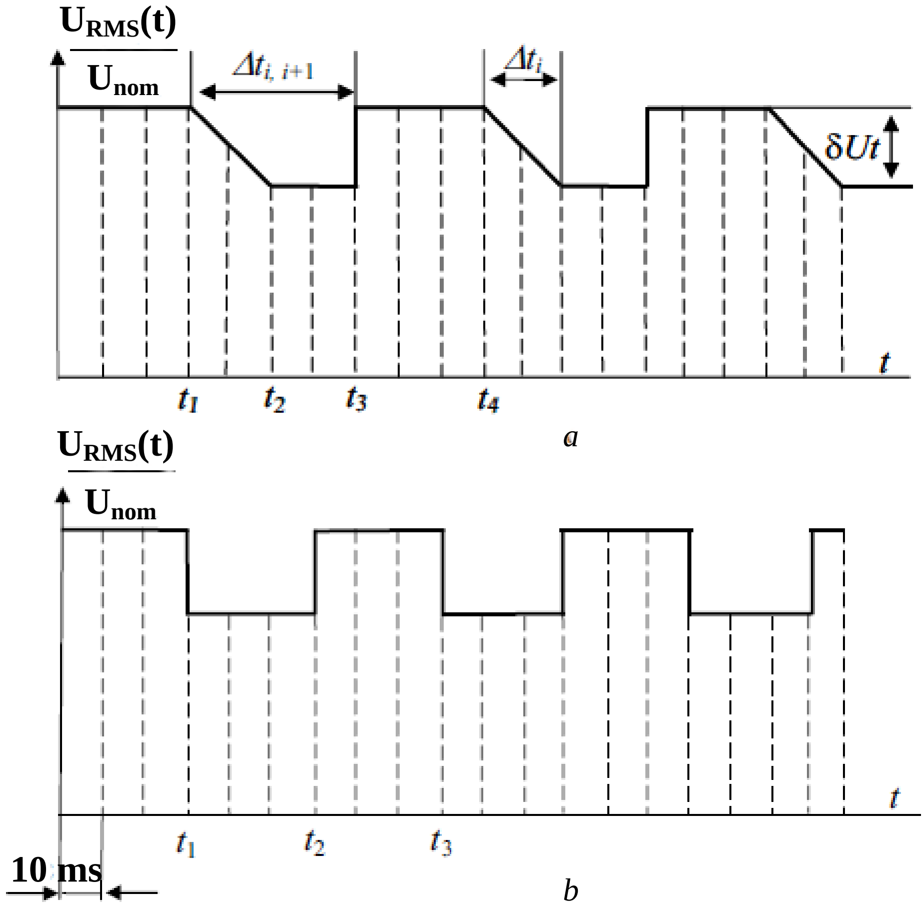


Fig 2.1. *Arbitrary shape (a) and meander-shaped (b) voltage fluctuations*

The time interval between changes in voltage $\Delta t_{i,i+1}$ in seconds or minutes in accordance with the above figure (Figure 2.1) is calculated by the formula:

$$\Delta t_{i,i+1} = t_{i+1} - t_i \tag{2.4}$$

where t_i, t_{i+1} – the starting moments of the successive voltage changes, s, min.

If the time interval between the end of one and beginning of the following change occurring in the same direction is less than 30 ms, the change is considered to be one.

The maximum allowed range of peak-to-peak voltage values δU_t at the common connection point of the electrical network with voltage fluctuations, the envelope of which has the meander shape (Fig. 2.1), depending on the voltage change repetition frequency $F_{\delta U_t}$ or the interval between voltage changes $\Delta t_{i,i+1}$ are equal to values acquired by the curve 1 (Fig. 2.2). For power consumers with incandescent lamps in the premises, where a significant eyestrain is required, the limit values δU_t are determined by the curve 2.

The maximum allowed value of the sum of steady voltage deviation δU and the peak-to-peak voltage (voltage swing) δU_t in the connection point to the electrical network with voltage at 0.38 kV equals ±10% of nominal voltage.

The maximum allowed value for short-term flicker indicator P_{st} with voltage fluctuations equals to 1,38, and for the long-term flicker indicator P_{lt} with the same voltage fluctuation is 1,0. The short-term flicker indicator is determined within 10 min of observation. The long-term flicker indicator is determined within 2 hours of observation.

Flicker - subjective human perception of the light flux vibration from artificial light sources, due to voltage fluctuations in an electrical network, which supplies these sources.

Flicker indicator - a measure of a person's susceptibility to the effects of flicker for a fixed period of time.

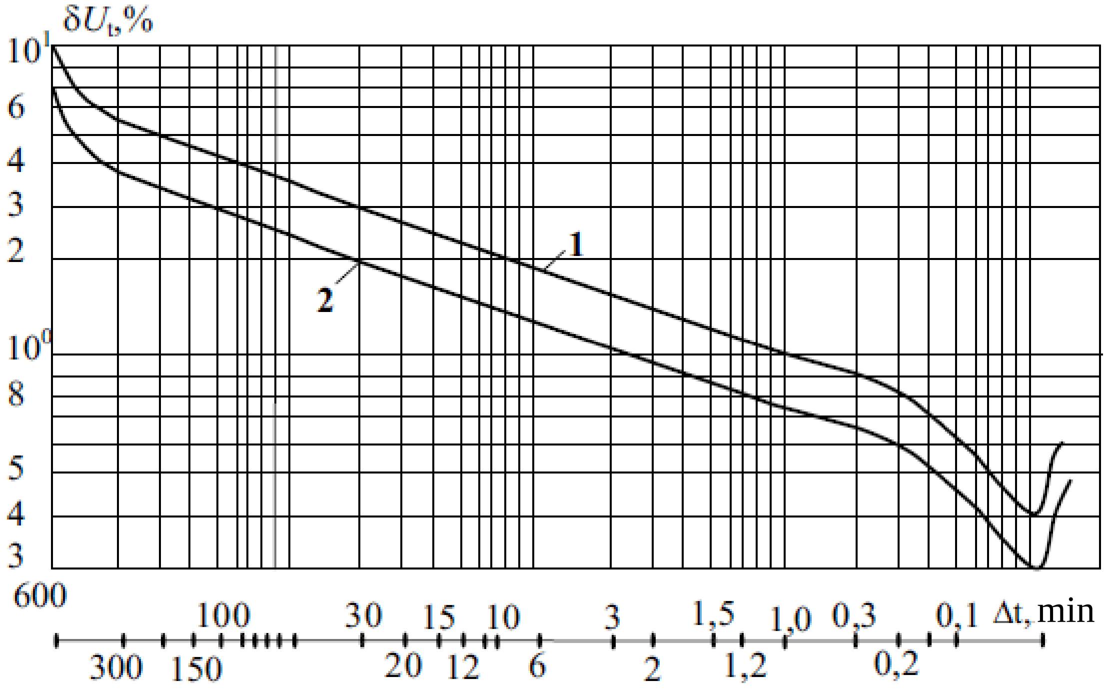


Fig 2.2. *Maximum allowed peak-to-peak voltage ranges depending on the time interval between changes in voltage* Δt

2.2. Influence of voltage fluctuations on the operation of current-using equipment

As noted above, the GOST 32144-13 limits the voltage fluctuation values only at the terminals of lighting installations and radio equipment. This is primarily due to the fact that the voltage fluctuations negatively affect a person's vision. Flickering lights (flicker effect) causes unpleasant psychological effects, an eye fatigue and an exhaustion, thereby reducing the productivity. The degree of eye irritation depends on the magnitude and frequency of the flickering light.

The study [9] showed that the human eye is most sensitive to the incandescent light flickering with a frequency, which is in the range of 3... 10 Hz. At the same time, the eye begins feeling these flicker from 0.25% of nominal voltage, and the unpleasant feelings occur, when a voltage is equal to 0.4% of the nominal one.

The degree of voltage fluctuations impact on the vision depends on the light source type. For example, with the same voltage fluctuations, incandescent bulbs have a much greater effect on the vision, than gas-discharge lamps, since the latter are less sensitive to voltage fluctuations at the above frequencies, but more sensitive at frequencies above 20 Hz.

The voltage fluctuations greater than 10% may lead to the failure of gas-discharge lamps. Their ignition period depending on the lamp type can be a few seconds or even minutes.

There are various ways to determine the allowed values of the voltage fluctuations appeared due to by current-using equipment work, depending on the influence of flickers on human caused by these fluctuations.

In Russia, for example, the maximum allowed voltage fluctuation range U_t is estimated by curve 2 (Fig. 2.2) and the maximum allowed flicker indicators P_{st} and P_{lt}. In Japan, for this purpose the standard of the voltage fluctuations at a frequency of 10 Hz is taken. The special researches have shown that at the effective voltage value of 100V the voltage fluctuations with a frequency of 10 Hz should not exceed 0.32 ... 0.45 V (0.32V - the average value $\Delta U_{10av.}$ and 0.45 - the maximum value ΔU_{10max}, which corresponds to 0.32 and 0.45%). At the same time, ΔU_{10} refers to the amplitude of the voltage alternating component (effective value). Voltage fluctuations at other frequencies reduce to a 10 Hz frequency with the help of experimental curve (Fig. 2.3), which shows the dependence of the relative eye sensitivity to the voltage fluctuations on the fluctuation frequency. The sensitivity to fluctuations at a frequency of 10 Hz is taken as a unit. From the curve, it follows that 1% of fluctuations influencing a person's vision at 1 Hz is equivalent to 0.26% fluctuations at a frequency of 10 Hz.

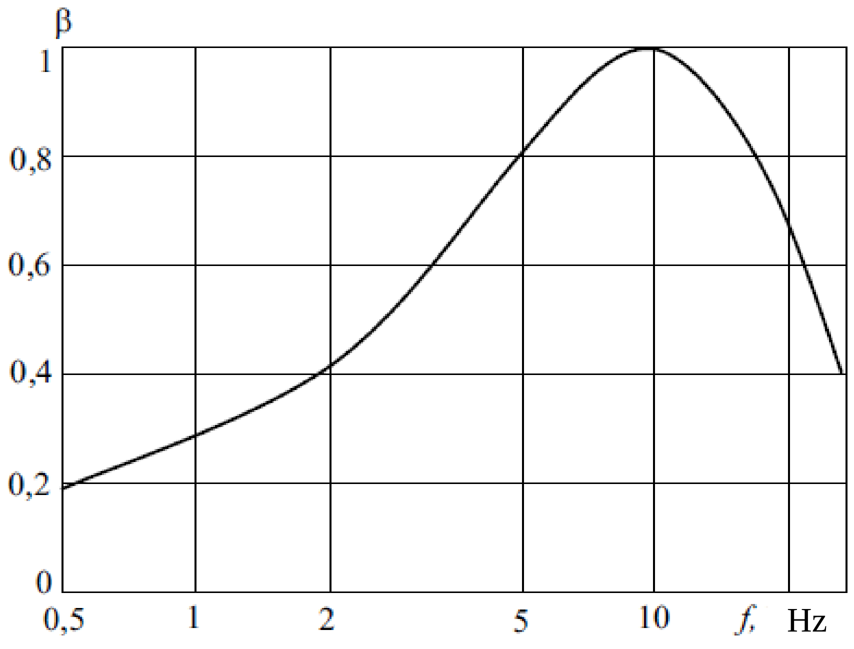


Fig 2.3. *Dependence of relative vision sensitivity on the voltage fluctuation frequency*

If there are fluctuations of different frequencies, the level of voltage fluctuations, reduced to 10 Hz, is determined by the formula:

$$\Delta U_{10} = \sqrt{\left(\beta_{f_1} \Delta U_{f_1}\right)^2 + \cdots + \left(\beta_{f_n} \Delta U_{f_n}\right)^2}, \quad (2.5)$$

where β_f - the relative sensitivity (Fig. 2.3); ΔU_f - the frequency fluctuations; ΔU_{10} - an equivalent voltage fluctuation, reduced to the 10 Hz frequency.

In addition to effects on the human vision, the voltage fluctuation has negative impact on the other current-using equipment work. With the deep voltage fluctuations (more than 15%), the magnetic starter terminals can fall out, causing a breach in the production process. The voltage fluctuations in a range of 10 ... 15% can lead to the failure of capacitors and valve rectifier devices. The voltage fluctuations in the network, which feeds an electric arc furnace, lead to an increase in the melting duration.

At the metallurgic plants, continuous rolling mills are also considered as an equipment sensitive to voltage fluctuations. To obtain high-quality products, metal stretching or compression during rolling are not allowed. This requirement is ensured by a constant speed ratio of the mill stands. The voltage fluctuations of more than 5% lead to a speed mismatch of the mill stand drives. This mismatch leads to a mill dysfunction, defective goods, and product underruns.

Voltage fluctuations have noticeable influence on the low power induction motors. Fluctuations are not acceptable for the textile, paper and other industries, presenting particularly high demands on the accuracy of the drives speed, which are usually asynchronous (induction) motors.

The voltage fluctuations impact on the electrolysis plants has been studied in details [9]. In the production of chlorine and caustic soda, voltage fluctuations in a range of 5% caused a sharp increase in an anode wear, malfunction of individual process plants and reduced productivity of the enterprise as a whole. At relatively high frequency and range of voltage fluctuations, the electrolysis plant lifespan is reduced from 9 to 7 months. Voltage fluctuations in the chemical fiber factories lead to the rotation speed fluctuations of bobbin machine induction motors. As a result, nylon threads are torn or of different thickness. It leads to the defective goods and underproduction.

Voltage fluctuations have a significant impact on the contact welding. This impact is on both the quality of the welding process, and the reliability of the welding control circuit. The voltage quality in the networks of the contact welding has very severe limitations on the peak-to-peak voltage range: ±5% for standard steels welding and ±3% for the titanium and other heat-resistant steels and alloys welding. The duration of allowed voltage fluctuations for contact welding control equipment is limited to no more than 0.2sec in order to avoid the equipment faulty operation, especially when controlling by means of logical elements.

The current-using equipment, which is sensitive to voltage fluctuations, includes computers, X-ray machines, radio stations, TV stations, etc. When a computer is working in a control mode, sometimes it is enough to have one of two fluctuations of 1 ... 1.5%, to have a failure in the computer and as a result, errors occur in the control commands. Such a failure in the computer calculations leads to inadequate results. Therefore, in the national and foreign usage practice the self-contained power supply or the static voltage converters/regulators are used to feed a computer.

2.3. Methods and means of voltage fluctuation reduction

To reduce the impact of abruptly variable loads, which cause the voltage fluctuations, different methods are used. The simplest way is achieved by feeding the current-using equipment with abruptly variable load with individual lines, which are connected directly to a power source, bypassing the shop substations.

The combined feed of the quiescent I_q and shock I_s loads from the same source is possible in a dual reactor. In this case, the load is connected to the different reactor sections as shown in Fig. 2.4.

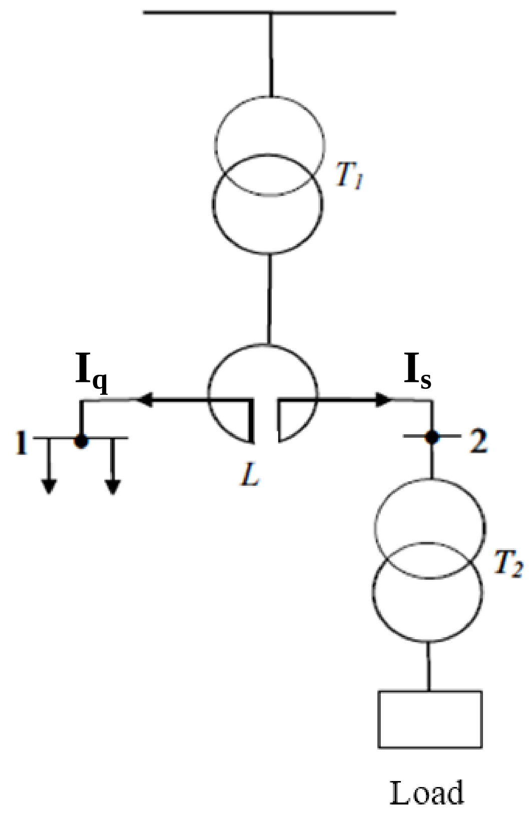


Fig 2.4. *Scheme with a dual reactor usage*

Sections of quiescent 1 and shock 2 loads are connected opposite to each other. The voltage drop in each of the them from the currents I_q and I_s is determined by the expressions:

$$\Delta\dot{U} = jX_L(\dot{I}_s - K_M\dot{I}_q);$$
$$\Delta\dot{U} = jX_L(\dot{I}_q - K_M\dot{I}_s), \quad (2.6)$$

where X_L is the inductance of the reactor section; $K_m = M/L$ is the mutual induction coefficient = 0.5 ... 0.6. As follows from (2.6), the use of dual reactor reduces the voltage fluctuations.

For the abruptly variable loads and the quiescent loads in networks with voltage of 6 ... 10 kV, the power transformers with split windings are used. The quiescent load is connected to one tap of the transformer low voltage winding, while the abruptly variable load is connected to another tap.

An effective way to reduce the voltage fluctuations is the use of synchronous motors and synchronous compensators, which have natural regulating effect.

The reduction of voltage fluctuations K_u due to the natural regulating effect of the electric motor is approximately measured by the equation:

$$K_U = \frac{1}{X'_d} - \frac{1}{X''_d}, \tag{2.7}$$

where X'_d and X''_d - the relative values of the transient and subtransient reactance on the direct-axis.

The use of synchronous machines in overdrive mode improves the power factor and voltage level in the network, as well as reduces the unbalance and voltage non-sinusoidality that can be explained by decreasing the equivalent negative sequence resistance and the resistance at the harmonics frequencies.

Voltage fluctuations due to the swing of active and reactive loads can be approximately calculated by the formula:

$$\delta U = \frac{(\Delta PR + \Delta QX)}{U^2}, \tag{2.8}$$

where ΔP and ΔQ - changes (swings) of active and reactive power, MW and MVAr; R and X – active and reactive resistance per phase, Ohm; U – phase-to-phase voltage, kV.

This formula can be converted to the form:

$$\Delta U = \frac{\left(\Delta P \frac{R}{X} + \Delta Q\right)}{S_{SC} \frac{Z}{X}}, \tag{2.9}$$

where S_{sc} – short-circuit power in the network point, where the voltage fluctuations are checked, MVA; Z - impedance, Ohm.

Taking into account that the active resistance of the power supply system elements is much smaller than the reactance (except of cables), the given formula (2.9) can be simplified:

$$\delta U = \frac{\pm \Delta Q}{S_{SC}}, \tag{2.10}$$

Thus, it follows from (2.10), the value of the voltage fluctuations is determined by the swing of reactive power and the network short-circuit power. Therefore, to limit the voltage fluctuations, the current-using equipment with abruptly variable loads should be connected to the network with the greatest short-circuit power.

When feeding together the electric arc furnace and the general shop loads, the voltage fluctuations at the 6 ... 35kV buses of a step down transformer can be accurately (for practical purposes) defined by the formula:

$$\delta U = \sqrt{3}\Delta I(R\ cos\varphi + X\ sin\varphi), \tag{2.11}$$

where ΔI- the current surge of arc furnace, A; R and X – active and reactive resistance of the section between power source and buses of 6 … 35 kV, Ohm.

Neglecting the resistance and accepting φ=90º we have:

$$\delta U\% = \frac{\sqrt{3}\Delta I}{U} \cdot 100. \tag{2.12}$$

Taking the calculated peak-to-peak current as a 100% I_{nom}, we obtain

$$\Delta I = I_{nom} = \frac{S_t}{\sqrt{3}U_{nom}} \cong \frac{S_t}{\sqrt{3}U},$$

then (2.12) will have simpler form assuming that $X = U^2 / S_{sc}$

$$\delta U\% = \frac{S_t}{S_{SC}} \cdot 100. \tag{2.13}$$

As you can see, formula (2.13), which determines the voltage fluctuations in the arc furnace operation, is similar to (2.10) and shows that these fluctuations are mainly due to short-circuit power.

When several arc furnaces work together, it is necessary to put a correction factor k taking into account the increase of voltage fluctuations. For arc furnaces having the same capacity, $k = \sqrt[4]{n}$.

In networks with valve-type converters, voltage fluctuation can be calculated directly from (2.10). For such converters, supplying current-using equipment, a wide range of voltage and current change is typical. In this regard, the reactive power surges ΔQ are determined by the converter operation mode, i.e., by the current multiplicity I_d/I_{dnom}, consumed by the converter, and its voltage regulation coefficient $e_d = U_d/E_{d0}$ (where I_d - the nominal rectified current; U_d – the rectified voltage of the converter; E_{d0} – the converter E.M.F. in open-circuit mode). With that said, on the basis of (2.10) it is possible to determine the required short-circuit power of the network within allowed limits of voltage fluctuations.

Self-test questions

1. What key indices characterize the network voltage fluctuations and what are the regulatory requirements for them?
2. How are the voltage fluctuations determined according to the voltage waveform?
3. What is the impact of flicker effect on a person's vision?
4. Influence of voltage deviations on the current-using equipment work.
5. What are the main causes of voltage fluctuations in the electrical network?
6. What are the main methods and ways to reduce the voltage fluctuations?

3. NON-SINUSOIDAL POWER SUPPLY MODES

As a result of the production processes intensification, the improvement and implementation of the new technologies at enterprises, there is a continuous increase in the use of valve converters, one phase and three phase electric welding installations, powerful electric arc furnaces, volt-ampere characteristic of which are nonlinear. The power transformers, high-power magnetic amplifiers, gas-discharge lamps have the same characteristics. A key feature of this equipment is the consumption of non-sinusoidal currents from the electrical network, when sinusoidal voltage is supplied to its terminals.

Non-sinusoidal currents waves can be regarded as complex harmonic fluctuations, containing a set of different frequency simple harmonic fluctuations. Higher current harmonics, passing through the network elements, cause the voltage drop in the resistance of these elements, which are superimposed on the fundamental voltage wave sine, lead to the distortion of the voltage waveform, deterioration of power quality in the supply network, i.e., the problem of electromagnetic compatibility of current-using equipment with the supply network rises.

3.1. Normalization of indices for non-sinusoidal power supply modes

Voltage non-sinusoidality is characterized by the following indices:

- Voltage THD (Total Harmonic Distortion) factor K_u (%);
- *n-th* harmonic distortion factor $K_u(n)$ (%).

The voltage waveform total harmonic distortion factor (or coefficient of non-sinusoidality) is defined as the ratio of the root-mean-square value of the non-sinusoidal voltage harmonic content to the fundamental frequency voltage:

$$K_U = \frac{\sqrt{\sum_{n=2}^{\infty} U_n^2}}{U_1} \cdot 100\ \% \approx \frac{\sqrt{\sum_{n=2}^{\infty} U_n^2}}{U_{nom}} \cdot 100\ \%$$

Where U_n - rms voltage of the *n-th* harmonic; *n* - number of the last considered harmonic.

When calculating K_u, harmonics, which magnitudes are less than 0.1%, may be neglected.

The normally allowed and the maximum allowed values of the voltage waveform distortion in networks with different nominal voltage are shown in Table. 3.1 in percentage terms.

Table 3.1 *Voltage THD (Total Harmonic Distortion) factor K_u*

Normally allowed values at U_{nom}, kV				Maximum allowed values at U_{nom}, kV			
0.38	6…20	35	110…220	0.38	6…20	35	110…220
8.0	5.0	4.0	2.0	12.0	8.0	6.0	3.0

The values of the voltage THD factor averaged over a time interval of 10 minutes, must not exceed the normally allowed values (specified in Table 3.1) within 95% of the time interval of one week and must not exceed the maximum allowed values within 100% of the time interval of one week.

The normally allowed values of *n-th* harmonic distortion factor at the common connection points with a different nominal voltage U_{nom} are shown in Table. 3.2 in percentage terms.

Table 3.2. *n-th harmonic distortion factor*

Odd harmonics, are not multiples of 3, with U_{nom}, kV					Odd harmonics, multiples of 3 at U_{nom}, kV					Even harmonics at U_{nom}, kV				
n	0.38	6…20	35	110…220	*n*	0.38	6…20	35	110…220	*n*	0.38	6…20	35	110…220
5	6.0	4.0	3.0	1.5	3	5.0	3.0	3.0	1.5	2	2.0	1.5	1.0	0.5
7	5.0	3.0	2.5	1.0	9	1.5	1.0	1.0	0.4	4	1.0	0.7	0.5	0.3
11	3.5	2.0	2.0	1.0	15	0.3	0.3	0.3	0.2	6	0.5	0.3	0.3	0.2
13	3.0	2.0	1.5	0.7	21	0.2	0.2	0.2	0.2	8	0.5	0.3	0.3	0.2
17	2.0	1.5	1.0	0.5	>21	0.2	0.2	0.2	0.2	10	0.5	0.3	0.3	0.2
19	1.5	1.0	1.0	0.4						12	0.2	0.2	0.2	0.2
23	1.5	1.0	1.0	0.4						>12	0.2	0.2	0.2	0.2
25	1.5	1.0	1.0	0.4										
>25	1.5	1.0	1.0	0.4										

The values of the *n-th* harmonic distortion factor $K_u(n)$ averaged over a time interval of 10 minutes must not exceed the values specified in Tables 1-3, within 95% of the time interval of one week. The values of the *n-th* harmonic distortion factor $K_u(n)$ averaged over a time interval of 10 minutes must not exceed the values specified in tables 1-3, increased by 1.5 times, within 100% of the time of each period of one week.

3.2. Influence of higher harmonics on power supply systems

The higher harmonics lead to additional losses in electric machines, transformers and networks; the reactive power compensation with capacitor banks is getting more difficult; the lifespan of electric machines insulation shortens; the automation devices work is deteriorating, including teleautomatics and communication.

Losses from higher harmonics in electric machines. Temporal higher current harmonics cause additional losses in the electric machines windings. Additional losses in the machine steel are small and usually neglected.

The main part of the additional losses in synchronous machines is at the stator winding and the damper system. In high-voltage induction motors, losses in the windings of the stator and rotor are almost identical. The calculation of losses from higher harmonics is rather complicated. It may therefore be recommended to determine the losses from the waves shown in Fig. 3.1 and Fig. 3.2.

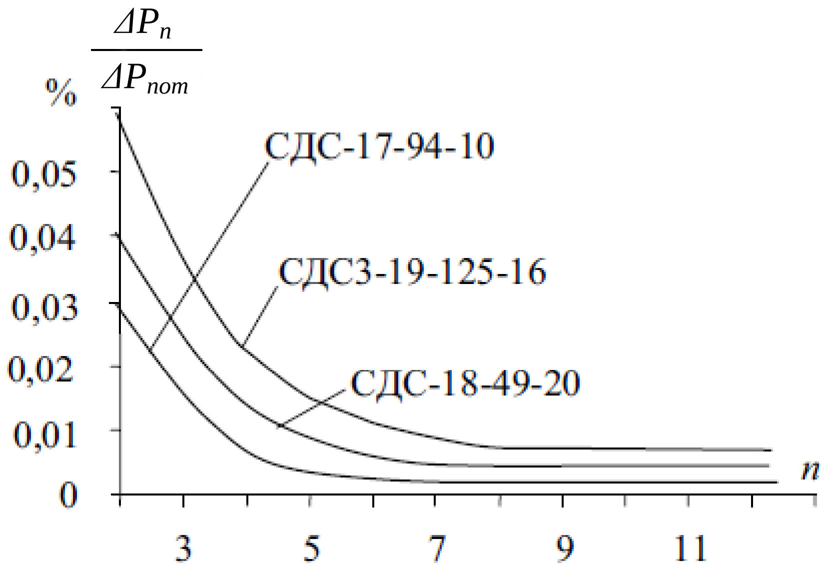


Fig. 3.1. *Waveforms of relative losses from the higher harmonics in synchronous motors*

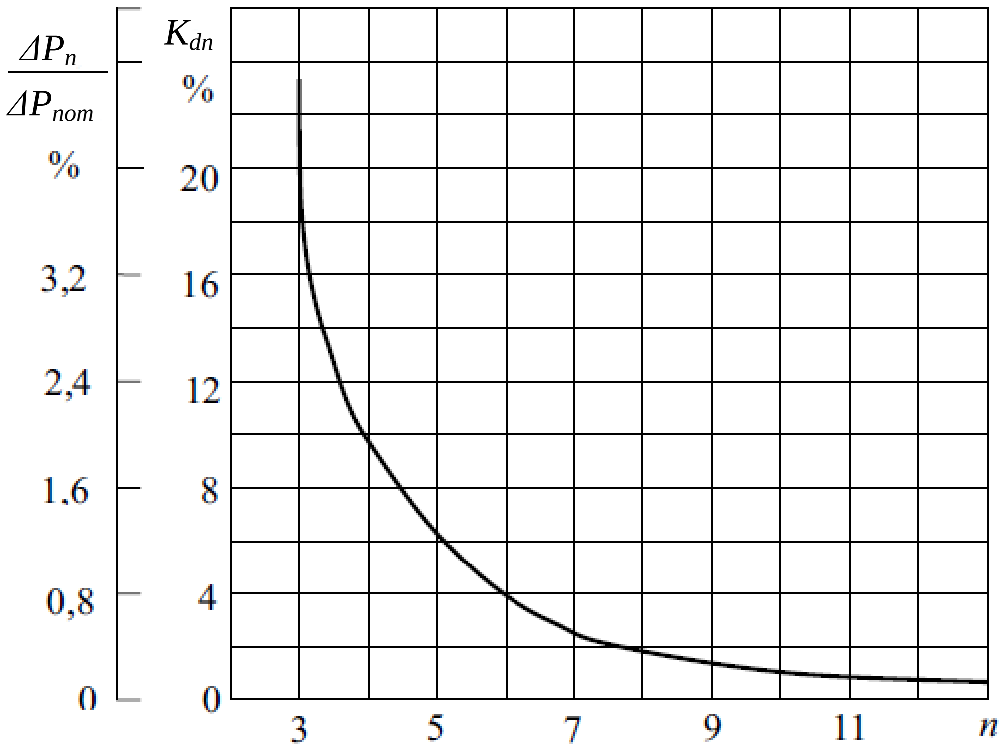


Fig. 3.2. *Relative losses from the higher harmonics in induction motors*

These figures show the relation of power losses ΔP_n at the voltage equal to 1% of the fundamental harmonic, to the total nominal losses ΔP_{nom}. The values ΔP_{nom} are given in the electric motor documentation.

The specific losses for a single harmonic will be different for the direct rotating field of this harmonic and for the reverse rotating magnetic field. In figures, you can see specific losses for the averaged losses from direct and reverse phase sequence of the higher voltage harmonics vectors.

Analyzing the waveforms of relative losses, it is easy to see that the ratio of $\Delta P_n / \Delta P_{\text{nom}}$ has the greatest value for the low-order harmonics, in the first place of the second and the third harmonics. The losses caused by harmonics above the 13th are small and can be neglected.

The total losses $\Delta P_{\Sigma n}$ caused by all the voltage harmonics is defined as:

$$\Delta P_{\sum n} = \sum_{n=2} \Delta P_n \left(\frac{U_n}{U_1}\right)^2 . \tag{3.1}$$

The calculations show that even in cases of unacceptable distortion (K_u = 10 ... 15%), the additional losses from the temporary harmonics in the synchronous motor (SM) with laminated stator and rotor does not exceed a few percent of the nominal losses. Therefore, overheating of the salient-pole synchronous motors with laminated poles in practice is not observed.

The losses from the higher harmonics in the SM with massive poles are much larger. The same applies to the synchronous compensators. The operation of machines with massive poles using non-sinusoidal voltage is dangerous, because it can overheat and damage the excitation winding.

The additional losses in induction motor from the *n-th* current harmonic:

$$\Delta P_n = 3I_{nom}^2 (R_{st.n} + R'_{r.n}), \tag{3.2}$$

where $R_{st.n}$ and $R'_{r.n}$ - the stator active resistance and the rotor reduced resistance at the frequency of *n-th* harmonic.

At higher frequencies in the stator and rotor windings, the surface effect appears abruptly and the resistance increases, so

$$R_{st.n} = R_{st}\sqrt{n}\,; \quad R'_{r.n} = R'_{r.}\sqrt{n}. \tag{3.3}$$

For high voltage asynchronous (induction) motors, it can be assumed that $R_{st} \cong R_r$.

A calculation formula for defining the total losses from the higher harmonics can be represented as

$$\Delta P_{\sum n} = \Delta P_{Cu.nom} K_s^2 \sum \left(\frac{U_n}{U_1}\right)^2 \left(\sqrt{n} + \sqrt{n \pm 1}\right) = \Delta P_{Cu.nom} \sum K_{dn}, \tag{3.4}$$

where K_s – starting current ratio; $\Delta P_{Cu.nom}$ – nominal losses in copper of the stator; K_{dn} – coefficient, which takes into account an increase in losses in copper of the stator due to temporary *n-th* harmonic.

The graphical dependence $K_{dn} = f(n)$ is presented in Fig. 3.2. The ordinate axis shows averaged values of K_{dn} for cases, where the *n-th* current harmonic forms direct and reverse order systems. During waveform construction, the averaged value of K_s is equal to 5.5. The nominal losses in the stator copper of large electric machines are on average equal to 20% of the total losses in the motor ΔP_{nom}. With this in Fig. 3.2 the second Y-axis is given, which shows additional power losses from the higher harmonics in relation to the total nominal motor losses $\Delta P_n / \Delta P_{nom}$. The application of these waveforms is very useful for determining induction motors losses due to the higher harmonics.

At the enterprises, as shown by the research [3], the overheating of induction motors even in network with high rate of higher harmonics was not observed neither at full nor at low loads.

Power losses in transformers. Active power losses from the higher current harmonics in the transformers are calculated by the formula:

$$\Delta P_{\Sigma n} = 3\sum_{n=2} I_n^2 R_{SC} K_{nm}, \tag{3.5}$$

where I_n – current of *n-th* harmonic flowing through the transformer; *Rsc* - transformer short-circuit resistance at the nominal frequency, and K_{nm} – coefficient, which takes into account an increase in the short-circuit resistance for higher harmonics due to skin and proximity effects. For the power transformers, the following can be taken K_{5m} = 2,1; K_{7m} = 2,5; K_{11m} = 3,2; K_{13m} = 3,7.

Power losses in capacitors. In the dielectric of capacitors, additional active losses from non-sinusoidal voltages appear.

$$\Delta P_{\Sigma} = \omega C\ tg\delta \sum_{n=1}^{13} nU_n^2\ , \tag{3.6}$$

where $tg\delta$ - dielectric losses coefficient, shall be the same for all harmonics up to n = 13; U_n – voltage of *n-th* harmonic at the buses after connecting capacitor banks with a capacitance *C.*

Losses in the *L-C* filter are composed of losses in the reactor and losses in the capacitors at the harmonic frequencies, to which the filter is configured, and a first harmonic. The quantity of losses from the *n-th* current harmonic can be calculated:

$$\Delta P_{fn} = 3I_n^2 X_r\left(n\ tg\delta + \sqrt{n}\ ctg\varphi_r\right)\ , \tag{3.7}$$

where X_r – reactor inductive resistance for the fundamental frequency; $ctg\varphi_r = R/X_r$.

Losses at the fundamental frequency in the battery and the reactor can be found:

$$\Delta P_{f1} = U^2 \omega C a^2 tg\delta + 3I^2 R_r \ , \qquad (3.8)$$

where U and I - linear (phase-to-phase) voltage and current in the filter branches; $a = n / (n^2\text{-}1)$; n – is the number of harmonic the filter is tuned to.

The influence of higher harmonics on insulation. The distortion of the voltage waveform has a significant impact on the occurrence and flow of ionization processes in the insulation of electric machines and transformers. With the presence of gaseous inclusions in insulation, the ionization occurs, the essence of which is in the formation of space charges and their subsequent neutralization. The neutralization of charges is related to the energy dissipation, resulting in the electrical, mechanical and chemical effects on the dielectric. As a result, local defects in the insulation develop, which reduce its electric resistance, increase the dielectric losses and, ultimately, reduce its lifespan.

The number of discharges in gas inclusions depends on the voltage waveform applied to the insulation.

The research [13] showed that, at the same voltage waveforms amplitudes, $tg\delta$ will be greater for the pointed shape of the waveform and smaller for the flattened waveform (compared to a sinusoidal). These differences are not as great, if we make a comparison with the same actual values of the identical voltage waveforms.

The experience shows that, due to the higher harmonics voltage waveforms in industrial networks often take a more pointed shape, so the presence of higher harmonics leads to accelerated insulation aging of electric machines and transformers.

With the presence of higher harmonics in the supply network, the process of capacitor dielectric aging also goes more rapidly compared to its work under the sinusoidal voltage. This is explained by the fact that the physico-chemical processes in dielectrics, leading to their aging, considerably accelerate at high frequencies. In the same way, additional heating caused by the higher harmonics flow leads to aging.

The research [13] showed that, for example, with a coefficient of voltage non-sinusoidality equal to K_u=5%, which is allowable, according to GOST 32144-13, after 2 years of operation, the capacitor $tg\delta$ doubles.

With the non-sinusoidal voltage supply, the accelerated insulation aging of power cables also occurs. To confirm this, the results were compared to the measurements of cables current leakage, operating in virtually identical environments. The part of the tested cable worked at almost sinusoidal voltage, the other part worked at the voltage waveform harmonics level in the range of 6…8.5% (with the dominance of the 5^{th} and 7^{th} harmonic). The leakage currents, in the second case, after 2.5 years of operation were an average of 36%, after 3.5 years at 43% higher than in the first case.

The influence of higher harmonics on calculation of electrical energy. The electrical energy metering devices in the presence of non-sinusoidal currents and voltages give a large error. In particular, the common induction watthourmeters have a negative frequency error at frequencies of higher harmonics (Figure 3.3).

The resulting error of measuring devices due to non-sinusoidality equals

$$\gamma_\Sigma = \sum_{n=2}^{n} \Delta P_n^* \gamma_n n, \tag{3.9}$$

where $\Delta P_n^* = \frac{\Delta P_n}{P_1}$; γ_n - error for the *n-th* harmonic; P_1 and ΔP_n - power at the first and *n-th* harmonic, respectively.

Thus, in the presence of non-linear power consumers, there is "overcount" of the consumed electrical energy. For example, at high voltage distortion K_U = 7 ... 10%, the measurement error may reach 4 ... 6%. 11th and 13th harmonics have the greatest influence on the accuracy of induction watthourmeters. The counting error leads to an imbalance of consumed electrical energy due to metering the energy of varying quality.

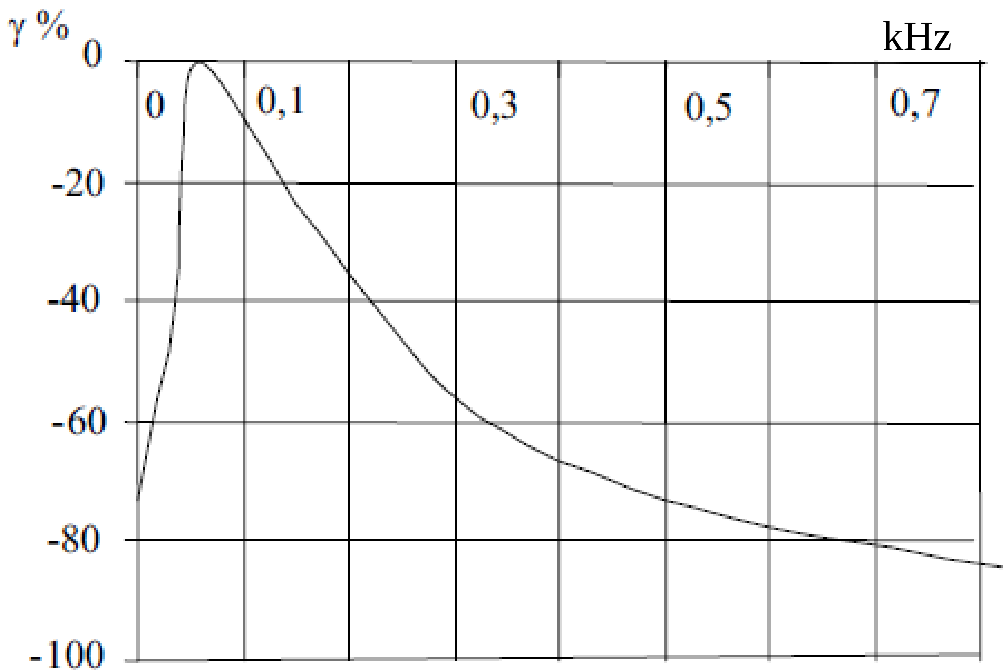


Fig. 3.3. *Frequency characteristics of the watthourmeter*

- The greater electrical energy measurement accuracy in non-sinusoidal regimes is provided by electronic meters.
- The voltage and current measurement in the presence of higher harmonics also lead to additional errors.
- The higher harmonics degrade the work of automation systems and remote control.
- The reliability of power supply systems is reduced.

3.3. Main sources of harmonics in power supply systems of enterprises

Valve converters. The sources of harmonics in power supply systems are power-consuming equipment with nonlinear characteristics. A typical nonlinear load is valve converter.

The most widespread valve converters are the converters presented the three-phase bridge circuit (Larionov`s circuit) (Figure 3.4). Such bridge circuits are widely used because of their good energy performance, as well as they serve as a basis to build more complex multi-bridge converters.

This scheme makes it possible to straighten the so-called six-phase or so-called six-pulse rectification circuit. The connection in series or in parallel of several rectifier bridges, when feeding them with the voltage shifted to the appropriate angle, gives 12, 18, 24, 48, ...-phase rectification circuits (multiples of six). The shift of voltage angle is performed by using the appropriate connection scheme of the primary or secondary windings of the transformer.

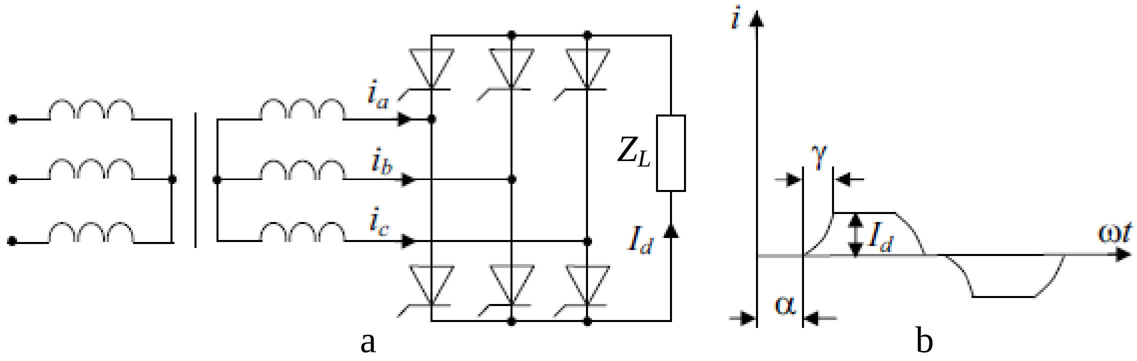


Fig. 3.4. *Three-phase bridge circuit: a - scheme, b - diagram of the current in phase*

The phase current curve of the converter operating on the active-inductive load, is a curvilinear trapezoid. The curve shape depends on the commutation γ and control α angles (Fig. 3.4, *b).* The commutation angle γ is determined by the formula:

$$\gamma = \arccos(cos\alpha - I_{d*}X_{c*}), \qquad (3.10)$$

where I_{d*} - relative (as a fraction of nominal) value of the rectified current; X_{c*}- the relative value of inductive resistance of the commutation contour, reduced to the power of the converter transformer. For uncontrolled converter, it is obvious, α = 0; cos α = 1.

In the voltage waveform during switching, the commutation distortion appears. The shape, size and number of these distortions depends on the rectification scheme, the number of rectification phases, the converter power, the parameters of the supply network, the control angle of converters.

The distorted voltage and current curves of the supply network during the converter operation are periodic in nature that allows making their harmonic analysis due to the presence of harmonics, which are multiple to the fundamental frequency

[9]. The order of higher harmonics is given by

$$n = mk \pm 1, \tag{3.11}$$

where m - number of rectification phases; k = 1, 2, 3, ... - sequential series of natural numbers.

For the bridge converter with symmetrical control, in which m = 6, in the curve of supply voltage there are odd harmonics, which are not multiples of three: n = 5, 7, 11, 13, 17, 19, 23, ..., for 12-phase scheme n = 11, 13, 23, 25, 35, 37, ..., for 24-phase scheme n = 23, 25 , 47, 49, 71, 73, etc.

The amplitude of the *n-th* harmonic is given by equation:

$$I_n = \sqrt{I_{na}^2 + I_{nr}^2}, \tag{3.12}$$

where the active component of the harmonic current:

$$I_{na} = \frac{2\sqrt{3}E_m}{n\pi X_c} sin\frac{n\pi}{3}\left\{\frac{1}{n+1} sin\left[(n+1)\frac{\gamma}{2}\right] sin[(n+1)\Psi]\text{-}\right.$$
$$\left.-\frac{1}{n-1} sin\left[(n-1)\frac{\gamma}{2}\right] sin[(n-1)]\Psi\right\}; \tag{3.13}$$

the reactive component of the harmonic current:

$$I_{nr} = \frac{2\sqrt{3}E_m}{n\pi X_c} sin\frac{n\pi}{3}\left\{-\frac{1}{n+1} sin\left[(n+1)\frac{\gamma}{2}\right] cos[(n+1)\Psi]\right.$$
$$\left.+\frac{1}{n-1} sin\left[(n-1)\frac{\gamma}{2}\right] cos[(n-1)]\Psi\right\}; \tag{3.14}$$

E_m - the e.m.f. amplitude in the supply network; $\Psi = \alpha + \gamma/2$ – the phase shift angle between the curves of the e.m.f. and first current harmonic, X_k – the resistance of the commutation contour.

For the first harmonic:

$$I_{1a} = \frac{3E_m}{2\pi X_c}\, sin\gamma\; sin2\Psi; \qquad I_{1r} = \frac{3E_m}{2\pi X_c}\,(\gamma - sin\gamma\; cos2\Psi).$$

It is worth noting that the rms current in the network differs negligibly (not more than 2%) from the corresponding values of the 1st harmonic.

Fig. 3.5 shows the curves of the relative values of harmonic currents $I_{n*} = I_n/I_1$ for different n. The initial phase of *the n-th* harmonic is determined accurately by the equation:

$$\Psi_n = n\Psi. \tag{3.15}$$

In practical calculations, Ψ is convenient to find by the formula:

$$\Psi = arccos\frac{U_d}{U_{do}}, \tag{3.16}$$

where U_d and U_{d0} - averaged values of the converter rectified voltage, in the load mode and open-circuit mode, respectively.

If we neglect the commutation process ($\gamma \approx 0$), for example, when the bridge converter is connected without transformer to the buses, to which capacitor banks are also connected, the current curve in the network becomes rectangular-stepped shape. In this case, it is

$$I_{n*} \approx 4n. \tag{3.17}$$

This formula has a practical extension also for the case, when the bridge converter has a transformer, but the values of I_{n*} are too high: for n = 5 and 7 the error can reach 10 ... 15%, for n = 11 and 13 error is equal 20%. It is not recommended to use a simplified formula for n > 13.

When the converter is working to a resistive load (eg, resistance furnace), the values I_{n*} will be quite lower: at α = 0 is I_{5*} = 0.816, I_{7*} = 0.113, I_{11*} = 0.085, I_{13*} = 0.065.

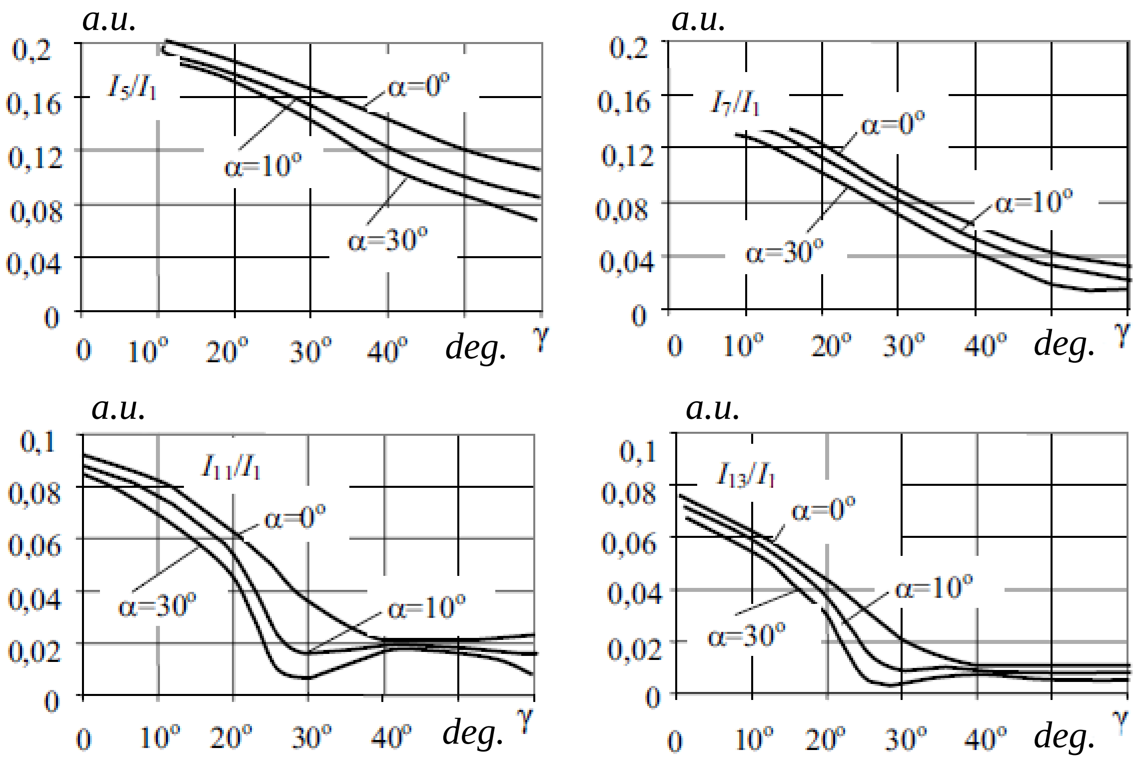


Fig 3.5. *Curves of relative values of the higher current harmonics for three-phase bridge converter*

The relative (as a fraction of the nominal phase voltage) E.M.F. value of *n-th* harmonic of the converter E_{n*} can be found:

$$E_{n*} = K_l \frac{S_c}{S_{SC}} \xi(n), \tag{3.18}$$

where S_c and S_{sc} - the nominal values of the converter power and short-circuit power after its transformer, K_l - the load factor of the converter up to the full power; the coefficient $\xi(n)$ should be found using I_{n*} values from fig. 3.5:

$$\xi(n) = \frac{nI_{n*}}{1 - nI_{n*}}. \tag{3.19}$$

The e.m.f. values for harmonics n = 11, 13, can reach several tens of percent, and for n = 30 ... 40 – only 2%.

In the transient state of the converter working modes, the relation between the values of higher current harmonics in the network remains the same as for the steady state. However, there are harmonic multiples of three with an amplitude of up to 0.5% of the current amplitude at the fundamental frequency and even harmonics, especially the 2nd and 4th with an amplitude of up to 2%.

In addition to the harmonic spectrum of rectifier phase currents, determined by the rectification circuit, there are the so-called "abnormal" or noncanonical harmonics with orders that do not correspond to the number of rectification pulses.

The reasons for appearing non-canonical harmonics are:

- the deflection of control angles from the nominal value;
- the power supply of the valve converter from a network with distorted voltage waveform;
- the power supply of the valve converter from the network with the voltage asymmetry.

Typically, non-canonical harmonics can be explained by the random events and are determined by probability values. The distribution of their peak values obeys the Rayleigh law and the distribution of phases obeys the law of equal probability.

As an example of a quantitative dependence of these harmonics on the control angle error, it is possible to point out that the error $\Delta\alpha \leq 3^o$ causes of non-canonical harmonics at 2 ... 3%. Since they are small compared with the canonical, then in the subsequent calculations they are not counted.

Bridge converter with asymmetric control. Various converters with improved characteristics are built based on the three-phase bridge circuit. For example, the semi-controlled bridge converter provides a halving the phase shift angle of the network current first harmonic related to the voltage $\varphi_1 \cong \alpha/2$, where α – control angles of valves. Such converters are used in irreversible motor drives, in the excitation systems of synchronous machines, welding machines, etc.

The valve asymmetric control for anode and cathode groups causes the appearance of odd and even harmonics in the phase currents. Neglecting the commutation processes, the amplitudes of phase current higher harmonics can be calculated by the formulas:

$$I_{n*} = \frac{1}{n}\frac{\left|sin\frac{n\alpha}{2}\right|}{cos\frac{\alpha}{2}} \quad for \quad n = 2,4,6; \tag{3.20}$$

$$I_{n*} = \frac{1}{n}\frac{\left|cos\frac{n\alpha}{2}\right|}{cos\frac{\alpha}{2}} \quad for \quad n = 5,7,11; \tag{3.21}$$

It should be noted that when feeding two identical asymmetrical bridge converters from the common buses, it is advisable to include controlled valves in a converter in the anodic group, in another case - in the cathode group. Even current harmonics in the network, in this case, are compensated.

Another common option for the special rectification circuit is a double-bridge circuit with in-series connection of controlled and uncontrolled bridges. Such scheme is characterized by a decrease in the non-sinusoidality coefficient in half compared with the controlled bridge.

When calculating the higher current harmonics of twelve-phase converters, it is important to consider the phase shift of similar harmonics in parts of the valve windings with different connection schemes (triangle and star). Harmonic currents with the numbers

$$n = 12q \pm 1 \quad (q = 0,1,2, \dots)$$

have the same phase, while the harmonics with numbers

$$n = 6q \pm 1 \quad (q = 1,3,5, \dots)$$

are in antiphase and cancel each other. Consequently, multi-bridge converters improve the harmonic content of currents due to the compensation of 5^{th} and 7^{th} harmonics.

Thyristor power regulators. They are widely used to regulate the modes of heating furnaces. The power of installations varies widely, while the power of transformers can reach 2.5 MVA. The introduction of thyristors and their phase control is accompanied by deteriorating both the energy characteristics of installations systems and the power quality.

Let's consider the work of the simplest power supply circuit of the electric resistance furnace with the thyristor power regulator, consisting of in-series-connected resistance and controlled back-to-parallel connected thyristors. Fig. 3.6 shows the single phase electric circuit of the installation, as well as the voltage and current diagram. As can be seen from the diagram, the current in the circuit is a non-sinusoidal periodic function, which depends on the time, and determined by the control angle α.

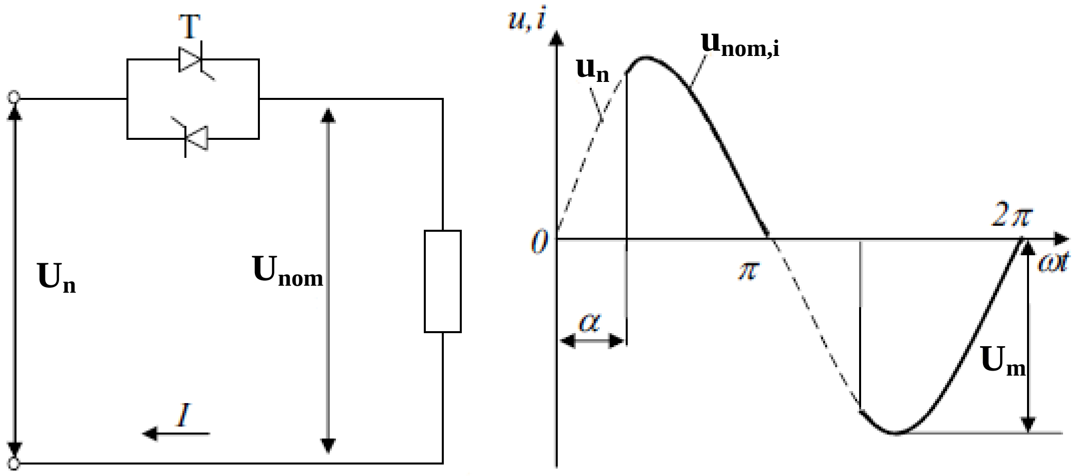


Fig 3.6. *The circuit with thyristor switches and active resistance: a - power supply scheme, b - voltage and current diagram*

The harmonic analysis of such functions is performed by representing these functions with Fourier trigonometric series. The Fourier series expansion is time-consuming procedure and therefore rationally in this case to use the simplified formulas.

Based on statistical analysis of experimental data, there are provided some formulas for approximate calculation of the higher current harmonics consumed by the furnace with thyristor control.

$$I_n = \frac{0.7S_{ft}}{\sqrt{3}U_{nom}n} \quad for\ n = 5,7,11,13;$$
$$I_n = \frac{0.1S_{ft}}{\sqrt{3}U_{nom}n} \quad for\ n = 2,3,4, \tag{3.22}$$

Where S_{ft} – the furnace transformer power, kVA; U_{nom} – nominal network voltage.

The higher harmonics of the installations for contact welding and arc welding. An approximate calculation of the current harmonics of welding machines with thyristor control modes by means of symmetric bipolar cells is possible by the formula:

$$I_n = \frac{S_p K_L K_n}{U_{nom} n^2} - \text{for single} - \text{point machines}$$
$$I_n = \frac{1}{m}\sum_{n=1}^{m}\frac{S_p K\ K_L K_n}{U_{nom} n^2} - \text{for multipoint machines} \tag{3.23}$$

where S_p- nameplate power of one transformer welding machine or multi-point machines; K_L – full power load factor; U_{nom} – nominal machine voltage; K, m

- number of transformers in one group and the number of groups; K_n – coefficient of harmonics (for n = 1, 3, 5, 7, and K_1=0.97, K_3=2.0, K_5=2.3, K_7=1.4).

The calculation error by these formulas does not exceed 15%, harmonics higher than 7 can be ignored.

Nowadays, the welding with direct current is widely used. The welding rectifiers are performed using the three-phase bridge circuit based on uncontrolled valves. The operating mode of the welding rectifier is a three-three-valve mode. For this mode, the currents of higher harmonics can be approximately calculated by the formula:

$$I_n = \frac{100}{n^2}\%, \quad for\, n = 5,7,11,13 \tag{3.24}$$

An accuracy of this calculation is within 1%.

For single-phase welding transformers, the current of harmonics can be approximately calculated as

$$\frac{I_n}{I_1} \approx \frac{0.3}{n^2}. \tag{3.25}$$

The third harmonic has the largest share, seventh and higher harmonics do not exceed 1%.

Power transformers are a source of higher harmonics of the magnetizing current. Due to the magnetic circuit asymmetry of three-phase three-rod transformers, the actual values of edge phases magnetizing current of 1.3 ... 1.35 times greater than the average phase magnetizing current. Therefore, the magnetizing currents have all odd harmonics. The greatest ones, except of the first, are 3, 5, 7 harmonics.

The rms values of harmonics of magnetizing currents I_{ph} can be found:

$$I_{ph} = I_\mu K_{ph}, \tag{3.26}$$

where I_μ – the nominal value of magnetizing current. The values of K_{ph} are shown in Table. 3.3.

Table 3.3. *The values of coefficient* K_{ph}

harmonics number	The extreme phase	The average phase
3	0.1	0.2
5	0.29	0.22
7	0.12	0.1

When there are voltage deviations at the transformer terminal from the nominal values at ΔV (%), harmonics of the magnetizing current should be recalculated according to the formula:

$$I'_{ph} = I_{ph}(1 + \Delta V \cdot \lambda).$$

The values of coefficient λ at ΔV = 1 % are shown in table 3.4.

Table 3.4. *The values of coefficient λ*

n	$U<U_{nom}$	$U<U_{nom}$
1	-0.05	0.12
3	-0.05	0.14
5	-0.05	0.16
7	-0.05	0.2

With an increase in the voltage over than 3 ... 5% of nominal value, harmonics of the magnetizing current increases to 1.5 ... 2 times. With a large installed capacity of shop substation transformers, it can lead to a marked increase in the voltage harmonics in the network.

Electric arc furnaces are abruptly variable loads that generate higher current harmonics, especially during the charge melting. However, in comparison with the valve converters, the furnaces have the level of harmonics 2 ... 4 times lower. Since the nonlinearity of the arc furnace depends on many factors: the furnace power, electrode materials, composition and preparation features of the charge, the control system of arc burning, etc., it is very difficult to predict the levels of higher harmonics by calculation methods. Therefore, to estimate the higher current harmonics for the furnace, it is recommended to use the measurement results shown in Table. 3.5.

Table 3.5. *The percentage of higher current harmonics for different type furnaces*

n	ДСП-5	ДСП-10	ДСП-25	ДСП-50	ДСП-100	ДСП-200
2	7	8	9.5	6.1	5.1	6.8
3	11.2	9.2	4.8	4.4	7.2	5.1
4	2.7	2	4.8	2.9	2.3	4.2
5	8.9	2.8	6	5.4	5.5	2.6
7	4.9	1.6	1.3	5.7	2.1	0.7
9	1.3	0.7	0.2	1.4	1	0.3

Gas discharge lamps are widely used in industrial and urban lighting networks. Their share weight reaches 75 ... 80%. The non-linear volt-ampere characteristic of lamps due to presence of the arc discharge circuit is the reason for distorting the current curve consumed from the network. The magnitudes of higher current harmonics are shown in Table. 3.6 as a percentage of the 1st harmonic current.

The thyristor dimmers for incandescent lamps also leads to an appearance of higher harmonics in the lighting networks. The harmonics n = 3, 5, 7 are the greatest ones, while their relative values are within 1,5 ... 6%. In general, as for the electric arc furnaces, the harmonic current of the fluorescent lamp is unstable.

Table 3.6. *The percentage of higher current harmonics for lamps*

n	Fluorescent lamps with ballast resistance		Lamps	
	inductive	inductance-capacitance	Gas-discharge mercury lamp with compensation.	Gas-discharge sodium lamp with compensation.
3	4	16…21	18	19
5	0.6	0.4…3	5.8…7.2	9.5
7	0.2	0.5…1.2	1…5.2	1…1.4
9	0.2	0.1…0.6	1…1.4	2.4…3
11		0.3…1.1	5.4…8.8	11
13		0.2…0.3	2.6…8.8	4.5…5.9
15		0.2	0.2…0.4	0.4…0.7
17		0.4	1…4.4	6.6…7.4
19		0.5	0.1…1	2.2…3.4
21		0.7	0.8…0.9	0.7…7.2
23			5…9.4	7…10
25			0.1…1	3…10

3.4. Calculation of voltage non-sinusoidality coefficients in electrical network

The problem of higher harmonics is an important part of the general problem of the electromagnetic compatibility between the power consumers and the supply power network.

Design and operating agencies face the challenges of the reliable determination of the voltage non-sinusoidality, the spectral composition and the level of harmonic currents and voltages in order to limit them.

The voltage non-sinusoidality limitation with the greatest efficiency can be achieved at the design stage by the power supply companies, but it requires additional costs. Therefore, this limitation is both technical and economic problem that cannot be considered without the problem of the reactive power compensation. This is explained by the fact that the compensating device with a capacitive equivalent circuit (eg, capacitor banks, filter harmonics) in combination with an inductive resistance of the power supply network can lead to a resonance in the network at high frequencies and, consequently, an increase in the individual harmonics of voltage and current to unacceptable magnitudes.

In practice, the direct method for determining the voltage THD factor K_u during the work of converters is widely used and based on the harmonic analysis of switching pulses (dips and surges) [9, 13]. The most thorough examples of this method is described further.

3.4.1 Method of calculating the voltage non-sinusoidality by switching distortions at the operation of valve converters

Nowadays, as noted above, the most common scheme for powerful three-phase valve converters is a rectifier bridge circuit (Larionov`s circuit). This scheme makes it possible to straighten the so-called six-phase or six-pulse rectifier circuits. The in-series or in-parallel connection of several such bridges and their power supply with the voltage shifted by an appropriate angle, provides a multi-phase (multiples of six) rectifier circuits.

The power supply scheme of a powerful valve converter and the equivalent circuit diagram are shown in fig. 3.7. Depending on the phase sequence, control angle, the power consumed by the converter S_c and the parameters of the power supply network, the commutation distortions have a definite form and location in the supply voltage curve. The commutation distortions, for example, for six-phase rectifier bridge circuit are shown in Fig. 3.8. The converter supply is carried out from transformers with the connection diagram *Λ/Λ* and *Λ/Δ*.

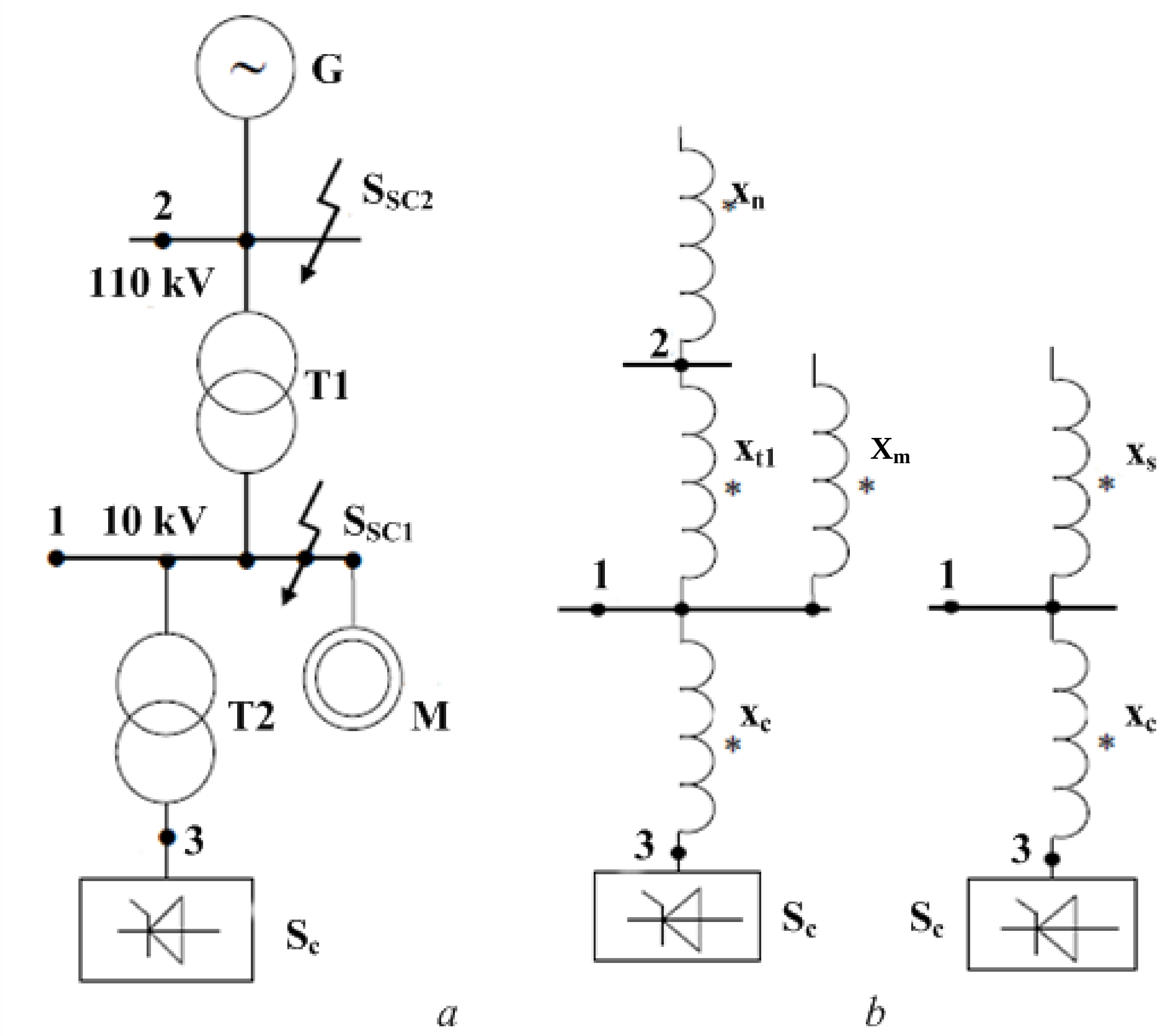


Fig. 3.7. *Single-line diagram of the powerful valve converter power supply (a) and equivalent circuit diagram (b)*

The method for calculating the coefficient of non-sinusoidality K_u is based on ***the calculation of rms values of commutation voltage distortions at any point in the networks*** that is equivalent to take into account all the higher harmonics. Therefore, to determine K_u, when operating the valve converters, there is no need to define the levels of individual harmonics. Moreover, in the case of converter`s asymmetric control due to the asymmetry of current harmonics in the network, the assessment of K_u with the equations based on the values of current harmonics is associated with the sufficient error.

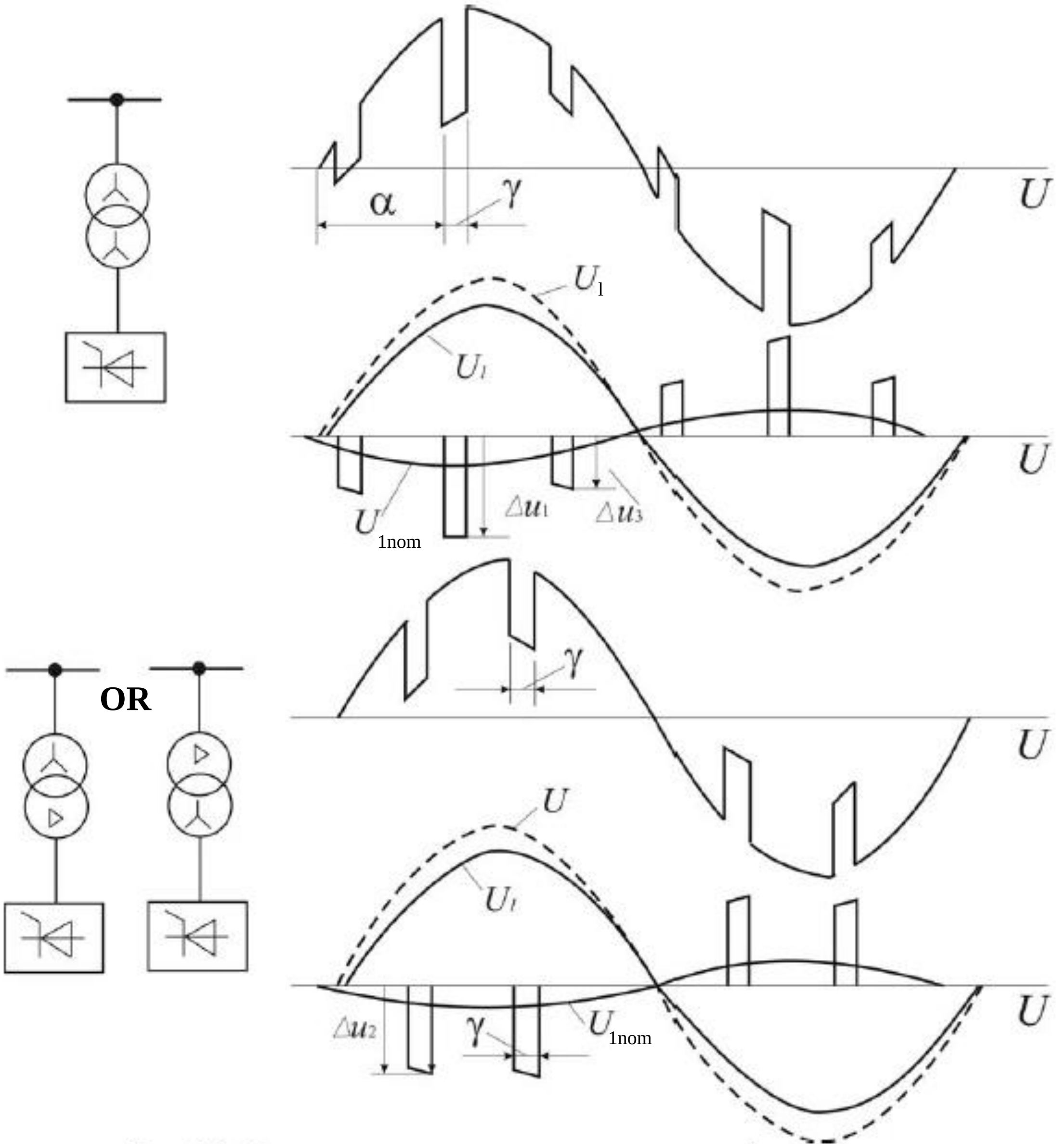


Fig. 3.8. *Commutation distortions of the voltage waveform at the 6-phase rectifier circuit*

The use of the proposed method allows one to avoid errors arising, when there is only a certain number of higher harmonics. Fig. 3.9 and Fig. 3.10 shows the curves clearly indicating the error that is obtained, when calculating K_u taking into account only a certain number of harmonics in relation to K_u, which is calculated taking into account all the harmonics up to $n = \infty$ the ratio with the formula:

$$K_U = \frac{\sqrt{\sum_2^n U_n^2}}{U_1} : \frac{\sqrt{\sum_2^{n=\infty} U_n^2}}{U_1}.$$

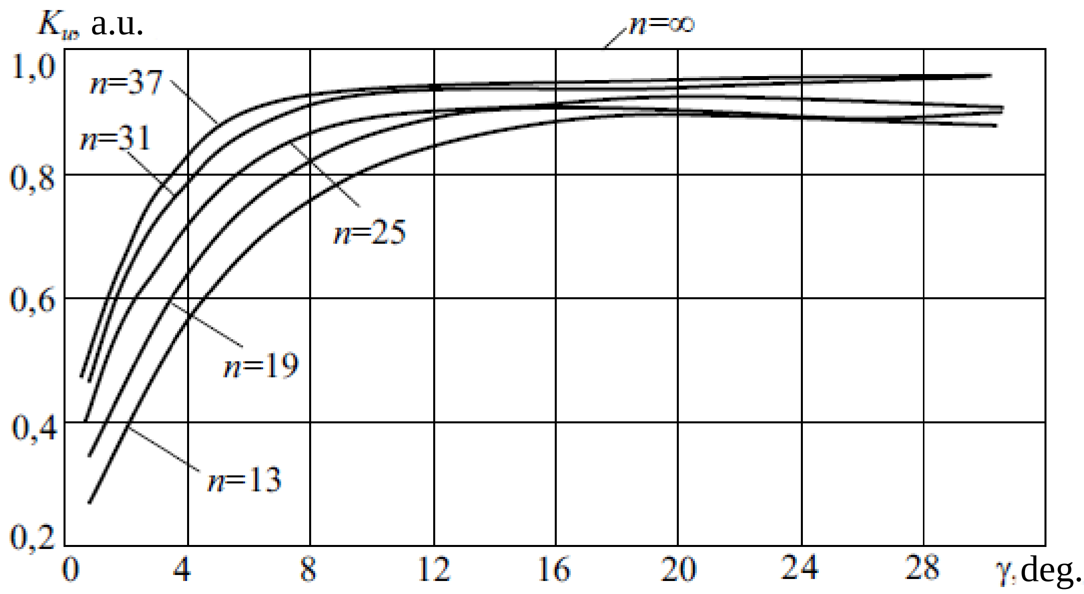


Fig. 3.9. *The dependence of $K_u = f(\gamma)$ when taking into account the different number of harmonics for a 6-phase rectifier circuit of the converter*

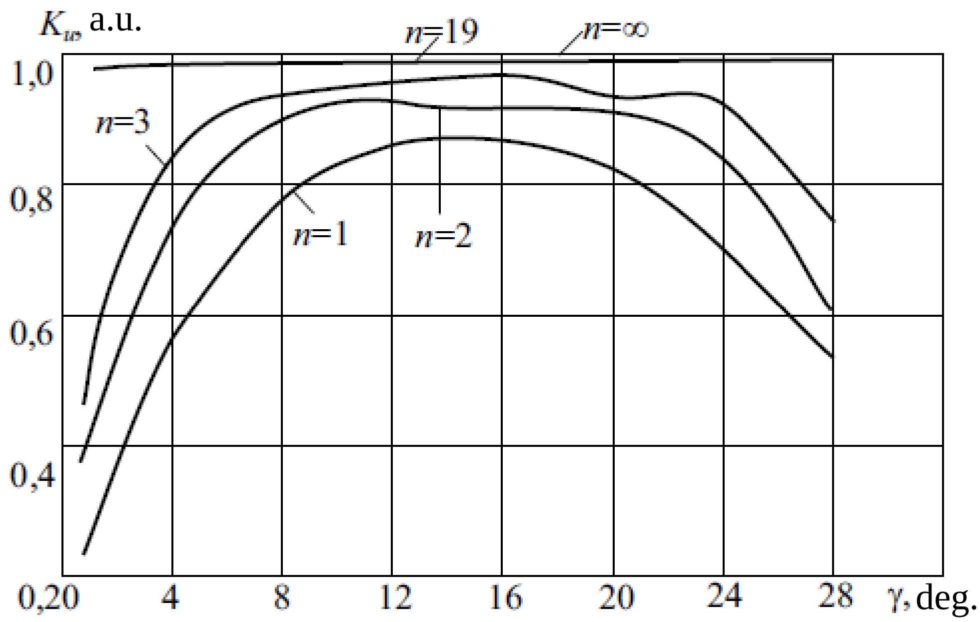


Fig. 3.10 *The dependence of $K_u = f(\gamma)$ when taking into account the different number of harmonics for a 12-phase rectifier circuit of the converter*

Based on these curves, the conclusion is evident that a certain position about the possibility of limiting the upper bound of the higher harmonics summation with the harmonic n = 13 is wrong. This limitation is even more unacceptable to the converter circuit with a rectification phase of more than 12, where, according to (3.11), the higher harmonics of order $n \leq 13$ are missing.

The method allows one to find K_u at any network point using the parameters obtained in the calculation of short-circuit currents, and is based on the following assumptions: the conductivities of the network elements are considered as non-capacitive ones.

With this assumption, during the calculations the error does not exceed 10 ... 15%. It is assumed that in the network nodes, which are closed to the valve converters, there are no capacitor banks, designed for the reactive power compensation. The abnormal harmonics are also not considered.

As mentioned before, the voltage THD factor (or coefficient of non-sinusoidality) K_u is determined by the formula:

$$K_U = \frac{\sqrt{\sum_2^\infty U_n^2}}{U_1} \approx \frac{\sqrt{\sum_2^n U_n^2}}{U_{nom}}. \tag{3.27}$$

When there is working valve converter, K_u is defined with the following sequence:

- the rms value of commutation voltage distortions U_{dis} is calculated;
- the first harmonic of the voltage in commutation distortions is determined U_{dis1} (fig. 3.8);
- the rms value of all higher harmonics (except for the first one) in commutation distortions is calculated by the formula:

$$U_{n\Sigma} = \sqrt{\sum_{n=m-1}^{\infty} U_n^2} = \sqrt{U_{dis}^2 - U_{dis1}^2}; \tag{3.28}$$

- the first harmonic in the distorted supply voltage curve is determined as

$$\overline{U}_1 = \overline{U}_l + \overline{U}_{dis1}, \tag{3.29}$$

where $\overline{U}_l$ – the rms value of an undistorted voltage waveform or line voltage envelope;

- According to (3.27), K_u is determined.

The calculations of voltage non-sinusoidality in the network are usually performed at the power supply design stage, that is why there is necessary to know the relations between the control angle α, switching angle γ used in electric drive and the supply network parameters. According to [13]:

$$\varphi = \alpha + \frac{\gamma}{2}, \tag{3.30}$$

where φ - the angle shift between the first harmonic of the voltage applied to the converter, and the first harmonic of the current consumed by the converter. Then we can write:

$$cos\left(\alpha+\frac{\gamma}{2}\right)=cos\varphi=\frac{P_c}{Q_c};\qquad(3.31)$$

$$sin\varphi=\frac{Q_c}{S_c},\qquad(3.32)$$

where, P_c – active power consumed by the converter at the side of alternating voltage; Q_c - reactive power consumed by the converter from the network; S_c – full power consumed by the converter.

For the angles α and γ, there exists a relation:

$$cos\alpha-cos(\alpha+\gamma)=\frac{2I_dX_\Sigma}{U_{l\,max}}\qquad(3.33)$$

where I_d – rectified current; X_Σ – inductive resistance of the commutation circuit; $U_{l\,max}$ – the amplitude of the supply linear voltage.

After transformations and simplifications, the formula (3.33) takes the simple form for the commutation angle when using converters with any phase sequence:

$$\gamma=\frac{6X_\Sigma}{m\cdot sin\varphi}\qquad(3.34)$$

where X_Σ - the equivalent inductance of the commutation circuit in per-unit values, reduced to the full power of the converter S_c.

The total coefficient of non-sinusoidality in the supply network with the valve converters with some simplifications and a sufficient accuracy for engineering calculations may be determined by the formula:

$$K_u=X_{s*}\sqrt{\frac{3sin\varphi}{\pi\cdot(X_{s*}+X_{c*})}-\frac{9}{\pi^2}}=\frac{S_c}{S_{sc}}\sqrt{\frac{0.955\cdot sin\varphi}{\frac{S_c}{S_{sc}}+X_{c*}}-0,91}\qquad(3.35)$$

where $X_{s*}=\frac{S_c}{S_{sc}}$ – the equivalent system resistance in per-unit values, reduced to the full power of the converter S_c, i.e. the resistance from the notional point in the network of infinitive capacity to the network point, where K_u is determined; S_{sc} – the short-circuit power in the point, where K_u is determined; X_{c*} - the inductance of the converter circuit in per-unit values, reduced to S_c i.e. the resistance from the point of commutation short-circuit appearance to the point, where K_u is determined.

This formula is valid for converters with any phase sequence.

When determining K_u, a special attention should be paid to X_{c*}. Most often, it requires determining K_u at the power supply buses of powerful thyristor converters. Under the converter, the bridge rectifier (or their group) and supply step-down transformer are meant.

In this case, X_{c*} is equal to the resistance of the step-down transformer and is determined by:

$$X_{c*} = X_{tr*} = \frac{U_{sc}\%}{100}(1 + \frac{K_{sp}}{4})\frac{S_c}{S_{nom.tr}} \tag{3.36}$$

where $S_{nom.tr}$ – step-down transformer nominal power; K_{sp}- the splitting factor for windings of this transformer; $U_{sc}\%$ - through short-circuit voltage of transformer, reduced to the full nominal power of transformer.

For two-winding transformer used in the three-phase rectifier bridge, $K_{sp} = 0$ and then:

$$X_{c*} = X_{tr*} = \frac{U_{sc}\%}{100} \cdot \frac{S_c}{S_{nom.tr}} \tag{3.37}$$

For three-winding transformers used in twelve-phase converters, in general

$$K_{sp} = \frac{U_{sc(sw1-sw2)}}{U_{sc}} \tag{3.38}$$

where $U_{sc(sw1-sw2)}$ – the short-circuit voltage between the split secondary windings of the transformer.

In general, for the transformer with split windings, $K_{sp} = 0 \dots 4$. If the low voltage transformer branches have good electromagnetic coupling with each other, then $K_{sp} = 0$. If the low voltage transformer windings do not have magnetic communication with each other or the converter is made by the scheme with two transformers having different wiring schemes, $K_{sp} = 4$.

3.4.2. Engineering (simplified) method for calculating the components of the harmonic spectrum for valve converters

The assumption, which simplifies and introduces some uncertainty in an approximate calculation method, is the assumption of a rectangular form of the commutation distortions (fig. 3.8). The error caused by this assumption depends on the control angle α and switching angle γ.

The smaller the angle α and the larger the angle γ, the greater the error in determining the voltage and current harmonics. In general, for rectifiers, this error does not exceed 10%, which is quite acceptable for practical calculations.

The effective (rms) value of the voltage higher harmonic at any supply network point with the converter working with any phase sequence can be defined by the formula:

$$U_n = \frac{m}{\pi n} U_l \frac{X_{S*}}{X_{S*} X_{c*}} \; sin\varphi \cdot sin\left(\frac{3nX_{\Sigma*}}{m \; sin\varphi}\right). \qquad (3.39)$$

The rms current value of any harmonic in the converter circuit is determined from the expression:

$$I_n = \frac{m}{\sqrt{3}\pi} \frac{S_c}{U_l X_{\Sigma*} n^2} \; sin\varphi \cdot sin\left(\frac{3nX_{\Sigma*}}{m \; sin\varphi}\right). \qquad (3.40)$$

To determine the rms value of the individual voltage harmonics at any point in the supply network, a series of curves is shown in Fig. 3.11.

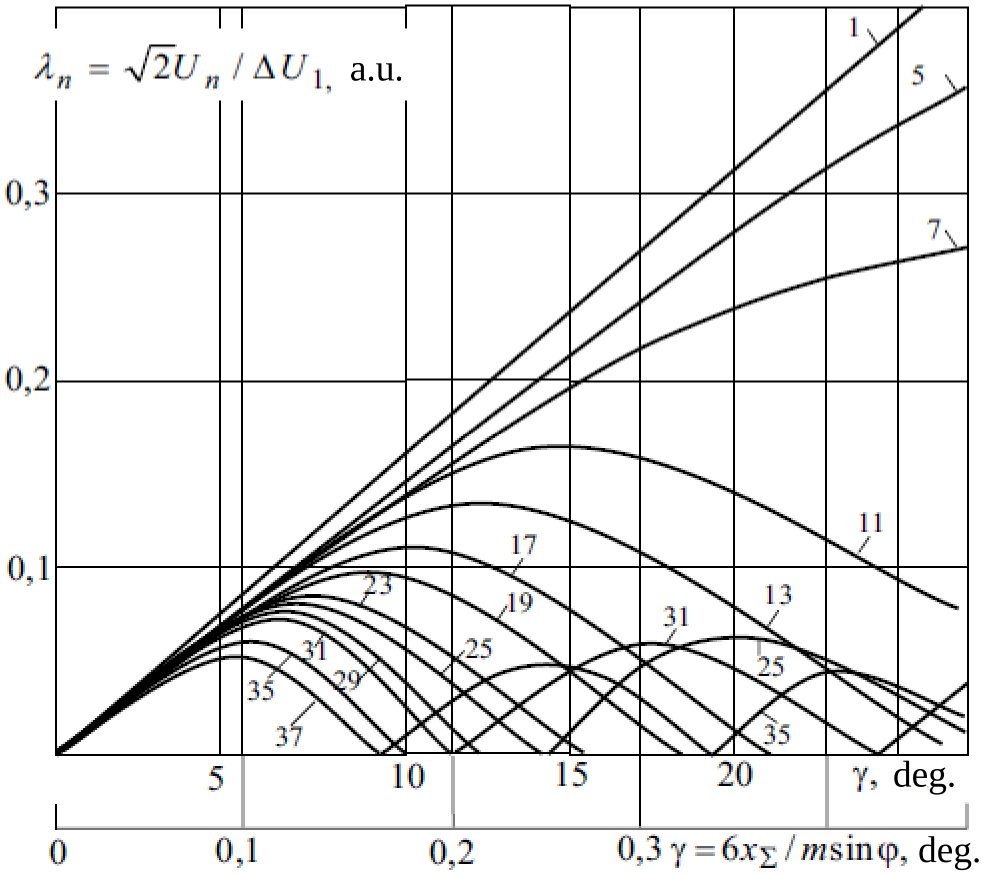


Fig. 3.11. *Nomograms for determining the individual voltage harmonics when using valve converters*

These curves represent the dependence $\lambda_n = f(\gamma)$, where $\lambda_n = \sqrt{2}U_n/\Delta U_1$ is the ratio of the *n-th* harmonic amplitude to the depth of main commutation distortion in per-unit values.

To determine the rms value of *the n-th* voltage harmonic it is necessary to find the commutation angle γ according to the formula (3.34). For the obtained value of γ, it is necessary to determine the coefficient λ_n using the curve corresponded to the *n-th* harmonic. Then, the effective value of *the n-th* harmonic is determined from the equation:

$$U_n = \lambda_n \frac{m}{6} \frac{\Delta U_1}{\sqrt{2}}, \qquad (3.41)$$

where $\Delta U_1 = \sqrt{2} U_l \frac{X_{S*}}{X_{S*}+X_{C*}} \, sin\varphi$ – the depth of the main commutation distortion in relative units; $\varphi = \alpha + \frac{\gamma}{2}$.

3.4.3. Determination of non-sinusoidality in the group of converters

When there is a group of valve converters, the calculation procedure for determining K_u is as follows. Using the above formulas or curves in Fig. 3.11, the levels of the higher voltage harmonics and their angles $\varphi_n \approx \varphi_1 n$ are determined for each converter.

The same voltage harmonics for all converters are geometrically summed

$$\overline{U}_{n\Sigma} = \sum_{i=1}^{k} \overline{U}_{ni} , \qquad (3.42)$$

where k - number of identical harmonics.

Then, the coefficient of non-sinusoidality for group of working converters is determined by the formula

$$K_{U\Sigma} = \frac{\sqrt{\sum_{n=5}^{p} U_{n\Sigma}^2}}{U_1}, \qquad (3.43)$$

where p - number of groups of identical harmonics.

Pay a special attention to the number of harmonics taken into account. The greater the number of converters and rectification phases, the greater the number of harmonics must be considered. With this aim, we propose the following empirical formula:

$$P = n_{max} = 4km + 1, \qquad (3.44)$$

where n_{max} - the highest harmonic taken into account; κ - the number of working converters; m – the number of rectification phases.

As seen from (3.44), with a large number of converters, a sufficiently large number of higher harmonics must be considered. At the same time, the complexity of calculations increases considerably. Therefore, when there is a group of converters, one tends to reveal some regularities that allow determining K_u by the simpler way.

1. So, if the converter circuits are the same and, at the same time, the control and switching angles for 6 and 12-phase rectifier circuits have such relations that commutation distortions of individual converters do not overlap, then K_u can be

easily calculated. In this case, K_u is calculated from each converter separately and then total coefficient of non-sinusoidality is determined:

$$K_{U\Sigma} = \sqrt{\sum_{i=1}^{k} K_{ui}^2}\,. \qquad (3.45)$$

2. The connection schemes of transformers of the converters are the same, the converters work in phase, i.e. $\alpha_1 = \alpha_2 = \ldots = \alpha_n$ or $\cos\varphi_1 = \cos\varphi_2 = \ldots = \cos\varphi_n$, the transformers of converters have the same parameters. In this case, the commutation distortions of converters are superimposed on each other, all the harmonics are added arithmetically and the K_u calculation reduces to the calculation of one equivalent converter with the following parameters:

$$S_{c.ec} = \sum_{i=1}^{n} S_{nom.c.i}\,; \quad S_{t.ec} = \sum_{i=1}^{n} S_{nom.t.i}\,;$$
$$cos\varphi_{ec} = cos\varphi_n; \quad U_{SC.ec} = U_{SC.t.i}.$$

3. The schemes of transformers are the same, the control angles of converters are the same, i.e.

$$cos\varphi_1 = cos\varphi_2 = \cdots = cos\varphi_n.$$

At the same time $S_{nom.t1} \neq S_{nom.t2} \neq \cdots \neq S_{nom.tn}$; $U_{SC.t1} \neq U_{SC.t2} \neq \cdots \neq U_{SC.tn}$. In this case, the parameters of the equivalent inverter will be determined by the following relations:

$$S_{c.ec} = \sum_{i=1}^{n} S_{c.i}\,; \quad S_{t.ec} = \sum_{i=1}^{n} S_{nom.t.i}\,;$$
$$U_{SC.ec} = \frac{S_{t.ec}}{\frac{S_{nom.t1}}{U_{SC.t1}} + \frac{S_{nom.t2}}{U_{SC.t2}} + \cdots + \frac{S_{nom.tn}}{U_{SC.tn}}} = \frac{\sum_{i=1}^{n} S_{nom.ti}}{\sum \frac{S_{nom.ti}}{U_{SC.ti}}}$$

These cases do not cover all possible variants of the valve converters work. In general, the work of valve converters is erratic, especially for independent processes. In these cases, with a sufficient accuracy for engineering calculations, it is possible to determine the coefficient of voltage waveform distortion in the estimated point of each individual converter, and the overall coefficient determined by the expression (3.45).

3.4.4. Calculation of voltage non-sinusoidality at the operation of electric arc furnaces

The level of higher harmonics during the work of electric arc furnaces (EAF) is relatively small, as noted above, compared to the higher harmonics generated by valve converters. However, they should be considered, since the powerful arc furnaces are constantly growing.

The appearance of higher harmonics in the supply networks when using EAF is random and cannot be described analytically. So, they are basically determined experimentally and presented in table 3.5.

Based on the experimental investigations, an experimental relation for determining maximum levels of individual harmonics during the EAF work was obtained.

$$I_n = \frac{I_{ft}}{n^2}, \tag{3.46}$$

where I_{ft} – the furnace transformer (nominal) current; n = 3, 4, 5, ... – the number of the harmonics. The current of the second harmonic is assumed to be equal the current of the third harmonic ($I_2 \approx I_3$). From this relation it is clear that in the calculations it is sufficient to consider harmonics up to the 7th, as the other harmonics are small.

For groups of identical EAF:

$$I_{n\,gr} = I_n \sqrt[4]{N}, \tag{3.47}$$

where N – the number of furnaces, working at the same time in the melting mode.

For groups of furnaces having different capacities:

$$I_{n\,gr} = I_{nmax} \sqrt[4]{\frac{\sum_{i=1}^{N} S_{ft\,i}}{S_{ft\,max}}}, \tag{3.48}$$

where $S_{ft\,i}$ – the capacity of *i-th* furnace transformer; $S_{ft\,max}$ – the highest capacity of transformer in the group of EAF; I_{nmax} – the current of the *n-th* harmonic of the furnace transformer with the highest capacity; N – the total number of working furnaces.

To determine K_u in the corresponding network point, it is necessary to find the level of the individual voltage harmonics generated by the EAF. The phase voltage of harmonic in the considered network point is defined from the equation:

$$U_n = I_n n X_s = I_n n \frac{U_{nom}^2}{S_{SC}}, \tag{3.49}$$

where I_n – the rms value of phase-to-ground current of the *n-th* harmonic; n – the number of harmonic; U_{nom} – nominal phase-to-phase voltage in the considered point; X_s – the resistance of the supplied network from the calculated point to the point of infinite capacity; S_{SC} – short-circuit power in the considered point.

The total coefficient of non-sinusoidality in the considered point at the EAF work can be found according to:

$$K_U = 100 \frac{\sqrt{\sum_{n=2}^{7} U_n^2}}{U_{ph.nom}}, \tag{3.50}$$

where $U_{ph.nom}$ – nominal phase (or phase-to-ground) voltage at the fundamental frequency in the considered point.

3.4.5 Calculation of the current harmonic content for the reactor with thyristor regulator

To reduce the voltage fluctuations in the supply network, the indirect compensation scheme of the variable reactive power component is used. This scheme includes the reactor, controlled by the antiparallel-connected thyristors.

Fig. 3.13 shows a diagram of thyristor-reactor group, and the supply voltage and current diagram in the reactor. The change in the control angle from α=0 to α=π/2 will lead to the change in the current flowing through the reactor from the maximum to zero. As can be seen from the diagram, the current in a reactor is essentially nonlinear. The percentage of current harmonics in the reactor varies depending on the angle α.

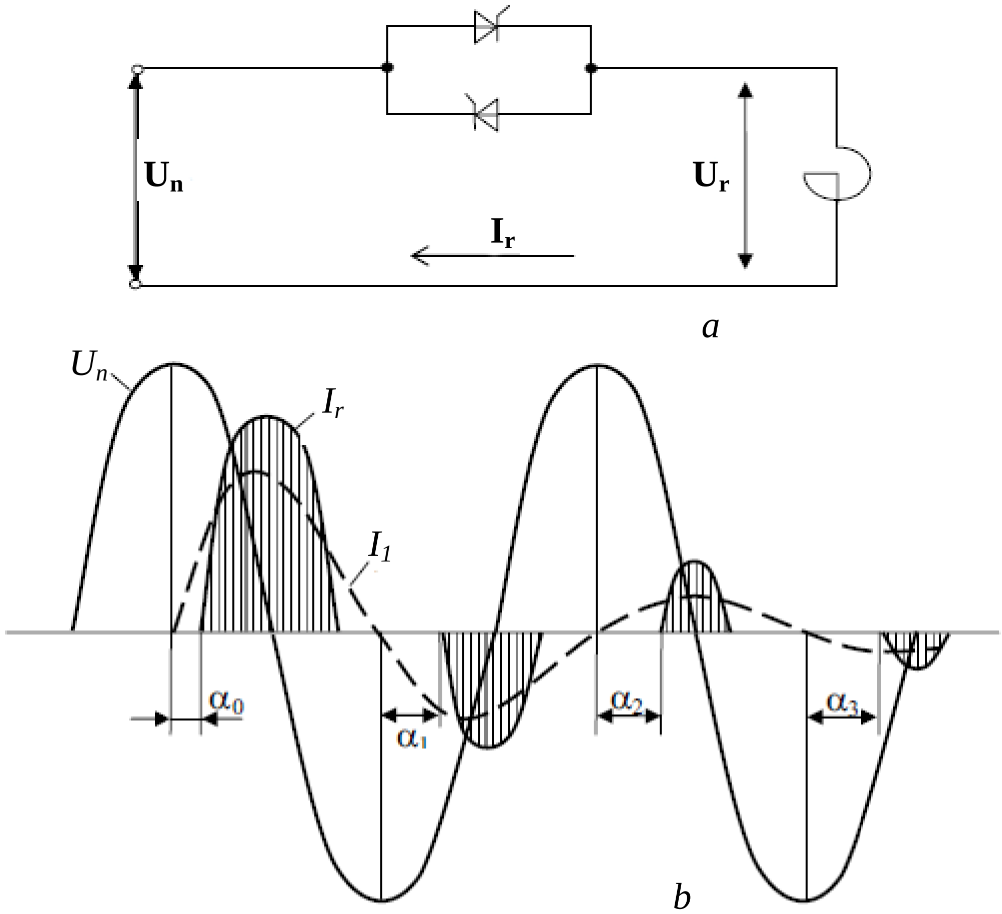


Fig. 3.13. *Thyristor-reactor group: a – scheme; b – voltage and current diagram*

The controlled reactor current is expressed by the formula:

$$I_r(t) = I_{r0m}(\sin\omega t - \sin\alpha) = \frac{Q_r}{\sqrt{3}U_{nom}}(\sin\omega t - \sin\alpha), \quad (3.51)$$

where I_{r0m} – the reactor current at the control angle α=0 (amplitude value).

Since this function is periodic (the period is 2π), we can make a harmonic analysis, expanding it into a Fourier series. Then, the reactor current can be written as:

$$I_r(t) = b_1 I_{r0} \sin\omega t + b_3 I_{r0} \sin 3\omega t + b_5 I_{r0} \sin 5\omega t + \cdots + b_n I_{r0} \sin n\omega t, \quad (3.52)$$

where b_n - coefficient of the Fourier series; n - number of harmonics (3, 5, 7, 11, 13th ……….).

According to the calculation results, the dependencies of the coefficients of the Fourier series on the control angle α are built and presented in Fig. 3.14.

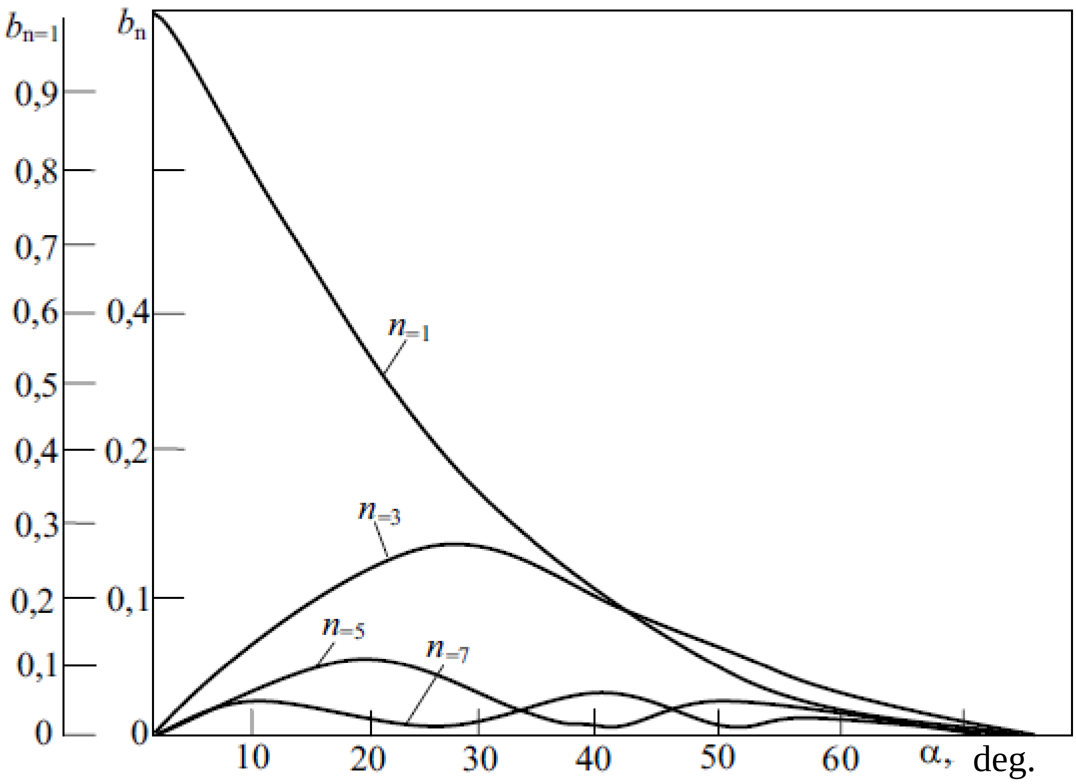


Fig. 3.14. *The graphical dependences of the Fourier series coefficients b_n on the control angle α*

As can be seen from Fig. 3.14, the maximum current value of the third harmonic is in the reactor at the control angle α = 30°, the fifth harmonic current - at α = 20°, the seventh harmonic current – at α = 10°. The rms value of the current harmonic is given by:

$$I_n = b_n I_{r0} = b_n \frac{Q_r}{\sqrt{3} U_n}. \quad (3.53)$$

The values of current harmonics calculated from (3.53) are used to check the capacitors and the filter-compensating devices for their overload with the higher harmonics of current, as well as to determine the non-sinusoidality coefficient in the supply network containing the working thyristor-reactor group.

The THD factor (non-sinusoidality coefficient) is determined by the formula, %

$$K_U = 100 \frac{\sqrt{\sum_{n=3}^{7} U_n^2}}{U_s}, \quad (3.54)$$

where U_n and U_s – the voltage of *n-th* harmonic and supply network, respectively.

The voltage U_n is determined by the formula:

$$U_n = I_n n X_S = I_n \frac{n U_c^2}{S_{SC}}, \quad (3.55)$$

where I_n – current of harmonic; X_S – the supply network resistance; S_{sc} – the short-circuit power in the point of the installation connection. For engineering calculations, it is sufficient to consider only the 3rd, 5th and 7th harmonics, since the higher order harmonics are too small.

When calculating the higher harmonics, it is necessary to keep in mind that when using devices of indirect compensation in networks with EAF, electric welding rectifier and valve converter, the thyristor-reactor group generates harmonics then, when they are not generated by the arc furnaces and welding systems, and vice versa. The level of current higher harmonics of the thyristor-reactor group, arc furnaces and welding systems is of the same order. Therefore, the higher harmonics are aligned. It is obvious that in such power supply systems, it is necessary to calculate only the maximum harmonics of arc furnaces and welding loads. The valve converters generate harmonics order of magnitude greater than thyristor-reactor group, so that in such systems only the higher harmonics of the valve converters must be taken into account.

3.5. Capacitor banks in electrical networks with higher harmonics

Since the nonlinear load (valve converters, arc furnace, etc.) work usually with a low power factor (cosφ= 0.4 ... 0.8), the need for the reactive power compensation is evident.

The most economical means of the reactive power compensation up to date are unregulated and regulated capacitor bank (CB). This is due to their known advantages over other means of reactive power compensation (synchronous motors, synchronous compensators). However, a CB usage is limited by the technical reasons. If in the network there are higher current and voltage harmonics, the capacitor connection leads to the resonance phenomena at frequencies of higher harmonics, which can disrupt the CB normal work.

The investigations of the capacitor bank working process in the presence of higher harmonics in the supply network, especially when working with valve converters, are of great practical importance to determine the possibility of applying CB in power supply systems at enterprises.

We will consider the essence of the phenomenon by the example of a simple power supply circuit shown in Fig. 3.15 feeding the powerful valve converter. The diagram shows three main elements involved in the resonant process: the valve converter, which is a source of higher current and voltage harmonics; the supply network, including all its components (including other loads), which is presented in the simplified form with the an equivalent inductively-active element; the capacitor bank (the capacitance-active circuit in the equivalent circuit).

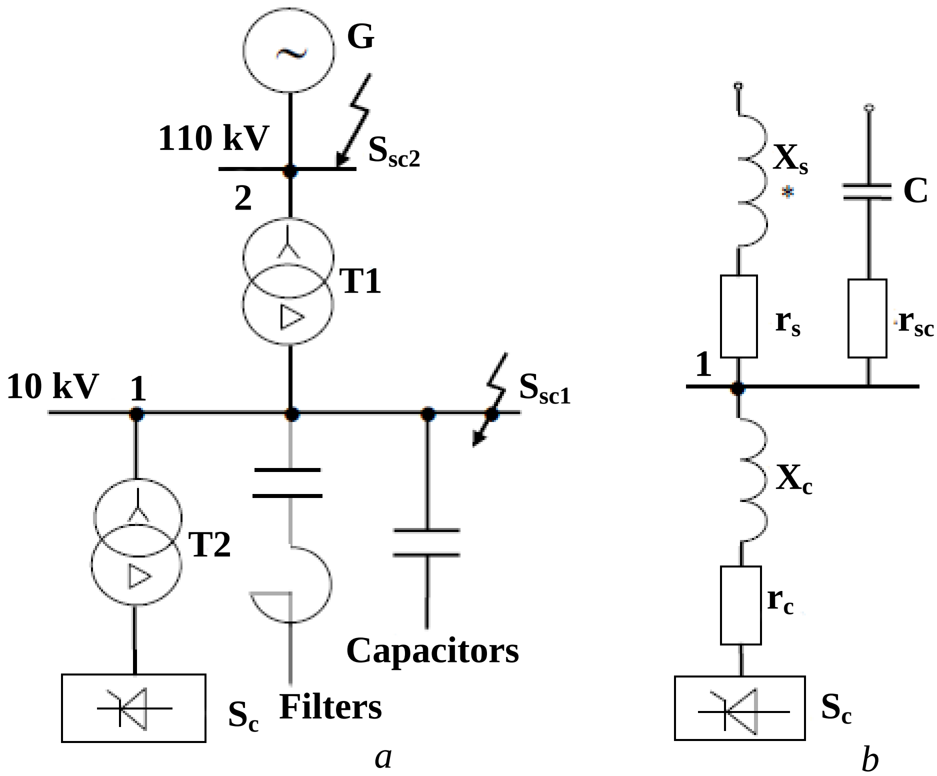


Fig.3.15. *Single-line diagram of the power supply network with the capacitor banks and filters of higher harmonics (a) and equivalent circuit (b)*

In the absence of capacitive elements (CB off), the frequency characteristics X_c and X_Σ of the supply network resistance at points 1 and 2 (Fig. 3.15) are linear (the curve 2 in the fig. 3.16), active resistances in this case can be neglected because of their smallness. Consequently, the depth of commutation distortion and individual voltage harmonics decreases linearly with the distance from the commutation point (to point 2 in Fig. 3.15).

The depth of commutation distortion ΔU_1 is proportional to $x_s/(x_s + x_c)$, where

x_s - the supply network equivalent inductance, i.e., the resistance from the conditional point of infinite power supply to the studied point of the power supply system; x_c – the converter circuit inductance, i.e. is the resistance from the commutation point to the studied point of the power supply system. At this, the width of the commutation distortion remains unchanged and is determined by the switching angle γ.

The inclusion of a capacitor bank drastically alters the linear frequency response of the supply network both at point 1 and at point 2 (Fig. 3.15 and 3.16). Moreover, the nonlinearity of the frequency response largely depends on the quality factor (Q-factor) of the supply network elements, i.e., the x / r ratio.

The nonlinearity of the frequency response at the point 1 can be explained by the fact that, when connecting CB, the parallel *LC-circuit* is formed. This *LC-circuit* consists of the supply network inductive reactance and capacitance of the capacitor bank. The formulas for determining the frequency response of *the LC-circuit* of the supply network are given in [9] and can be used for an accurate quantitative analysis of the characteristics. According to the formulas described in [9], the frequency characteristics of a parallel resonant circuit for different Q-factor values ($Q = x_s / r_s$) are constructed (Fig. 3.16). By comparing the frequency characteristics of the network without CB with the dependence Z_n / Z_1 as the function of the harmonics frequency for the parallel resonant circuit, it is possible to make a qualitative analysis of the mode, when the CB is overloaded with currents of higher harmonics.

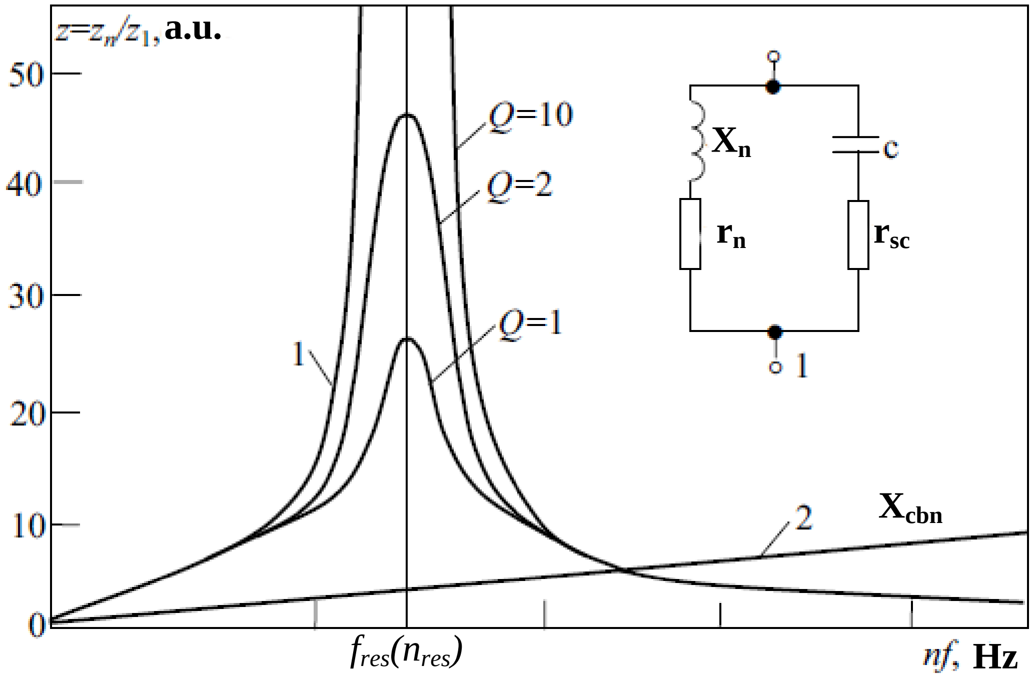


Fig.3.16. *Supply network frequency characteristics at point 1 (see Fig. 3.15): 1 - When the capacitor bank is connected for different values of* $Q = x_s / r_s$*; 2 - when the capacitor bank is disconnected.*

In the absence of capacitive elements in the network, the voltage of *n-th* harmonic at the substation buses (Figure 3.15) is determined by the voltage drop on a relatively small network inductive reactance for this harmonic x_{sn}. In this case, the circuit resistance can be neglected due to the high values of the quality factor in the order of Q = 30-50.

When connecting CB to the substation buses, which feeds a powerful converter load, the process changes dramatically. Whatever the CB value, there is always a such group (resonant group of harmonics), in which CB comes into the current resonance mode (or close to it) with the network inductance. The resistance of the parallel circuit in the resonance area increases sharply (Fig. 3.16).

The currents of the resonant harmonics group generated by the valve converter to the network are significantly reduced. This means that the voltages of the resonant harmonics group U_n directly applied to the CB minus a small voltage drop in the converter transformer. Consequently, the voltages of the resonant harmonics group at the point 1 grow significantly, while the capacitive reactance decreases with an increase in the harmonic number ($x_{cbn} = 1/n\omega c = x_{cb}/n$)

This leads to the fact that there are significant currents of resonating harmonics, which are comparable, and sometimes greatly exceed the current of the first harmonic. These currents flow through the capacitor bank. The CB overload with the currents of higher harmonics can reach, in practice, significant quantities (up to 400%) that leads to the complete failure.

Taking into account that the valve converters generate a spectrum of canonical harmonics to the network, ranging from $n = 5$ (six-phase rectifier circuit), it is theoretically possible to choose a capacitor bank with such power, which would come to a parallel resonance with the network inductance at frequencies below 250 Hz ($n < 5$) to avoid resonance phenomena and their consequences.

This method of solving the problem has no practical meaning because of too high power of the capacitor-based compensating devices (sometimes exceeding the power of the supply transformer). In addition, it is unacceptable for the power supply system due to the overcompensation and the appearance of voltage avalanche.

Thus, the direct CB application to compensate the reactive power in networks with valve converters is challenging. In each case, it requires to calculate the current overload of the capacitor banks for the resonant harmonics group. Sometimes, these calculations should be performed for sufficiently high order harmonics ($n > 71$), especially at low power (capacity) of capacitor banks.

Protection of capacitor banks from the higher harmonics. In networks feeding the nonlinear load, the connection of capacitors without protecting them from the higher harmonics is not valid because of the resonance (the current resonance) at high frequency. For normal operation, the capacitor banks intended to compensate the reactive power is necessary to protect with reactors installed in-series with the capacitor bank (Figure 3.17). The value of reactor inductive reactance must be designed in so manner that in the circuit the voltage resonance is created at a frequency less than the lower harmonics, which arises when using the non-linear load. The following condition should be met:

$$n_p \omega L = \frac{1}{n_p \omega C}; \qquad n_p < n_{min}, \tag{3.56}$$

where n_p - harmonic, on which you want to configure an in-series *LC-circuit*; n_{min} – the minimal harmonic arising at the work of the non-linear load.

In the case of improper capacitor protection, the resonance phenomena may appear due to the fact that the circuit consisting of the in-series connected reactor and capacitor reduces the harmonics with order higher than the resonance one (inductive character of the circuit) and increases the harmonics with order lower than the resonance one (capacitive character of the circuit). To properly protect the capacitor bank, it is necessary that this circuit would have an inductive character for all harmonics.

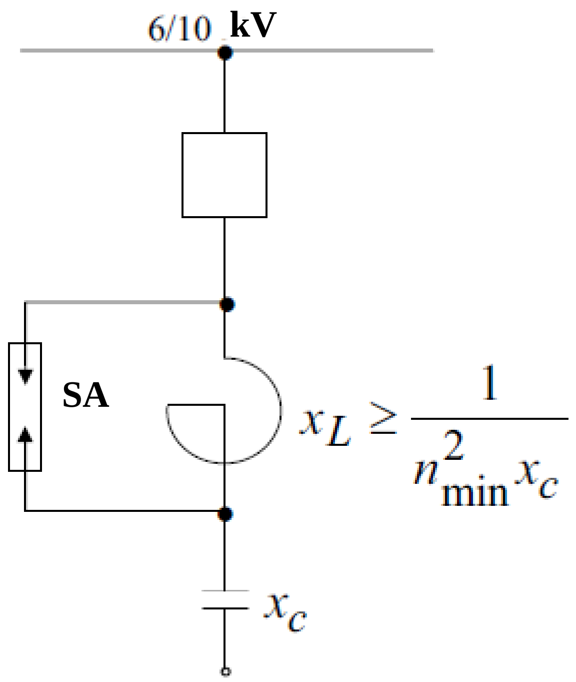


Fig.3.17. *Single-line diagram of the capacitor bank protection from the higher harmonics*

In practice, the capacitor protection from the higher harmonics is challenging due to the technical difficulties, for example, the low inductive resistance of existing concrete reactors. Therefore, to protect the high-voltage capacitors it is important to use low-voltage reactors that have a large inductive reactance.

The possibility of using low-voltage reactors can be explained by the fact that in normal operation mode, the fundamental frequency voltage is applied to the reactor:

$$U_{L_1} = \frac{1}{n_p^2 - 1} U_1, \tag{3.57}$$

where U_1 – voltage at the fundamental frequency applied to the *LC-circuit*; n_p – harmonic number to which the network is tuned.

The total voltage applied to the reactor can be calculated by the formula:

$$U_L = \sqrt{U_{L_1}^2 + \sum_{n_{min}}^{n=k} U_{L_n}^2}, \qquad (3.58)$$

where $U_{L_n} = I_n \frac{nX_n n\omega L}{nX_n + n\omega L - 1/n\omega C}$; I_n - the total current of *n-th* harmonic in the supply network with disconnected capacitor bank; x_n – the supply network inductive reactance; ωL - inductive reactance of the reactor at the fundamental frequency; ωC - capacitive reactance of the capacitor bank at the fundamental frequency.

To protect the low-voltage reactor from the voltage overloads at the connection time, or at the moment of capacitor breakdown, the reusable surge arrester is installed in parallel with the reactor (Figure 3.17). It is also important to note that the sequential connection of the reactor and capacitor bank leads to the increase in the capacitor bank voltage, including due to higher harmonics. Therefore, for reliable operation of the device for the reactive power compensation it is necessary to choose capacitors for increased voltage that, in turn, can be problematic because of limited opportunities.

3.6. Reduction of harmonic levels

3.6.1. Methods for reducing the levels of harmonics

Improving the curve shape of the network current. A promising way to reduce the non-sinusoidality in electric networks is to improve the curve shape of the current in the network with the valve converters. This can be achieved by compensating the higher harmonics, the superposition of the currents of 3rd, 9th, 15th, and higher-order harmonics with the currents in the transformer windings or by providing the special laws of converters control.

In the first case, in the third winding of the converter transformer (T), a magnetomotive force (MMF) of the higher harmonics is created (Fig. 3.18). The magnetic flux due to this MMF has a direction opposite to the main flow in the transformer. Such superposition of fluxes results in the compensation of higher harmonics. The filter F is a band-stop for the first harmonic. The amplifier has designed to enhance higher harmonics of the current.

The implementation of this scheme allows suppressing the canonical and the abnormal harmonics of the flow and the network currents of the converter. This scheme may in some cases (for example, for power transmission lines) to be less costly than in the case of resonant filters and converters.

The disadvantages of this scheme is its complexity, the need for a three-winding transformers, the low operation speed. The scheme may be appropriate for high-power converters operating in the "quiescent" mode.

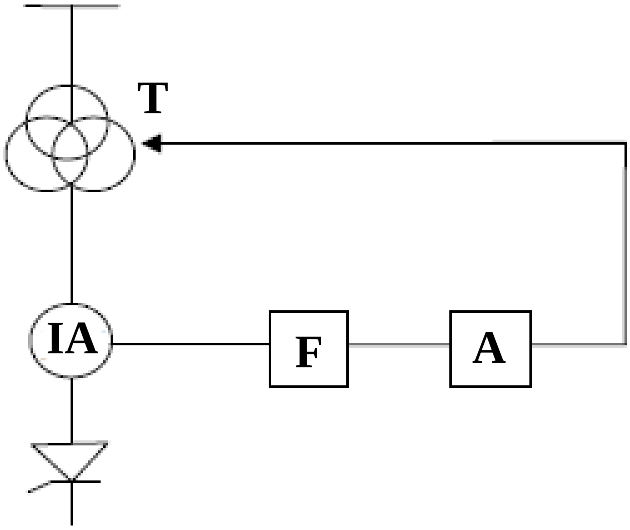


Fig.3.18. *Compensation circuit for higher harmonics of the magnetic flux of a rectifier transformer*

The positive effect of improving the harmonic content of the network current can be achieved by controlling the converter valves with special laws [13]. Such control systems should measure the higher harmonics of current and provide the improved coefficient of non-sinusoidality by influencing the magnitude of the thyristors switching angles or suppressing the individual harmonics. Nowadays, the implementation of such control laws, as a rule, is based on microprocessor technologies.

The increase in the number of converter phases. Among the methods aimed to reducing the levels of the higher harmonics generated by valve converters, the most common one is to increase the number of phases.

The most widespread method is to improve the network current harmonic content of valve converter by using the complex multi-bridge schemes, which provide 12, 18, 24, and more phase rectification. For example, a 12-phase rectifier circuit can compensate the 5, 7, 17, 19 and other higher harmonics. It is necessary to take into account that the effect of the reduction of the higher harmonic levels in poly-phase circuits can be seen, when converters have the same loads and when the phase control systems for valves are symmetric.

The reduction of harmonic levels by means of the supply network. This is generally achieved by the rational construction of the power supply system, at which the allowed level of voltage harmonics is implemented at the consumer buses.

The most common features are the use of high voltage converter transformers; the power supply of nonlinear loads from individual transformers or connecting them to the individual windings of the three-winding transformers; the connection of synchronous and asynchronous motors in parallel with non-linear loads.

3.6.2. Power resonant filters for energy purposes

Reducing the higher harmonic levels in electrical networks is the part of the overall task for ensuring the electromagnetic compatibility of power consumers, ie, the reduction of the nonlinear loads impact on the supply networks and the power quality improvement in enterprise networks.

The integrated solution for this problem, which is based on the use of multifunction devices, is economically more feasible than, for example, the use of measures to improve the network current form of the converter. An example of such multifunctional devices is the power resonant filters of higher harmonics, otherwise known as filter compensating devices (FCD) which generate the reactive power besides with a decrease in levels of higher harmonics.

Under certain conditions, such filters can also be used for balancing the system of linear voltages. Filters can be set for the separation of linear and nonlinear loads (barrier filters) or for shunting (absorption) higher harmonic currents.

The basis of the energy filter of higher voltage harmonics is the in-series connected inductive-capacitive circuits tuned to the appropriate number of harmonics (Fig. 3.19). The distortions of the network voltage from the non-linear power consumers are due to the voltage drop on the internal resistances of the network supplying these current-consuming devices.

The valve load in the electric system is usually considered as a generator of harmonic currents. In this case, it can be represented as a source of different harmonic currents I_n with the internal resistance r_{in} as shown in Fig. 3.20. According to the equivalent circuit, the current of *n-th* harmonic in the supply network can be defined as:

$$I_{sn} = I_n \frac{r_{in}}{r_{in} + r_c + jnX_C}. \tag{3.59}$$

The voltage for the network resistance from each *n-th* harmonic is equal to:

$$U_{sn} = I_n \frac{r_{in}(r_c + jnX_c)}{r_{in} + r_c + jnX_c} \tag{3.60}$$

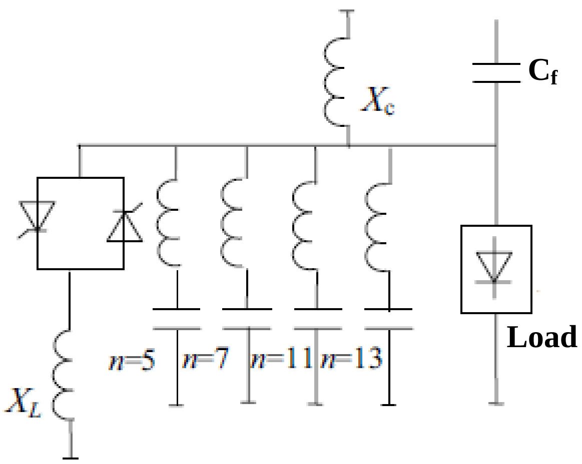


Fig 3.19 *The resonant filter scheme*

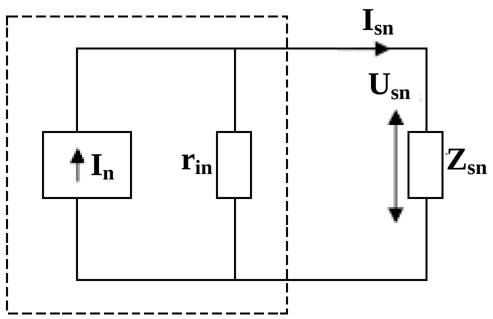


Fig. 3.20 *The valve load equivalent scheme*

The resonant *L-C* filters, tuned to the corresponding higher harmonics, usually n = 5, 7, 11, 13, can significantly reduce the distortion of the voltage waveform. The parameters of each branch of the resonant filter are determined from the condition:

$$n\omega L_f = \frac{1}{n\omega C_f}, \tag{3.61}$$

where n – the number of harmonic, which this resonance branch is tuned to.

Fig. 3.19 shows a scheme of the filter compensating device (FCD), consisting of the resonant filters and reactor X_L with controlled thyristors. In accordance with this scheme, a series of complete power resonant filters of 5, 7, 11, 13 harmonics for networks 6-10 kV, filters with a power of 1200 kVAr for 5 and 7 harmonics and filters with a power of 800 kVAr for 11 and 13 harmonics was developed and produced. The application of filters is useful, when you want not only to improve the harmonic voltage in the network, but also to compensate the reactive power in the considered point of the power supply system. When the reactor valves are fully open, the total reactive power of the installation is defined by the difference between the power generated by the filter Q_{fn} and the power consumed by the reactor Q_r. When closing the valves of the bipolar thyristor cell, the power consumed by the reactor decreases, and after valves being fully closed the power generated by the FCD becomes equal to the power of filters. Consequently, the total FCD reactive power at the fundamental frequency is defined as:

$$Q_{FCD} = Q_r - \sum_n Q_{fn} \tag{3.62}$$

The reactive power generated by the filter of *n-th* harmonic at the fundamental frequency is equal to

$$Q_{fn} = \left(U_1 \frac{n^2}{n^2 - 1}\right)^2 \omega Cn, \tag{3.63}$$

where $U_1 \approx 0.95U_{l.nom}$ – the main harmonic voltage of the phase-to-phase voltage in the network.

The dependence of the reactive power consumed by the reactor as a function of the valve control angle is defined as:

$$Q_r = \frac{U_l^2}{X_L}\left(1 - \frac{2\alpha}{\pi} - sin\frac{2\alpha}{\pi}\right), \tag{3.64}$$

where X_L – inductive reactance of reactors per phase.

In addition to the resonant *L-C* circuits tuned to the corresponding harmonics, the filter can contain the capacitor bank C_f, designed for suppressing the harmonics, whose numbers are greater than those that are suppressed by the resonant filters (Figure 3.19).

The most common scheme of FCD is shown in Fig. 3.21.

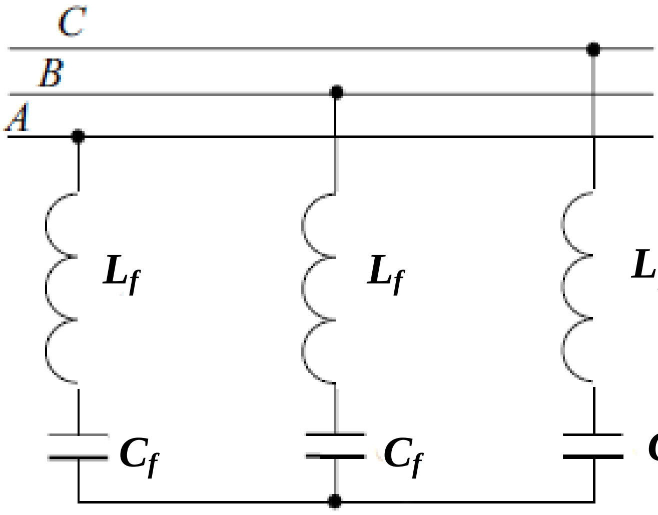


Fig.3.21. *Scheme of filter compensating device (FCD)*

The expression for determining the capacitor bank for the *n-th* harmonic of the current:

$$Q_f \geq 1.2 K_c U_{nom.f} I_{nf} \tag{3.65}$$

where $K_c = \sqrt{3}$ – for capacitor bank connected in star and $K_c = 3$ – for capacitor bank connected in triangle; I_{nf} – the phase-to-phase current of the *n-th* harmonic in the FCD circuit; $U_{nom.f}$ – nominal voltage of the FCD capacitor bank.

To account for the limitations of the capacitor bank power it is necessary to comply with the condition:

$$Q_f \geq Q_{1f} + Q_{nf} \tag{3.66}$$

where Q_{1f} and Q_{nf} - the reactive power at frequencies of 1^{st} and *n-th* harmonics.

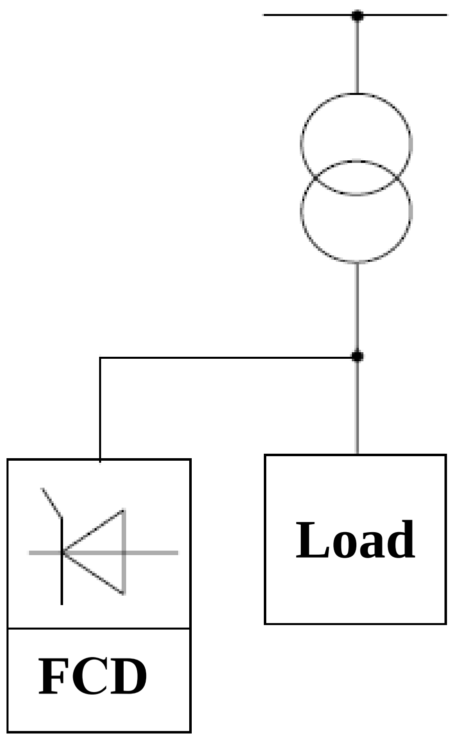
The single-line diagram of the filter connection is shown in the figure 3.22. The filter is connected in parallel with the load and causes a redistribution of the currents.

The current distribution coefficient between the filter and the network:

$$K_{dist} = \sqrt{\frac{1 + n_p tg^2 \varphi_{eq}}{\left(1 + \frac{R_f}{R_{eq}}\right) + n_p tg^2 \varphi_{eq}}}, \tag{3.67}$$

where R_f – the filter circuit active resistance; n_p – harmonic, at which the current distribution is assessed; $tg\varphi_{eq} = \frac{X_{eq}}{R_{eq}}$; X_{eq}, R_{eq} - equivalent resistances of the supply network and the load at the fundamental frequency without the capacitor bank:

$$Z_{eq} = \frac{(R_s + jX_s)(R_L + jX_L)}{(R_s + R_L) + j(X_S + X_L)}, \quad (3.68)$$



Fug. 3.22 *Single-line diagram of the filter connection*

The filters are completed from the commercially available equipment. Table 3.7 shows an example of FCD for 3, 5 and 7 harmonics.

The multiplicity factor of reducing the voltage of *n-th* harmonic after the filter connection:

$$K_{un}^{(p)} = \frac{R_f}{R_{eq}} \frac{K_{dist}}{\left(1 + n_p tg^2\varphi_{eq}\right)} \quad (3.69)$$

In practice, K_{un} is chosen from the structure of the voltage amplitude spectrum and the values of the individual components. Originally it is recommended to take $K_{un}^{(p)} < 0.2 - 0.25$.

To decrease the active resistance of the filters circuit, it is to apply the low resistance reactors, to use the circuit breakers instead of fuses and cut-off switches, to place filters in the immediate vicinity of the packaged transformer substations, to reduce the number of connections.

Table 3.7. *Typical FCD for 0.4 kV networks*

Rated power of CB, kVAr	Capacitor Type	Reactor type	Active resistance of filter, mΩ
3^{rd} harmonic filter			
84	КС1-0.38-14-371	2хФРОС-250-0.5	8…10
144	КС2-0.38-36-373	ФРОС-250-0.5	8…9
500	КС2-0.38-50-373	РСТС-410-0.101	7…8
5^{th} harmonic filter			
240	КС2-0.38-40-371	РТСТ-410-0.076	8…9
360	КС2-0.38-40-373	РТСТ-820-0.0505	6…7
678	КС2-0.38-4043	РТСТ-820-0.027	4…6
	КМ1-0.38-1343		
7^{th} harmonic filter			
145.5	КС1-0.38-18-343	РТСТ-660-0.064	7…8
276	КС1-0.38-12.5-341		
342	КМ1-0.38-13-343	РТСТ-660-0.034	6…7
	КМ1-0.38-13-343	РТСТ-660-0.027	4.7…6

3.7. Parallel operation of power harmonic filters in power supply systems

At the stage of power supply system design, the necessity is arisen to install several single harmonic filters connected in parallel, when:

- the rated current of the harmonic in the network is much higher than the highest filter rated current;

- there is a necessity to install filters in parallel due to the increase in the total power of compensating devices, in the case when there is a small value of the current of the filtered harmonic.

The parallel operation of the higher harmonic filters has its own characteristics. If the filter parameters have some deviations from the resonant configuration, the current distribution of the filtered harmonic in them is violated that may even lead to emergency situations.

The studies data for the scheme of enterprise power supply with two parallel filters of the same power ($Q_{f.nom}$ = 1200 kVAr, U_{nom} = 10 kV) for the fifth harmonic in the regimes with ten different combinations of parameters deviations from the resonant configuration filter elements are shown in Table 3.8. The equivalent diagram is shown in Fig. 3.23.

The designations in the equivalent diagram (Fig. 3.23) are as follows: R_1, R_2 - active resistances of the filter circuits; x_{sn}, I_{sn} - inductance and current of *n-th* harmonic of the supply system; I_n - the total current of *n-th* harmonic generated by all valve converters to the supply network, x_{L1}, x_{L2}, x_{c1}, x_{c2} - inductive and capacitive reactance of the first and second filters; I_{f1}, I_{f2} - currents of the first and second filters.

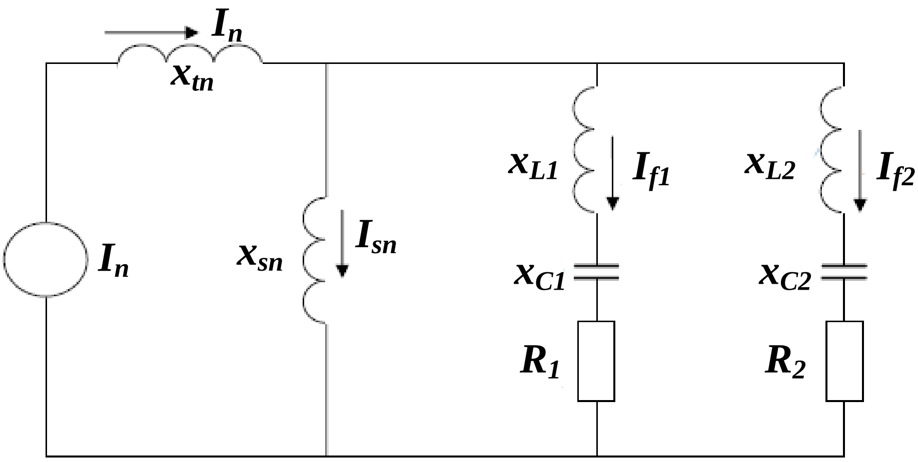


Fig.3.23. *The equivalent circuit diagram with parallel filters of higher harmonics*

Table 3.8. *Current distribution of filtered harmonics in parallel filters*

The considered mode	Deviation of the filter parameters in the parts I_n					
	1st filter		2nd filter	I_{f1*}	I_{f2*}	I_{sn*}
	α_1	β_1	β_2			
1	1	1	1	0.496	0.496	0.125
2	1.15	1	1	0.155	0.899	0.227
3	1	0.95	1	0.355	0.772	0.182
4	1	1.05	1	0.379	0.816	0.206
5	1	1.1	1.1	0.939	0.939	0.936
6	1	0.95	1.03	0.693	0.983	0.378
7	1.02	0.95	1.02	0.461	1.05	0.332
8	1.08	1.06	1.05	0.877	0.512	0.279
9	1.15	1	1.1	0.854	1.26	1.26
10	1.15	0.95	1.1	0.819	1.60	1.59
Note. The coefficient $\alpha_2 = 1$.						

From the analysis of the data in Table. 3.8, where α_1, α_2, β_1, β_2 - parameters characterizing the quantitative deviation of inductive and capacitive reactance of the parallel filters from the nominal values at the resonant configuration, it is possible to make some conclusions.

1. If there is a deviation of even a single filter parameter (inductance or capacitance), the current distribution in the filters is violated (modes 2, 3, 4). For example, in Mode 2 with a deviation of the first filter inductance by 15% in the upward side, the current of filtered harmonic in it is reduced by about a factor of 3 compared to the normal mode of filter resonant configuration (mode 1), and the current in the second filter is increased by 2 times. The second filter is overloaded with the harmonic current, while the first one is underloaded. In the network, the current $0{,}227I_n$ flows, which is 1.8 times greater than in the normal mode of resonance configuration, i.e. the filtration is much worse.

2. At the filters parameters deviation in the same side from the resonance configuration, there is a significant overload of both filters with harmonic currents and a significant deterioration in filtration. For example, in mode 5 with an increase in capacitance of each filter at 10%, both filters are overloaded with the filtered

harmonic current of 1.9 times compared to the normal mode. At the same time, the current of almost an entire harmonic (0,936 I_n) is flowing in the network. In this mode, the use of filters loses all meaning, since both filters are overloaded with the filtered harmonic current and there is almost no filtration.

3. More severe operating conditions occur when the filter parameters are deviated in different directions from the resonant configuration. So, in one experiment in the first filter there was a deviation from in an inductive reactance by 20% from the characteristic impedance (the resistance of an ideal filter), while in the second filter, there was a deviation in the capacitive reactance by 10%. In this case, the harmonic current in the first filter increased more than 1.6 times, in the second filter, the current increased 3.2 times. In the network, there was the passed current of 1,59I_n, i.e., the higher harmonic current than flowing in the network in the absence of filters.

This increase in the current of the filtered harmonic at the parallel connection of the mismatched filters to the substation buses is called ***antifiltration.*** This name fully reflects the physical essence of the phenomenon.

Thus, the parallel operation of filters with real deviations of their parameters from the resonant configuration is accompanied by the abnormal condition of the current distribution of filtered harmonics, and a significant deterioration in the filtration quality.

The radical means, preventing the occurrence of such regimes, is the method that can provide the normal current distribution, uniform loading of the filter elements with the harmonic currents and significantly improves the filtration ability of the parallel filters. The method is extremely simple and consists in connecting the mid-points of filters with a jumper, which has a small, equal to zero, resistance [9]. The resulting equivalent circuit is shown in Fig. 3.24.

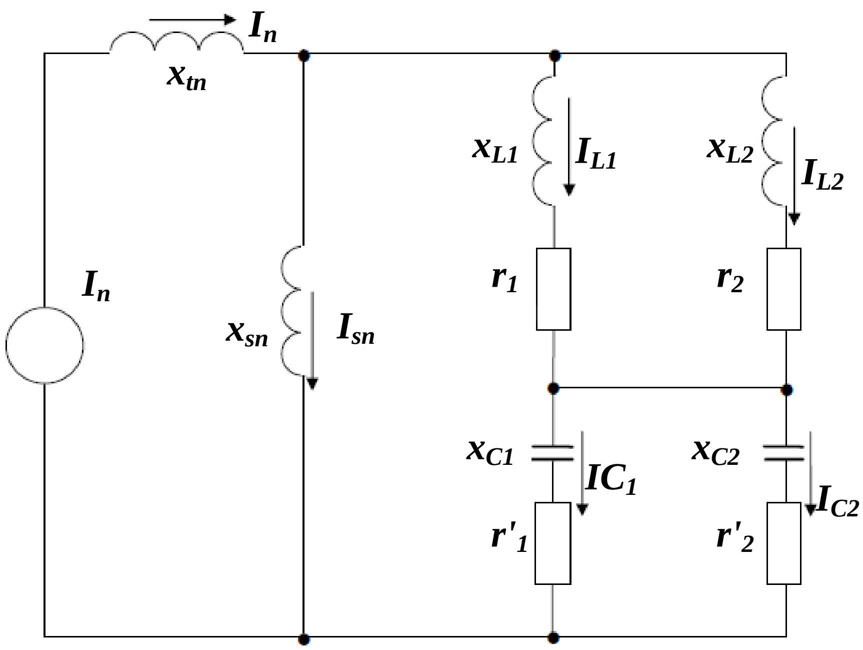


Fig.3.24. *The substation equivalent circuit in the presence of parallel-installed power filters of higher harmonics with connected mid-points (circuit with a jumper)*

The equivalent scheme contains the following designations: r_1 and r_2 - active resistance of reactor filters; $r_1^{`}$ and $r_2^{`}$ - active resistance of filter capacitor banks; I_{L1}, I_{c1} - currents of *n-th* harmonic in the reactor and the battery of the first filter; I_{L2}, I_{c2} - currents of *n-th* harmonic in the reactor and the battery of the second filter.

The results of the study [9] for such a scheme are presented in Table. 3.9. Comparing them with the calculation results for the current distribution in parallel filters mentioned in Table. 3.8, we can note the following.

Table 3.9. *Current distribution of filtered harmonics in parallel filters with a jumper*

Mode	Currents in parts of the I_n				
	I_{L1*}	I_{L2*}	I_{c1*}	I_{c2*}	I_{sn*}
1	0.496	0.496	0.496	0.496	0.125
2	0.346	0.398	0.372	0.372	0.268
3	0.442	0.442	0.453	0.430	0.156
4	0.561	0.561	0.547	0.575	0.194
5	0.938	0.938	0.938	0.938	0.936
6	0.470	0.470	0.489	0.451	0.130
7	0.437	0.446	0.457	0.426	0.157
8	0.517	0.559	0.536	0.541	0.161
9	0.418	0.480	0.470	0.427	0.149
10	0.372	0.428	0.430	0.371	0.219

1. In regimes characterized by the deviation of the one parallel filters parameter from the nominal value (modes 2, 3, 4) or by the deviation of both parameters from the resonant configuration in the same direction (capacitive or inductive), the scheme with a "jumper" does not improve significantly the filtration quality, but provides an alignment and uniformity of the current upload in the filter elements. Thus, in the mode 3, the current in the overloaded second filter was reduced from $0{,}722I_n$ in the original scheme to $I_{L2} = 0{,}442I_n$ and $I_{c2} = 0{,}43I_n$ in the circuit with a jumper. The filtration quality was also improved: the current flowing in the network is equal $0{,}156I_n$ vs. $0{,}182I_n$ in the original scheme.

2. In different direction unbalance modes from the filter resonance configuration (modes 6, 7, 8, 9, 10), the advantages of the scheme with a "jumper" are clearly seen. Besides the alignment of the current distribution in the filters, there is a significant reduction in filter loads with the harmonic current and the filtration quality improvement. It is especially seen in the mode 10 (see conclusion 3 of the previous studies). In the original scheme in this mode, the 1st filter was overloaded by 1.6 times, 2nd – by 3.2 times, the harmonic current flowing in the network was a larger than the total current generated by all sources, i.e., when there was an “antifiltration” mode.

Thus, the short-circuit connection of the mid-points of parallel filters working for one harmonic is a simple and inexpensive means of equalizing the harmonic currents, when the parameters deviate from the resonant frequency of harmonic, and allows protecting the parallel filters elements from the overload with the harmonic current. In addition, the scheme with a "jumper" allows you to maintain a high enough filtration quality of the current harmonics in the network.

Self-test questions

1. What are the main indices of voltage non-sinusoidality in power supply systems?
2. Describe the effect of higher harmonics on the basic elements of power supply system and electrical energy accounting.
3. Tell about the valve converters as sources of harmonics. What parameters is the current and voltage harmonic composition determined with?
4. What are the advantages of asymmetric controlled bridge converters over fully controlled converters, and why it is so?
5. Describe the thyristor power regulators, contact welding and arc welding installations as a source of higher harmonics.
6. What is the role of electric arc furnaces and gas discharge lamps in a distortion of the voltage waveform sinusoidality? How do they influence?
7. Tell about the method of calculating the voltage non-sinusoidality using the commutation distortions at the work of the valve converters.
8. What is the essence of engineering (simplified) method for calculating the components of the voltage harmonic composition of valve converters?
9. How to find the coefficient of non-sinusoidality for the group of converters?
10. How to calculate the currents of harmonics and the coefficient of non-sinusoidality at the work of EAF?
11. On what parameters and how do the harmonic currents and their voltage depend during the operation of the thyristor-reactor group?
12. What is happening in the supply network with non-linear load, when you connect a capacitor bank?
13. Why are the capacitor banks overloaded with the higher harmonics of current, when they are connected to the network with a nonlinear load?
14. How to protect the capacitor bank from the higher harmonics of current?
15. Name and describe the methods for reducing the harmonics in power networks.
16. Explain the structure, connection, purpose and principle of operation of the power resonant filters.
17. How is the power selection of the FCD carried out taking into account the indirect compensation of the reactive power consumption using a controlled reactor?
18. What are the features of the parallel operation of the higher harmonics filters?
19. By what method and how is the uniform loading of the filter elements and the improvement of the filtration ability of parallel filters achieved?

4. VOLTAGE UNBALANCE IN THE POWER SUPPLY SYSTEM

The voltage and current unbalance in the three-phase system is one of the most important indicators of the power quality. The reason for the appearance of voltage and current unbalance is the asymmetrical operation modes of the power supply system. The widespread use of various single-phase electrothermal installations having a significant power (up to 10,000 kW) and three-phase electric arc furnaces led to a significant increase in the proportion of asymmetric loads in power supply systems.

Voltage unbalance is characterized by the following indices:

- Negative sequence voltage unbalance factor K_{2u} (%), which is equal to the ratio of the negative sequence voltage at the fundamental frequency (U_2) to the nominal phase-to-phase (linear) voltage $U_{nom.p\text{-}t\text{-}p}$ *(or* $U_{nom.lin.}$*)*;
- Zero sequence voltage unbalance factor K_{0u} (%), which is equal to the ratio of the zero sequence voltage (U_0) to the nominal phase-to-ground (phase) voltage $U_{nom.p\text{-}t\text{-}g}$ *(or* $U_{nom.ph.}$*)*;

The normally allowed and the maximum allowed values of the negative sequence voltage unbalance factors in the common connection points to the electric networks are equal to 2,0 (**for 95**% of the time interval of one week) and 4,0 % (**for 100**% of the time interval of one week), respectively.

The normally allowed and the maximum allowed values of the zero sequence voltage unbalance factors in the common connection points to the 4-wire electric networks with the nominal voltage of 0.38 kV are equal to 2,0 (**for 95**% of the time interval of one week) and 4,0 % (**for 100**% of the time interval of one week), respectively.

4.1 Influence of unbalanced loads on the operation of current-using equipment

The influence of voltage and current unbalance and at the same time the non-sinusoidality of loads is convenient to be considered by the example of the induction motor, which is the most common type of power consumers.

For the analysis and calculation of unbalance (asymmetric) modes in the three-phase circuits, the method of symmetrical components is used. This method consists in the representation of any three-phase unbalanced system as a sum of three symmetrical components: systems of positive, negative and zero sequences.

The symmetrical voltage components of positive U_1, negative U_2 and zero U_0 sequences are determined by the known equations:

$$\begin{gathered}\dot{U}_1 = \frac{1}{3}\left(\dot{U}_A + a \cdot \dot{U}_B + a^2 \cdot \dot{U}_c\right);\\ \dot{U}_2 = \frac{1}{3}\left(\dot{U}_A + a^2 \cdot \dot{U}_B + a \cdot \dot{U}_c\right);\\ \dot{U}_0 = \frac{1}{3}\left(\dot{U}_A + \dot{U}_B + \dot{U}_c\right),\end{gathered} \tag{4.1}$$

where $\dot{U}_A$, $\dot{U}_B$, $\dot{U}_C$ – phase-to-ground voltages in the network; $a = e^{j\frac{2\pi}{3}} = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$ - a complex number called a phase factor; $a^2 = e^{j\frac{2\pi}{3}} e^{j\frac{2\pi}{3}} = -\frac{1}{2} - j\frac{\sqrt{3}}{2}$

Typically, the motor stator winding is supplied using the three-wire scheme. In this case, the system of unbalanced primary voltages - U_A, U_B, U_C can be represented as the sum of positive U_{A1}, U_{B1}, U_{C1}, and the negative U_{A2}, U_{B2}, U_{C2} sequences.

Then, the currents in the motor stator winding can also be represented as the sum of the currents of positive I_{A1}, I_{B1}, I_{C1}, and negative I_{A2}, I_{B2}, I_{C2} sequences, arising from the symmetrical system of positive and negative sequence voltages.

The positive and negative sequence currents can be determined using the equivalent circuit diagrams of the induction motor for positive and negative sequence voltages (Fig. *4.1 a,b)* [6].

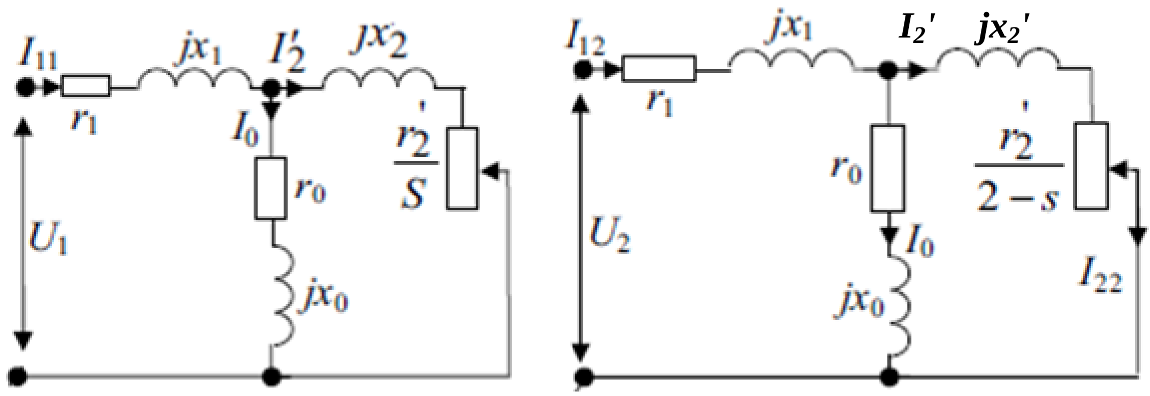


Fig. 4.1. *Equivalent circuit diagrams of an induction motor for voltages of positive (a) and negative (b) sequences*

The rotor slip relative to the positive sequence field:

$$S_1 = \frac{(\Omega_1 - \Omega)}{\Omega_1}, \tag{4.2}$$

where Ω_1 – positive sequence field rotation frequency; Ω – rotor speed.

The positive sequence current value is equal to:

$$\dot{I}_{11} = \frac{\dot{U}_1}{Z_{11}}, \tag{4.3}$$

where $Z_{11} = (r_1 + jx_1) + (z_0^{-1} + z_{21}^{-1})^{-1}$ - the stator winding resistance for positive sequence currents.

To determine the negative sequence current I_{12}, the equivalent circuit shown in in Fig. *4.1b* is used. This circuit differs from the equivalent circuit for the positive sequence current only with that, it has the rotor slip relative to the negative sequence field.

$$S_2 = \frac{(-\Omega_1 - \Omega)}{(-\Omega_1)} = 2 - S, \tag{4.4}$$

where Ω_1 – negative sequence field rotation frequency; $\Omega = \Omega_1 - S$ - rotor speed expressed in terms of slip relative to the positive field.

The negative sequence current is equal to:

$$\dot{I}_{12} = \frac{\dot{U}_2}{Z_{12}}, \tag{4.5}$$

where $Z_{12} = (r_1 + jx_1) + (z_0^{-1} + z_{22}^{-1})^{-1}$ - stator winding phase resistance for negative sequence currents; $Z_{22} = \frac{r_2'}{2-S} + jx_2'$ - equivalent rotor resistance for negative sequence currents.

The calculation of the resistances r_2 and x_2 for negative sequence currents is performed taking into account that the frequency of these currents f_{22} = (2 - $S)/f_1$ is much greater than the frequency of positive sequence currents in the rotor $f_{21} = Sf_1$. Total currents in each stator phase are equal to:

$$I_A = I_{11} + I_{12}; \quad I_B = a^2 \cdot I_{11} + a \cdot I_{12}; \quad I_C = a \cdot I_{11} + a^2 \cdot I_{12}; \tag{4.6}$$

The current unbalance degree is characterized by the ratio I_{12}/I_{11}.

The physical picture of the voltage unbalance and non-sinusoidality effect can be easily shown if, using the superposition method, you imagine the induction motor connected to the network with the voltage unbalance and non-sinusoidality in the form of a number of motors located on the same shaft and generating the equivalent torque [9]. In addition, each motor is switched on the voltage of its own frequency (i.e., the corresponding harmonic), own phase sequence, depending on the symmetric component, which it equates to, and has its own appropriate parameters: voltage, speed, etc.

If the shaft of the total number of motors has a rotational speed n_2 at the synchronous speed n_s, the slip of the motor connected to the positive sequence voltage of the first harmonic will be equal to:

$$S_1 = \frac{n_s - n_2}{n_s}. \tag{4.7}$$

For equivalent motors at higher frequencies of higher harmonics, the synchronous rotational speed is n times greater and the slip will be equal to:

$$S_n = 1 \pm \frac{1 - S_1}{n}, \tag{4.8}$$

where the “plus” sign corresponds to the symmetrical components creating counter-rotation fields, and a “minus” sign correspond to symmetrical components creating fields directed according to the main rotating magnetic field.

From (4.8), we see that for all harmonics, except of the first, the slip $S \geq 1$, since with an increase in n the second term approaches zero due to the growth of the denominator. This means that all equivalent motors, except of the first one, can be regarded as induction motors in the locked state, i.e., in the short-circuit mode. And only the motor connected to the voltage of the first harmonic has the torque and the losses as a real motor connected to a symmetrical sinusoidal voltage of 50 Hz. All other equivalent motors only cause some additional losses, leading to the rotor and stator overheating.

Thus, at a small unbalance the motor operates in the brake mode in relation to the negative sequence field, which corresponds to the slip $1 < S < 2$. The motor mechanical characteristic will have the form shown in the figure 4.2.

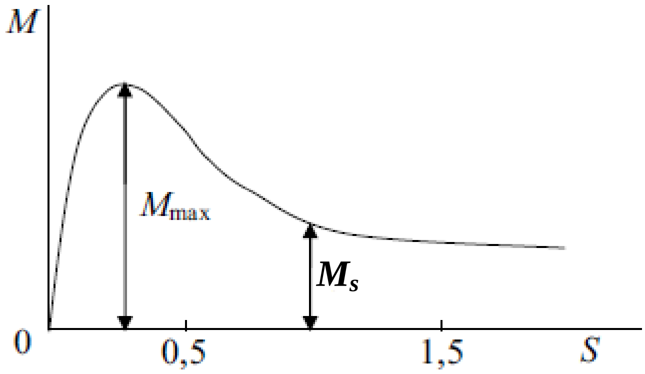


Fig. 4.2. *Mechanical characteristic of an induction motor at the slip 1 < S < 2*

When S = 2, the equivalent circuit for the negative sequence currents can be simplified in the same manner as for the short-circuit mode, when S = 1. Since $\left|\frac{r_2'}{2} + jx_2'\right| \ll |Z_0|$, the impedance components of the circuit for the negative sequence currents are defined as:

$$x_{12} \approx x_1 + x_2' \approx x_{SC};$$
$$r_{12} = r_1 + \frac{r_2'}{S} < r_{SC} \ll x_{12}. \quad (4.9)$$

Consequently, the negative sequence current value at S = 2 is equal to:

$$I_{12} = \frac{U_2}{\sqrt{r_{12}^2 + x_{12}^2}} \approx \frac{U_2}{x_{SC}}. \quad (4.10)$$

Since the motor short-circuit resistance x_{sc} is relatively small, the current I_{12} may reach significant values even at a low unbalance degree, characterized by the negative sequence voltage U_2. The current symmetry distortions, in this case, are much larger, by a factor of $1/x_{sc}$. Typically, x_{sc} = 0.2 p.u., therefore, the current unbalance is up to 5 times more than voltage unbalance. That is why, there are high requirements to voltage unbalance, which must not exceed the range of 4% both for negative and zero sequences.

The negative sequence current causes additional motor heating that reduces its lifetime and the useful capacity. For example, if the voltage unbalance is equal to 4%, the lifetime of the fully loaded motor is reduced by half, while the available motor capacity is reduced by 5 ... 10%, when the unbalance is 5% [8].

The torque M at the supply voltage unbalance is the sum of the positive sequence voltage torque and the torque, determined by the negative sequence voltage:

$$M = M_1 + M_2, \tag{4.11}$$

where

$$M_1 = \frac{mU_{11}^2 r_2'}{S_{\Omega_1}\left[\left(r_1 + \frac{r_2'}{S}\right)^2 + x_{SC}^2\right]},$$

$$M_2 = \frac{mU_{12}^2 r_2'}{(2-S)\cdot\Omega_1\left[\left(r_1 + \frac{r_2'}{2-S}\right)^2 + x_{SC}^2\right]},$$

In motor mode, when $0 < S < 1$, the torque M_2 acts opposite to the torque M_1. To maintain the same resulting torque, when there is a voltage unbalance, it is required to increase the value M_1 by the value M_2 that leads to an increase in the slip S, an additional increase in losses or the reduction in efficiency.

The current and voltage unbalance have the analogous negative effect on the entire supply network. The supply network throughput is reduced, since usually only one phase is loaded to the minimum value. The ripple of the rectified voltage increases due to the voltage inequality in the phases of the converter installations. The electric lighting works in an abnormal mode with different luminous fluxes of lamps connected to different phases. When there is a voltage unbalance, the phases of capacitor banks are unevenly loaded with the reactive power: in the phase with the low voltage the produced reactive power goes down, while in other phases it increases as the square of voltage. This, in turn, leads to the increase in the voltage unbalance.

4.2 Types of unbalanced loads

The electrical networks at the enterprise that distribute the power at voltages below 1 kV, are mainly constructed as three-and four-wire. The operation modes of these networks with unbalanced loads are different, while at the symmetrical mode they are the same.

The schematic diagram of a three-phase four-wire network of 380 V is shown in Fig. 4.3. The load and source (step-down transformer (6...10) / 0,4 kV) at the low voltage side are connected in a star. The linear wires A_a, B_b, C_c connect the terminals of the source and load and transfer the linear currents I_A, I_B and I_C to the consumer. The zero (neutral) wire 00' connects the zero-points (neutrals) of the source and the load. The neutral wire current I_0 for asymmetrical load is not equal to zero.

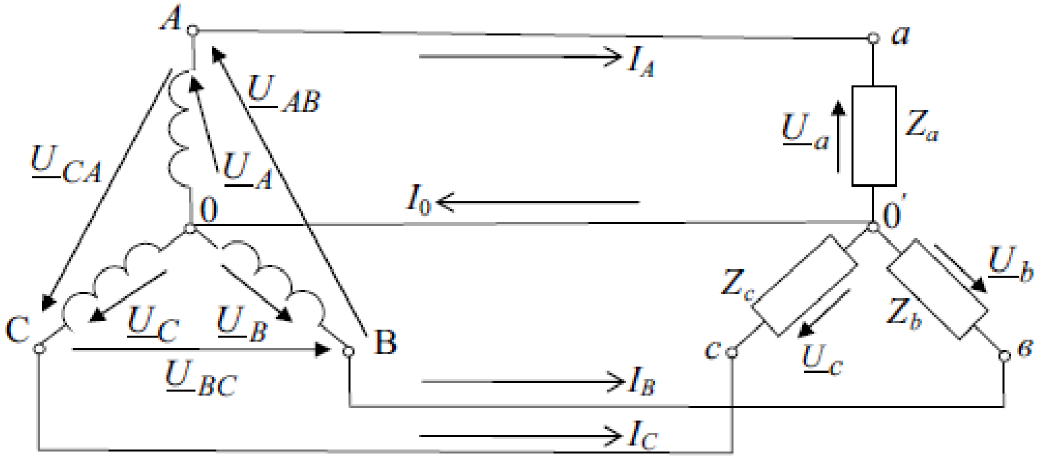


Fig. 4.3 *The schematic diagram of a three-phase four-wire system, when the source and load are connected in a star*

Analyzing the modes of power systems at enterprises under unbalanced loads, we will assume that the voltage transferred from the sources is symmetrical (Fig. 4.4), while the resistance of the linear wires and the neutral wire is equal to zero. With such assumptions, each phase operates independently from others. The currents in the phases will depend only on the load resistances, and their values are generally different.

$$I_A = \frac{U_A}{Z_A}; \quad I_B = \frac{U_B}{Z_B}; \quad I_C = \frac{U_C}{Z_C}. \tag{4.12}$$

The current in the neutral wire is the vector sum of phase currents (Figure 4.5)

$$\underline{I}_0 = \underline{I}_A + \underline{I}_B + \underline{I}_C$$

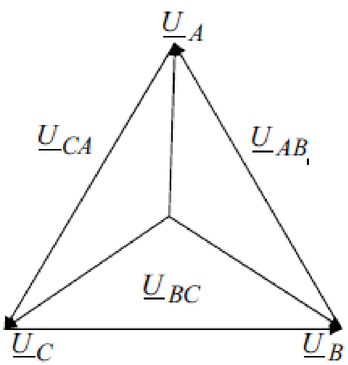


Fig. 4.4. *Vector diagram of voltage source*

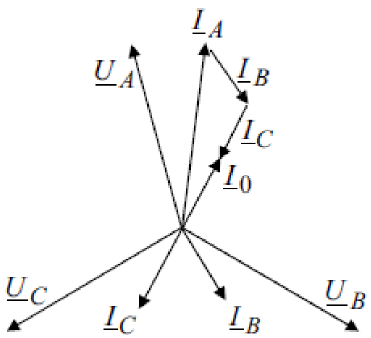


Fig. 4.5 *Vector diagram of currents in phases and neutral wire at unbalanced load*

If to delete the neutral wire in the circuit shown in fig. 4.3, then at the unbalanced loads the current in the neutral wire is interrupted and the potential difference occurs between the points 00', which is called a neutral-point displacement voltage $U_0 \neq 0$. The larger the loads unbalance, the greater the neutral-point displacement voltage U_0. The vector diagram of voltages is distorted. Instead of the diagram shown in Fig. 4.4, there is a diagram with abruptly changed, unbalanced voltages, as it is shown in Fig. 4.6. The neutral current will be equal to I_0=0, and the sum of phase currents $\underline{I}_A + \underline{I}_B + \underline{I}_C = 0$. Consequently, the load unbalance in the scheme of the star will lead to the unbalance of the phase-to-ground voltages in the load. And only for balanced loads, the currents and voltages in all phases of a three-wire systems are identical.

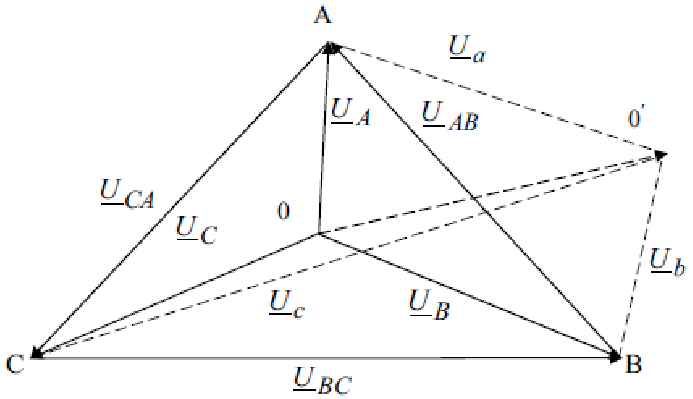


Fig. 4.6. *Vector voltage diagram of source and load in a three-wire circuit with an unbalanced load*

In distribution networks of 6 ... 10 kV at enterprises, the secondary windings of the transformers at the main step-down substations and the primary windings of shop transformers (6 ... 10) / 0.4 kV are connected in the triangle. The three-phase scheme is presented in fig. 4.7. In contrast to the connection scheme in a star, the phase-to-ground voltages in the scheme with triangle connection are equal to phase-to-phase voltages $U_{ph}=U_{lin}$. In three-wire circuits, only when there is a balanced load, the vectors of linear and phase currents form the balanced system.

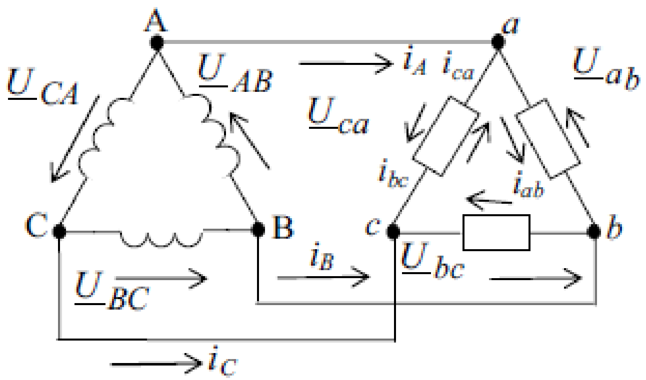


Fig. 4.7. *The diagram of a three-wire three-phase system when connecting a source and load in a triangle*

Under the load unbalance in three-wire circuit connected in star and triangle, the voltage is conveniently calculated by the method of symmetrical components.

For the case of single-phase load (Fig. 4.8 *a)* the symmetric components (Fig. 4.8 *b)* and the vector diagram of currents (Fig. *4.8* c) are built.

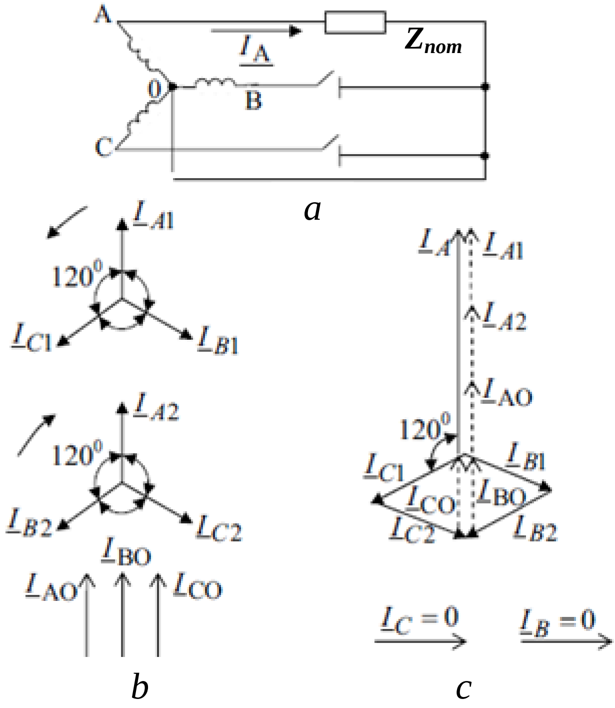


Fig. 4.8. *Scheme (a) and vector diagrams (b, c) of currents in three-phase network at the single-phase load*

Electric arc furnaces can be considered as an example of a strong unbalanced loads. These installations are usually three-phase units of 6...10 kV and 35 kV and work with the insulated neutral.

When operating the electric arc furnaces in the network, there is the fluctuation of the arc currents in different phases that results in the formation of the unbalanced system by the rms values of currents at any time moment. The current unbalance in phases leads to the voltage asymmetry in the supply and distribution networks. The EAF capacities are large, thus the current and voltage unbalance often exceeds the allowed values especially during the melting process.

Since the primary and secondary circuits of furnaces are three-wire without the neutral wire, the zero-current component is missing. Three-wire system current modules form a triangle. When analyzing the unbalance mode in this case, it is advisable to calculate the unbalance factor using the modules (rms) of phase currents, which can be measured by three pointer indicators.

The greatest value of the unbalance factor occurs at the beginning of melting. The experience shows that if to make the melting process at the negative sequence unbalance factor $K_{2u} \leq 2$ *%*, then the specific power consumption per 1 ton of metal, the melting time and the wear of furnace equipment are reduced.

Moreover, such three-phase loads as electric arc furnace create an unstable, constantly changing unbalance of the phase loads during the working process. Thus, the unbalanced load and the caused voltage and current unbalance can be permanent, transient or intermittent in three-phase network of industrial enterprises.

4.3 Reduction of voltage unbalance

The measures for decreasing the voltage unbalance are mainly reduced to a uniform distribution of single-phase loads in phases in such a manner to prevent the voltage unbalance from exceeding the allowed limits. However, this method does not allow one to achieve the desired results always. In such cases, to reduce the voltage unbalance it is necessary to use the special balancing systems.

Balancing of unbalanced loads with low power factor can be implemented by using an asymmetric capacitor bank (Figure 4.9), where $C_{BC} \neq C_{AB} \neq C_{AC}$. As a results of such scheme application, it is possible to compensate the unbalance of reactive components of currents. Active components remain unchanged.

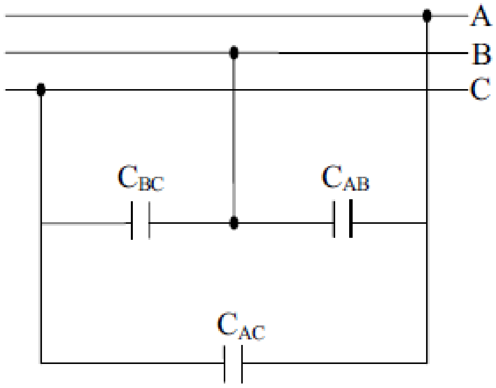


Fig. 4.9. *The diagram of voltage balancing by using capacitor banks*

Fig. 4.8 shows the circuit scheme and vector diagram of positive, negative and zero sequence currents for all three phases in the presence of loads only in one phase *A*, as well as the resulting vectors and currents. This load mode is created, for example, when connecting a resistance furnace to the 0.4 kV buses of four-wire network without the loads in phases *B* and *C*. As can be seen from Fig. 4.8, the redistribution of loads over the phases cannot be done. In this case, it is necessary to use balancing systems.

Balancing the loads is usually performed by inductance or capacitance, because the use of active resistance for balancing would lead to additional active power consumption.

Fig. 4.10 shows a balancing scheme for a single-phase load (Steinmetz`s scheme). The load Z_{ld} is connected to the voltage U_{BC}, while the balancing capacitance *CB* and inductance *L* are connected to other two phases of triangle. In parallel with the load Z_{ld}, the capacitance *C* is connected, which compensates the load reactive component. This allows considering the load as purely active, at which the greatest effect of balancing is achieved. The required capacity of the capacitor bank and inductance *L* is determined from the condition:

$$Q_C = Q_L = \frac{P}{\sqrt{3}}, \tag{4.13}$$

where *P* – active power of single-phase load.

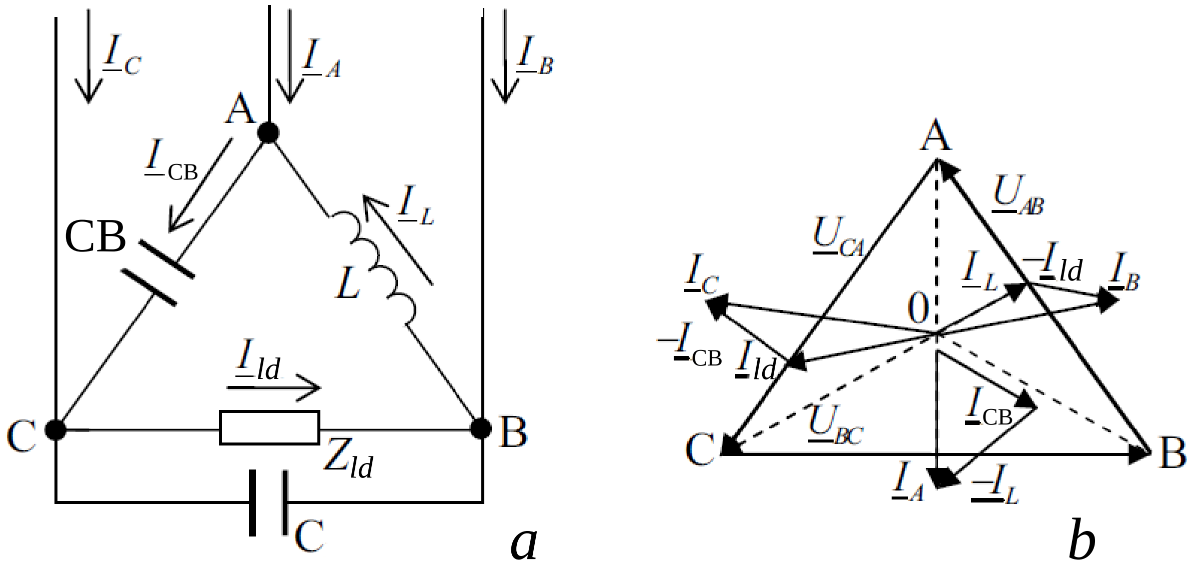


Fig. 4.10. *Balancing a single-phase (two-phase) load: a - Steinmetz's scheme; b - vector diagram*

Fig. 4.10, *b* presents the vector diagram of voltages and currents in the phases of the load and balancing unit, built from the center O. The load current I_{ld} is purely active and have the same direction as the voltage U_{BC}. Current I_L in the phase *AB* is inductive and lags behind the voltage U_{AB} by 90º. The current I_{CB} in phase *CA* is capacitive and leads the voltage U_{AB} by 90º.

By summing the vectors of the triangle phase currents (I_{ld}, I_L, I_{CB}) for the nodes *A, B, C,* we can find the line currents I_A, I_B, I_C, forming a star of currents in the three-phase circuit. An appropriate choice of inductance and capacitance allows one to achieve the balance of linear (phase-to-phase) currents within the regulations.

If the resistive load R_n is changing in the technological process, it is necessary to adjust the parameters of a balancing unit *L, C* in such a manner to avoid the unacceptable unbalance at the partial load. For this purpose, adjustable capacitor banks and reactors with the core magnetization can be used.

The promising options to improve the voltage symmetry of three-phase system are the circuits for conversion the number of phases ensuring the uniform load in the network. The various systems for converting the number of phases are necessary in greater extent for: high voltage transmission lines; rectifiers and inverters; traction load of railways, electrified with alternating current; some types of electrotechnological installations, induction motors and other power-consuming equipment. In principle, the phase number converter can be done with a transformer or with the help of thyristor converters.

An example of the phase converter with using transformers is a scheme of Scott, shown in Fig. 4.11. The circuit consists of two transformers T_1 and T_2, and ensures the formation of two-phase voltage system $U_1 = U_2 = U$ with a symmetrical load of phases in the three-phase supply voltage system at the uniform loading of the secondary circuit phases of a three-phase two-phase transformer.

The phase converter with symmetric loading of the supply system can be made by the rectifier-inverter converter scheme shown in Fig. 4.12. The circuit consists of a rectifier that converts the three-phase network voltage into DC voltage with uniform loading of power supply phases. The rectified voltage with a single-phase autonomous voltage inverter AVI is converted to single-phase alternating current. Backward diodes BD are used to complete the circuit of load reactive current having an inductive character. Thus, the considered thyristor phase converter allows you to make a connection of single-phase load without introducing unbalance in the supply network. The rectifier-inverter converter can perform the inverse transformation of single-phase voltage into three-phase symmetrical one. In this sense, the static converters of power supply parameters can solve the electromagnetic compatibility problem for *n-phase* power consumers with the supply network contain any number of phases.

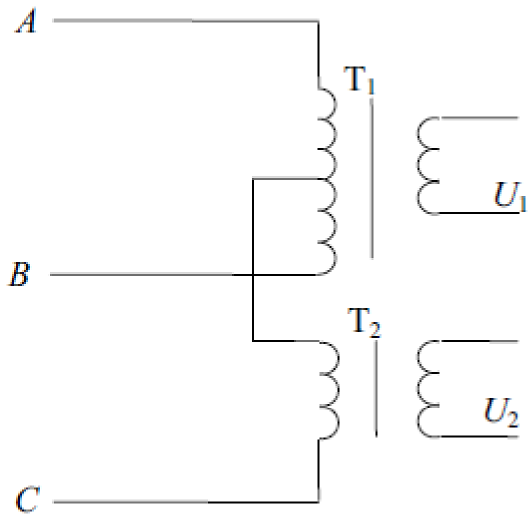


Fig. 4.11. *A scheme of Scott*

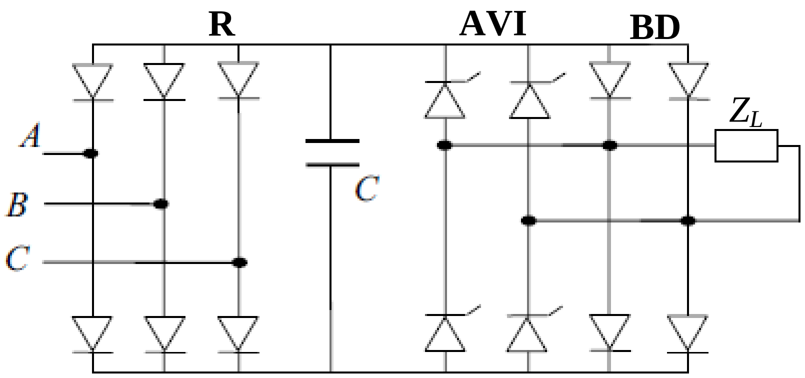


Fig. 4.12. *Three-phase - single-phase valve converter*

It should be noted that in addition to the classical conversion schemes of frequency and the phase numbers for the AC voltage, there are special conversion schemes for changing the number of phases by means of transformer-thyristor devices, whose operation is based on the summation with a particular algorithm of voltage half-waves in the three-phase network. The main advantage of such schemes compared to the thyristor phase converters is less content of higher harmonic components in the curves of the network and load currents.

To make a decision about the choice of a balancing unit, it is firstly necessary to determine the negative sequence voltage. In an extensive enterprise network, this is usually performed by the method of symmetrical components with representing the equations of unbalanced loads in complex form. For practical purposes, you can use a simpler expression for the unbalance factor, %:

$$K_{2U} = \frac{S_{S.Ph.L}}{S_{SC}} \cdot 100, \quad (4.14)$$

where $S_{S.Ph.L}$ – the rated power of the single-phase load; S_{SC} – short-circuit power in the connection point of single-phase load.

If in this load node, there is a source of the higher harmonics, it is necessary to check whether there are the resonances at frequencies of the generated harmonics in the balancing system. If there is an CB overload with currents of higher harmonics due to this reason, it is necessary to provide their protection.

Self-test questions

1. Name the regulatory parameters that characterize the voltage unbalance.
2. How does the voltage unbalance affect the induction motor operation?
3. What is the effect of voltage unbalance in the supply network on various elements of the power supply system?
4. What are the main types and examples of unbalanced loads in industrial power networks?
5. Describe the main ways to reduce the voltage unbalance in the power supply system.
6. Explain with the help of vector diagrams the essence of balancing the single-phase load with the help of the Steinmetz`s scheme.

5. DYNAMIC CHARACTERISTICS OF POWER QUALITY INDICES

The power quality indices discussed earlier characterize the steady state working modes (continuous changes in characteristics) of the current-consuming equipment of the energy supplying organizations and consumers and provides a quantitative assessment to the features of the technological production process, transmission, distribution and consumption of electrical energy.

In this section, under the dynamic characteristics of the power quality indices we will understand the indices, which characterize the short-term interference appearing in an electrical network as a result of the commutation process, thunderstorm atmospheric conditions, the work of protection and automation equipment, and post-accident conditions. For quantitative evaluation of these indices, the amplitude, duration, frequency of their appearance and other characteristics, which are set but not normalized by the standard, should be measured. Statistical processing of this data allows us to calculate the summary indices, characterizing the specific electrical network, in terms of the short-term interference probability.

5.1 Frequency deviations and fluctuations in the supply network

The frequency deviation is understood as the difference between the averaged frequency value $f_{av.}$ and the nominal value of the fundamental frequency f_{nom}

$$\Delta f = f_{av.} - f_{nom} \qquad or \qquad \Delta f = \frac{f_{av.} - f_{nom}}{f_{nom}} \cdot 100, \% \tag{5.1}$$

The averaged frequency value $f_{av.}$ in Hertz is calculated as the result of averaging the *N* observations f_i over a time interval equal to 20 s, according to the formula:

$$f_{av.} = \frac{\sum_{i=1}^{N} f_i}{N}. \tag{5.2}$$

The number of observations *N* must be not less than 15.

The power quality by the frequency deviation is considered to comply with the standard, if all measured within one week values are in the range of frequencies limited by the maximum allowed values ±0.4 Hz and not less than 95% of the measured frequency deviation values are in the range limited by the normally allowed values ±0.2 Hz.

The frequency swing is the difference between the highest f_{max} and lowest f_{min} values of the fundamental frequency over a certain time period

$$\delta f = f_{max} - f_{min} \quad or \quad \delta f = \frac{f_{max} - f_{min}}{f_{nom}} \cdot 100, \%. \tag{5.3}$$

The frequency fluctuations are the frequency changes occurring at a rate of 0.2 Hz per second. The frequency swing should not exceed 0.2 Hz.

The power consumers at enterprise due to their low power compared with a total capacity of all system generators almost cannot have a significant effect on the frequency deviation in the power system. The exception is the powerful current-consuming equipment with abruptly variable load nature in relation to the short-circuit power at the connection point.

The changes in the deviations and the frequency fluctuations range, even within rigidly established limits, affect the operation of current-consuming equipment. Asynchronous and synchronous electric motors with a constant torque on the shaft change their speed ω depending on the network frequency.

The induction motors with a torque, which is velocity-dependent in the second degree, significantly alter their performance at the frequency deviations. There may even the process failures. The characteristics of a number of consumers, such as electric resistance furnaces, arc furnaces, light bulbs do not depend on the frequency changes.

The frequency deviations negatively affect the enterprise networks, in which the power and voltage losses are increased. In case of installing the power reactors with protective filters, the resonance phenomena are possible. For example, at a certain frequency deviation in the circuit "the protective reactor - resonant capacitor bank", there is a voltage resonance at the harmonic frequency *n*. With a further decrease in the frequency, the circuit will have a capacitive nature for all higher harmonics of the source. This may cause capacitor bank overload with currents, and can also lead to a redistribution of the higher harmonics in the network.

5.2 Voltage dip

A voltage dip is understood as a sharp voltage decrease in the network below $0.9U_{nom}$, followed by its restoration to the original or close to it level (Fig.5.1). The voltage dip is characterized by the voltage dip duration Δt_d. The limiting value of Δt_d according to GOST 32144-13 is 60 seconds.

The measurement of the voltage dip duration Δt_d in seconds is performed as follows. It is necessary to fixate the initial time t_{start} of a sharp voltage drop below $0.9U_{nom}$ (with a duration less than 10 ms) of the RMS voltage envelope defined at each half-cycle of the fundamental frequency (Figure 5.1). Then the final time moment t_{finish} is fixated, when the rms voltage value becomes $0.9U_{nom}$. The voltage dip duration Δt_d in seconds is calculated using the formula:

$$\Delta t_d = t_{finish} - t_{start} \tag{5.4}$$

The power quality by the voltage dip duration in the common connection point is considered to comply with the standard, if the greatest from all measured over a long observation period (usually one year) values of the voltage dip duration does not exceed the limit.

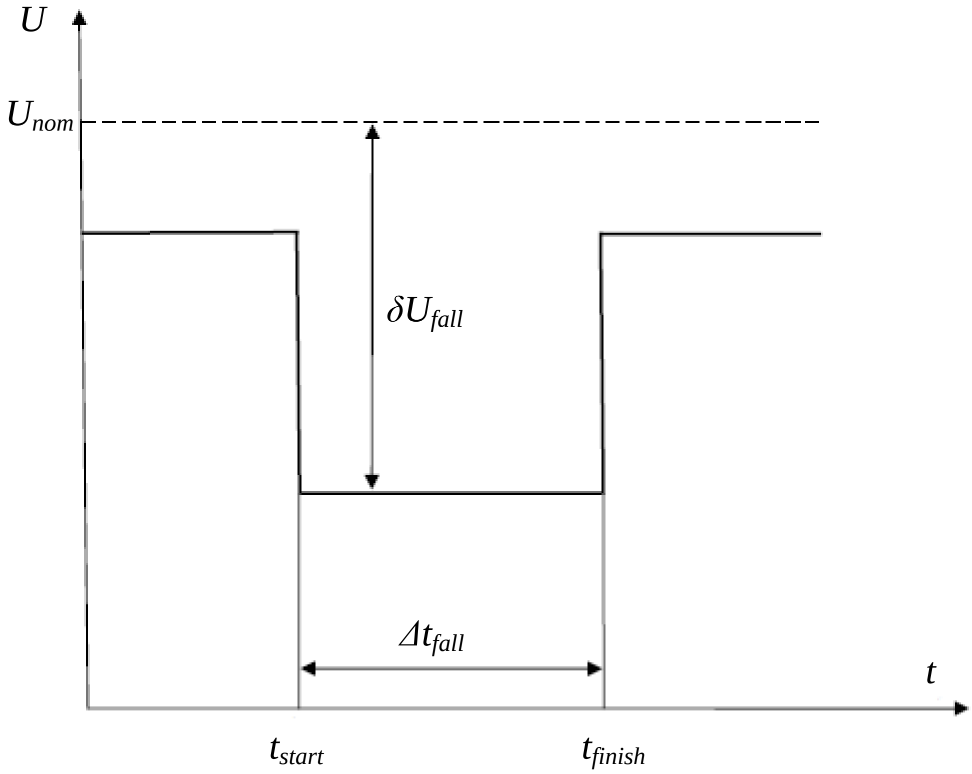


Fig. 5.1. *Voltage dip*

To determine the depth of the voltage dip δU_d, it is necessary to measure the rms voltage U at every half-cycle of the fundamental frequency during the voltage dip. From the obtained data, the minimal rms voltage U_{min} is determined. The voltage dip depth δU_d is defined as:

$$\delta U_d = \frac{U_{nom} - U_{min}}{U_{nom}} 100, \% \tag{5.5}$$

The relative frequency of voltage dip occurrence F_d as a percentage is calculated by the formula

$$F_d = \frac{m(\delta U_d, \Delta t_d)}{M} \cdot 100, \tag{5.6}$$

where $m(\delta U_d, \Delta t_d)$ – the number of voltage dips with the depth δU_d and duration Δt_d over the observation period T; M – the total number of voltage dips during the observation period T.

5.3. Surge voltage

The surge voltage, i.e. the sharp voltage change in the electrical network point, followed by the restoration up to nominal or closed to it voltage, is characterized by the index of surge voltage U_{imp}.

The surge voltage U_{imp} (V, kV) is measured as the maximum voltage value at its sharp change (pulse rise time not more than 5 ms) (fig. 5.2).

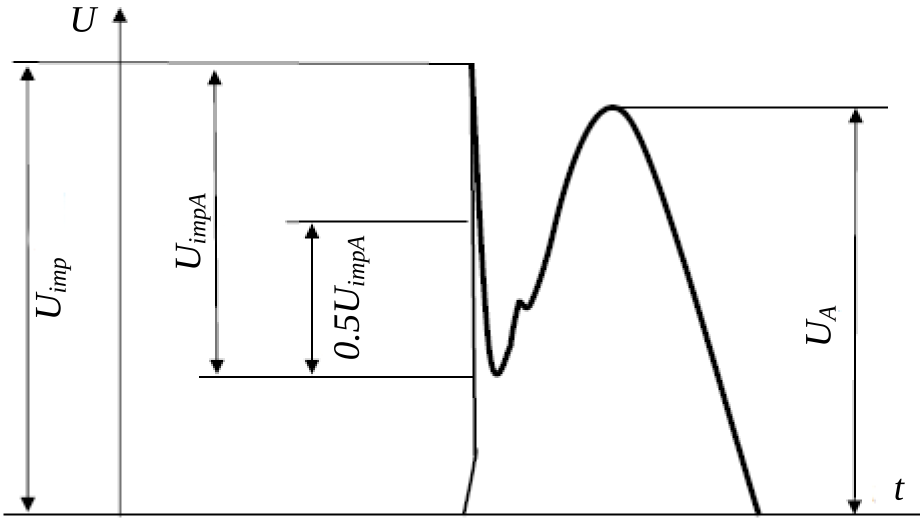


Fig. 5.2. *Parameters of the surge voltage*

To determine the surge voltage duration at the level of 0.5 its amplitude $t_{imp0.5}$ in microseconds, milliseconds, it is necessary to separate the surge voltage from the general curve and define the amplitude of this surge U_{imp} as the its maximum value (V, kV). Then define the time moments $t_{start0.5}$ and $t_{finish0.5}$, corresponding to the intersection of the surge voltage curve by a horizontal line drawn at half of the surge amplitude. The surge voltage duration at the level of 0.5 its amplitude is determined by the formula:

$$\Delta t_{imp0.5} = t_{finish0.5} - t_{start0.5}. \tag{5.7}$$

The surge voltage value is not regulated by the GOST standard, which provides only the reference values of the surge voltage. For example, the values of commutation surge voltages with their duration of 1000 ... 5000 ms at the level of 0.5 its amplitude are shown in Table. 5.1.

Table 5.1. *Commutation surge voltage*

Nominal network voltage, kV	0.38	3	6	10	20	35	110	220
Commutation surge voltage, kV	4.5	15.5	27	43	85.5	148	363	705

5.4. Temporary overvoltage

The temporary overvoltage (or voltage swell) is characterized by the corresponding index $K_{over.U}$ (fig. 5.3).

To determine the temporary overvoltage index, the voltage amplitude values U_A (V, kV) are measured on each half-cycle of the fundamental frequency at the sharp (the front duration not much than 0.5 ms) voltage increase over the level of $1.1\sqrt{2}U_{nom}$. From the measured values, determine the maximum voltage U_{Amax}. In order to eliminate the influence of the commutation surge voltage value on the temporary overvoltage coefficient, the U_{Amax} definition is performed in 0.04 s from the moment the voltage exceeds the level of $1.1\sqrt{2}U_{nom}$.

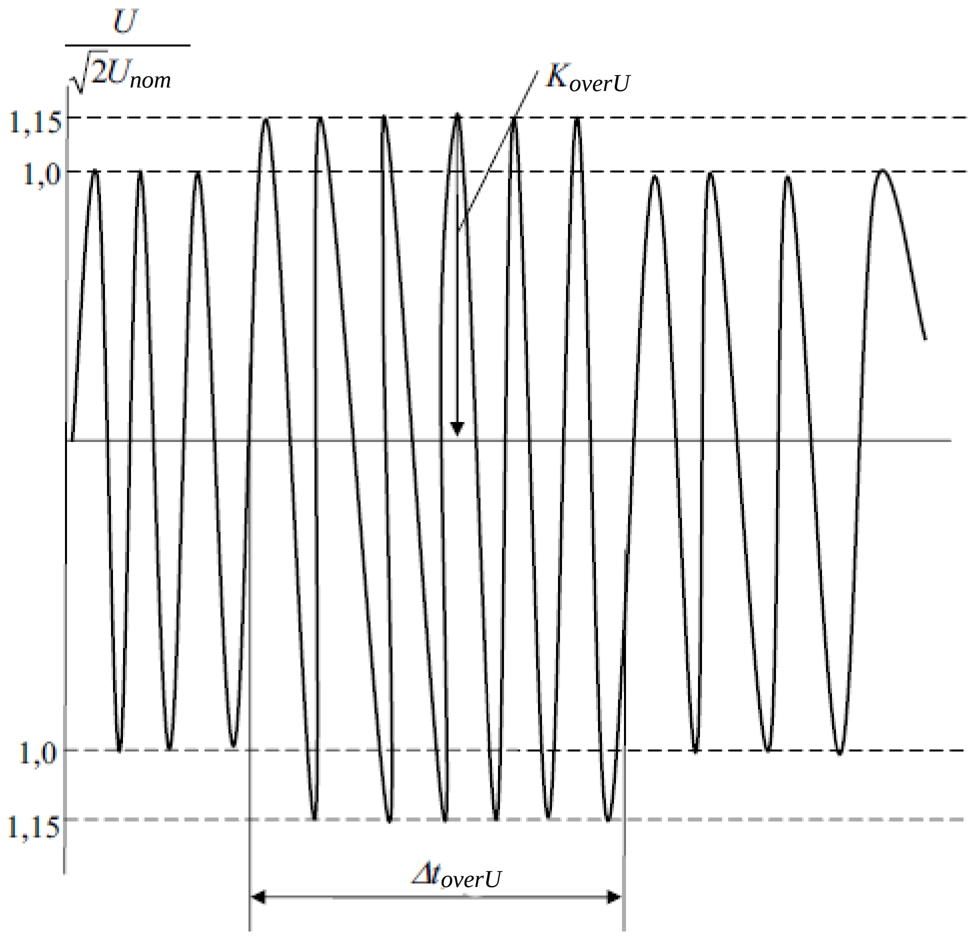


Fig. 5.3. *Temporary overvoltage*

The temporary overvoltage coefficient (p.u.) is calculated by the formula:

$$K_{over.U} = \frac{U_{Amax}}{\sqrt{2}U_{nom}}. \tag{5.8}$$

The temporary overvoltage duration Δt_{overU} is defined as the difference between the time moment $t_{f.overU}$ of voltage decay to the level of $1.1U_{nom}$ and the moment $t_{s.overU}$ the rms voltage exceeds the level of $1.1U_{nom}$.

$$\Delta t_{overU} = t_{f.overU} - t_{s.overU}. \tag{5.9}$$

The temporary overvoltage coefficients in the connection points of general purpose electrical networks in dependence on the temporary overvoltage duration are shown in Table. 5.2. On the average, during the year, up to 30 temporary overvoltages may occur at the connection point.

Table 5.2. *Temporary overvoltage coefficient $K_{over\ U}$.*

Temporary overvoltage duration, s	Up to 1	Up to 20	Up to 60
Temporary overvoltage coefficient	1.47	1.31	1.15

Self-test questions

1. What power quality indices characterize the short-term interferences?
2. How are deviations and fluctuations in the frequency of the supply voltage determined?
3. What is a voltage dip and what parameters is it characterized by?
4. What parameters characterize the surge voltage?
5. What should be considered as a temporary overvoltage in the supply network and what are the characteristics of the temporary overvoltage?

6. VOLTAGE QUALITY AND ELECTROMAGNETIC COMPATIBILITY IN POWER SUPPLY SYSTEMS WITH ABRUPTLY VARIABLE LOADS

6.1. Voltage deviations and fluctuations

During the work of abruptly variable loads, the most noticeable power quality decline is manifested in the form of voltage fluctuations and deviations from its nominal value.

The main issues arising when working in power supply systems with abruptly variable loads are the determination of calculated active and reactive loads, the determination of fluctuations swing for active and reactive power and the associated fluctuations of voltage and frequency, the calculation and choice of devices parameters, which improve the power quality.

The large voltage deviations δU and voltage fluctuations δU_t in the supply network arise when working the powerful (relative to the circuit power) consumers, the load of which has an abruptly variable character. Arc furnaces, welding machines and controlled valve converters can be attributed to these consumers.

The appearance of the voltage deviations and voltage fluctuations will be considered by the example of the load with a powerful valve converter [9]. Its power supply scheme and the equivalent circuit diagram are shown in Fig. 6.1. The equivalent total resistance of the supply network is represented by inductive x_Σ and active r_Σ resistances. The ratio of inductive and active resistances in the enterprise supply industrial networks can be assessed within $x_\Sigma / r_\Sigma = 10 ... 30$.

The voltage vector diagram is presented in fig. 6.2.

The load current of the valve converter I_L is represented by the vector sum of active and reactive current components. At the switched off valve converter, the voltage at the buses is equal to the open-circuit voltage $U_L=U_{oc}$ and, if assuming no other loads, it coincides with the voltage vector of the power supply system. When you switch on the load, the load current flows through the resistance of the power supply system that creates a voltage change at the buses both by the phase and by the amplitude.

The voltage change is represented by the vectors $I_a r_\Sigma$; $I_a x_\Sigma$; $I_r r_\Sigma$; $I_r x_\Sigma$. As can be seen from the vector diagram, the voltage change mainly depends on two vectors such as $I_a r_\Sigma$; $I_r x_\Sigma$ (it is fair taking into account that in practice angle δ does not exceed 10 º). Therefore, with sufficient accuracy for practical calculations, the voltage deviations and voltage fluctuations can be determined by the formula:

$$\delta U = \delta U_t \approx \frac{I_a r_\Sigma + I_r x_\Sigma}{U_{nom}}. \tag{6.1}$$

The difference between the voltage deviations and voltage fluctuations in this case consists only in the voltage change rate. The formula (6.1) can be transformed to the form:

$$\delta U = \delta U_t \approx \frac{P\frac{r_\Sigma}{x_\Sigma} + Q}{S_{SC}}, \tag{6.2}$$

where P and Q - active and reactive power of the converter; S_{sc} - short-circuit power at the supply buses.

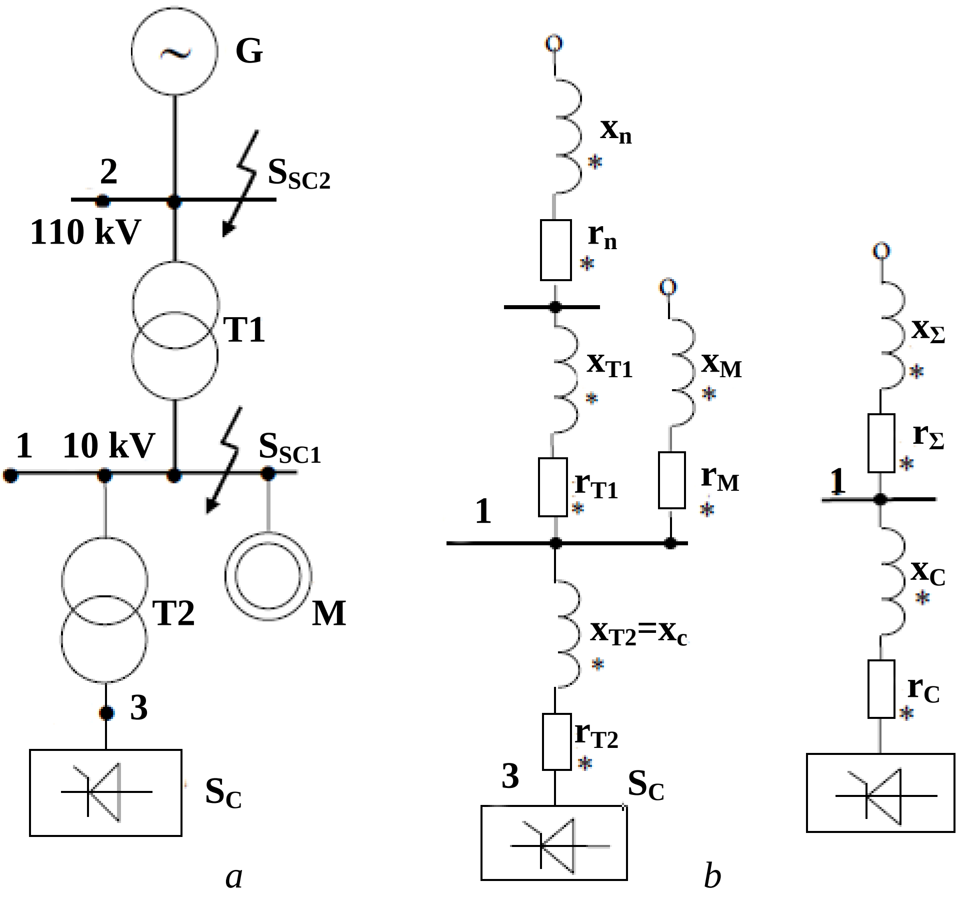


Fig. 6.1. *Power supply scheme of a powerful valve converter (a) and equivalent circuit diagram of the power supply (b)*

Any change in the load also leads to a change in the voltage, thus:

$$\delta U = \delta U_t \approx \frac{\Delta P\frac{r_\Sigma}{x_\Sigma} + \Delta Q}{S_{SC}} = \frac{\Delta P(0.03 - 0.10) + \Delta Q}{S_{SC}}, \tag{6.3}$$

From (6.3), it follows that the voltage deviation is mainly determined by the reactive power change. The active power change in industrial networks has a little effect on the voltage due to the ratio of active and reactive resistances of the power supply system r_Σ / x_Σ. For approximate calculations, it can be taken:

$$\delta U = \delta U_t \approx \frac{\Delta Q}{S_{SC}}, \tag{6.4}$$

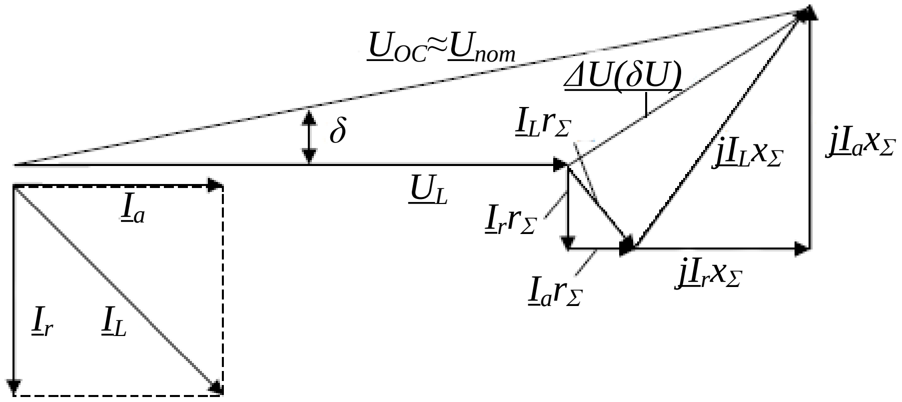


Fig. 6.2. *Vector diagram of voltages*

The main power quality standards by the voltage fluctuations for power consumers are the general rules for lighting sources. The voltage fluctuations cause light bulbs flickering, a malfunction in television, communications and power static converters. The impact of light flicker on the vision depends on the magnitude of voltage fluctuations and their frequency. The study [9] showed that the human eye is most sensitive to the incandescent light flickering with a frequency, which is in the range of 4... 10 Hz. At the same time, the eye begins to feel these flickers from 0.25% of nominal voltage, and the unpleasant feelings occur, when a voltage is equal to 0.4% of the nominal. The fluorescent lights are less sensitive to voltage fluctuations at the above frequencies, but more sensitive at frequencies above 20 Hz. The most detailed information about these effects in power supply systems described in Section 2.

In different countries, there are various ways to determine the allowed values of the voltage fluctuations caused by the current-using equipment work, depending on the influence of flickers on human caused associated with these fluctuations [9].

In the Russian Federation, the allowed values of voltage fluctuations from the frequency of their repetition for different power consumers are normalized by the GOST 32144-13 (see Figure 2.2). The work schedules of an abruptly variable loads are the initial data for determining the admissibility of voltage fluctuations in the considered point in the network. If the load variations are different in the values, it is necessary to determine the equivalent voltage fluctuation. The equivalent voltage fluctuation swing is determined by the formula, %:

$$\delta U_{t.eq} = 100\frac{\sqrt{\frac{\sum_{i=1}^{n}\delta Q_i^2}{n_k}}}{S_{SC}}, \tag{6.5}$$

where δQ - the value of the *i-th* reactive power swing defined according to the load schedule; n_k – the total number of swings during the calculation cycle.

To check the acceptability of $\delta U_{t.eq}$, the average fluctuation frequency is calculated:

$$f_{av} = \frac{n_k}{T}, \tag{6.6}$$

where T - cycle time of the load according to the graph of changes in the consumed reactive power.

Based on the analysis of the frequency change for the most characteristic abruptly variable loads, it can be concluded that the repetition frequency of voltage fluctuations at their work is within certain limits.

To simplify the definition of allowed voltage fluctuations $\delta U_{t.al}$ for the most characteristic power consumers, Fig. 6.3 shows the range of changes in the frequency of fluctuation swing occurrence of their largest reactive loads, and, consequently, the voltage fluctuations during their work. For example, for cold rolling mills $\delta U_{t.al} = 4.2$ %, for continuous hot rolling mill - $\delta U_{t.al} = 2$ %, for blooming and slabbing mills - $\delta U_{t.al} = 1.6$ %, for EAF - $\delta U_{t.al} = 1.0$ % (Figure 6.3).

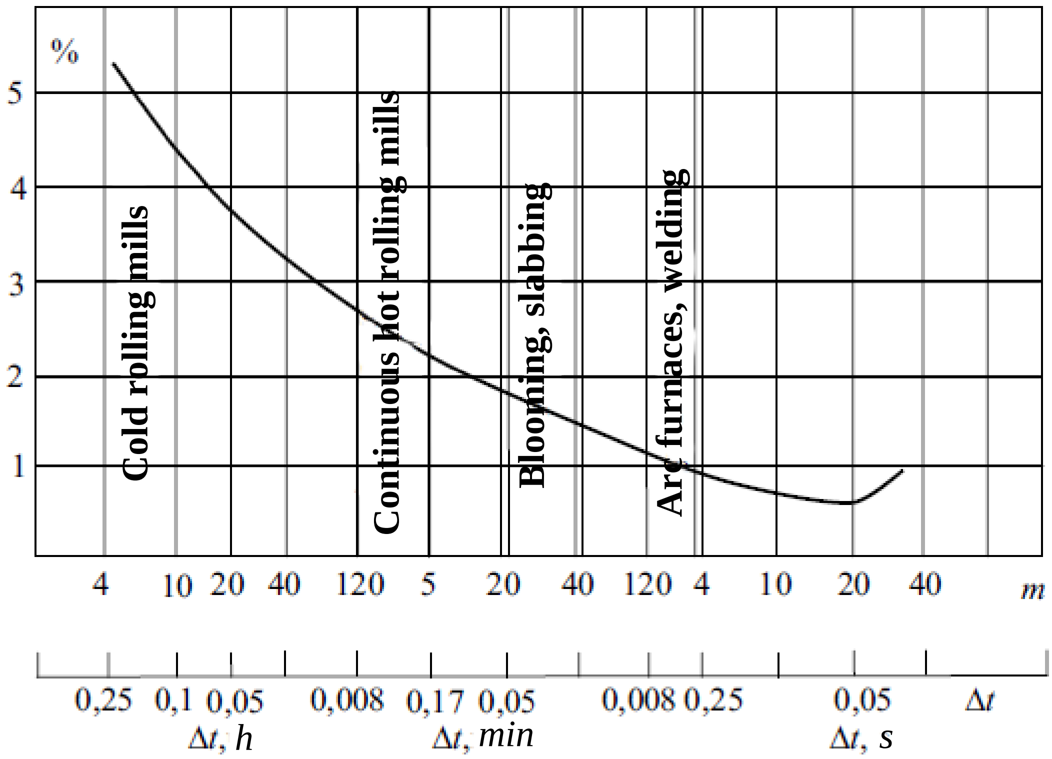


Fig. 6.3. *The dependence of the allowed voltage fluctuations $\delta U_{t.al}$ on the repetition frequency for different power consumers*

6.2 Frequency fluctuations during the operation of abruptly variable loads

The frequency deviations during the normal operation of power supply networks are allowed to be not more than ± 0.2 Hz. There is also allowed the temporary power supply system operation, as well as the part of the system, which has no automatic frequency control, with the frequency deviations up to ± 0.4 Hz. The frequency control is performed by powerful generators of the power supply system. The power consumers at enterprises cannot practically have any significant influence on the frequency deviation due to their low power compared with a total capacity of all system generators.

The frequency fluctuation is the difference between the highest and lowest values of the fundamental frequency at the frequency change rate greater than 0.2 Hz per second. The frequency fluctuations in the power supply system must not exceed 0.2 Hz over the frequency deviation. These rules do not apply to the post-disaster frequency recovery period in the power supply system.

The powerful current-consuming equipment (in relation to short-circuit power at the connection point) with abruptly variable character of loads can cause significant fluctuations in the voltage vector in the electrical network, and, consequently, the frequency fluctuations of the supply voltage. The fluctuations of the voltage vector appear significantly at the connection point of a powerful current-consuming equipment. This process is illustrated by the vector voltage diagram (see Fig. 6.2).

As can be seen from the diagram, the load current flow through the supply network resistance leads to the voltage vector U_L shift relative to the voltage vector in the absence of this load by the angle δ. This shift was mainly due to two components $j\underline{I}_a x_\Sigma$; $\underline{I}_r r_\Sigma$. In general, based on the vector diagram, we obtain:

$$sin\delta = \frac{I_a x_\Sigma - I_r r_\Sigma}{U_{nom}}, \tag{6.7}$$

where I_a – active component of the load current; I_r – reactive component of the load current; x_Σ – the total inductive resistance of the power supply system; r_Σ – the total active resistance of the power supply system; U_{nom} – nominal voltage at the given voltage step.

After transformations we obtain:

$$sin\delta \approx \frac{\Delta P - \Delta Q \frac{r_\Sigma}{x_\Sigma}}{S_{SC}}; \ \delta = arcsin\left(\frac{\Delta P - \Delta Q \frac{r_\Sigma}{x_\Sigma}}{S_{SC}}\right) \tag{6.8}$$

where ΔP – the active load change; ΔQ - the consumed reactive load change; S_{SC} – short-circuit power at the connection point of load. Taking into account that $r_\Sigma / x_\Sigma = 0.03 \ldots 0.1$, we obtain for the approximate engineering calculations:

$$\delta \approx arcsin\frac{\Delta P}{S_{SC}} \tag{6.9}$$

The changes in the active power would have a significant influence on the frequency fluctuation in the networks, if they do not occur quickly enough. At the valve loads of mills, the change in the angle δ occurs with a great speed. For example, the active power, consumed by the thyristor converters of the main drives, varies from 0 to a maximum value during the time less than 0.1 seconds. Therefore, the frequency fluctuations can reach a considerable size.

For comparison with the standards of GOST 32144-13, in engineering calculations the voltage vector fluctuations can be reduced to the frequency fluctuation. The instantaneous value of the phase (phase-to-ground) voltage vector before loading is defined as:

$$U_{oc} = U_{ph.max} \sin(\omega_0 t + \varphi_0) \quad (6.10)$$

where ω_0 – the fundamental circular (angular) frequency; φ_0 - initial phase of the voltage vector; $U_{ph.max}$ – the amplitude of the phase voltage; t – time.

The rotation angle of the voltage vector:

$$\varphi = \omega_0 t + \varphi_0 \quad (6.11)$$

After loading, in accordance with the vector diagram (see Figure 6.2.), the angle of the voltage vector can be expressed as:

$$\varphi_L = \omega_0 t + \varphi_0 - \delta(t);$$

The circular (angular) frequency during the load change:

$$\frac{d\varphi_L}{dt} = \omega_0 - \frac{d\delta(t)}{dt};$$

At the linear load change:

$$\Delta\omega = \frac{\delta}{\Delta t} \; or \; \Delta f = \frac{\delta}{2\pi \cdot \Delta t}.$$

Substituting the angle δ, we obtain:

$$\Delta f = \frac{\arcsin\left(\frac{\Delta P - \Delta Q \frac{r_\Sigma}{x_\Sigma}}{S_{sc}}\right)}{2\pi \cdot \Delta t} = \frac{\arcsin\left(\frac{\Delta P}{S_{sc}}\right)}{2\pi \cdot \Delta t} \quad (6.12)$$

For calculation convenience, taking into account that $\frac{\Delta P}{S_{sc}}$ cannot be more than 0.2 in real systems of the enterprise power supply, we obtain with an error less than 1%:

$$\Delta f = \frac{\Delta P}{2\pi \cdot S_{sc} \cdot \Delta t} \quad (6.13)$$

The determination of allowed frequency fluctuations, and therefore the allowed active power surges is relevant due to the increase in the absolute value of the active power of the abruptly variable loads (for example, load of rolling mills), and its growth rate, especially in the low-power supply networks.

Based on the allowed value of voltage fluctuations (0.2 Hz), we obtain the allowed value of active power surges:

$$\Delta P < \Delta f \cdot 2\pi \cdot S_{sc} \cdot \Delta t = 1.256 S_{sc} \cdot \Delta t \tag{6.14}$$

The allowed active power change rate:

$$\frac{\Delta P}{\Delta t} = 1.256 S_{sc} \tag{6.15}$$

When designing the power supply systems with abruptly variable loads, the verification calculations of the frequency fluctuations must be carried out. If necessary, the measures are included to increase the short-circuit power in the network point, which is joint for power consumers with abruptly variable loads and other consumers. If these measures are not enough, you have to allocate the abruptly variable loads to the separate transformers or to the separate winding of transformers with split secondary windings.

6.3. Voltage fluctuations during the operation of electric arc furnaces

The voltage fluctuations during the furnace operation caused by the fluctuations of the load current are divided into irregular with the frequency of 1 Hz and regular - 2 ... 10 Hz. The reasons for irregular fluctuations are the short-circuits between the electrodes and the charge, the arc breaks during the charge collapses, as well as unstable arc burning during melting. The regular (cyclical) fluctuations are due to the action of electromagnetic forces that try to push the arcs out from under the electrodes to the side of the furnace walls; the vibrations of electrodes; the conductivity changes in the arc combustion zone due to the evaporation ofvarious materials.

The values of the voltage fluctuations also depend on the technological furnace mode. The largest fluctuations occur when melting wells in scraps. Then they reduce during the formation of the bath and have a minimum value for the continuous melting of pellets. This pattern holds regardless of the furnace size. When working with short arcs at low *cosφ,* the value of fluctuations is less than when working with the long arcs at higher *cosφ* (at the same consumed power).

One of the main parameters of the arc furnace load, which determines the values of voltage fluctuations, is the reactive power surge. The value of the voltage swings depending on their repetition frequency in the considered network point, when working with the group of EAF, is generally defined by the formula:

$$\delta U_t = \frac{K_n K_m S_{ft}}{S_{SC}}, \tag{6.16}$$

where K_n - coefficient taking into account the ratio of the reactive power surge to a nominal furnace transformer power; K_m - coefficient taking into account the increase in the reactive power surge for group of furnaces related to the reactive power surge for one furnace; S_{ft} - nominal furnace transformer capacity; S_{SC} – short-circuit power in the network point, where the value of voltage fluctuations is defined.

In the formula (6.16), it assumes that the value of reactive power swing for one furnace is equal $\Delta Q_f = K_n S_{ft}$. The coefficient K_n is recommended to take less than 1, for example, for furnace ДСП-100 with the furnace transformers of 60 MVA $K_n = 0.65$. The probability of reactive power surge reaching the capacity S_{ft} is less than 1%. It is also necessary to take into account a slight increase in the voltage fluctuations during the active power surge associated with reactive power surges.

According to recommendations [9], it is agreed to determine the equivalent fluctuation swing by the formula:

for one furnace

$$\delta U_{t.eq} = \frac{S_{ft}}{S_{SC}} < 0.01; \tag{6.17}$$

for group of furnaces with the same capacity

$$\delta U_{t.eq} = \frac{\sqrt[4]{N} S_{ft}}{S_{SC}} < 0.01; \tag{6.18}$$

for group of furnaces with different capacities

$$\delta U_{t.eq} = \sqrt{\frac{\sum_{i=1}^{n} S_{ft.i}}{S_{ft.max}}} \cdot \frac{S_{ft.max}}{S_{SC}} < 0.01. \tag{6.19}$$

The equivalent voltage fluctuations for practical purposes are considered acceptable if they do not exceed 1%, as is shown in Fig. 6.3.

To determine the required operation speed of the compensating device during furnaces operation, it is important to know the reactive power surge rate. The carried out studies with operating furnaces have shown that in some cases the reactive power surge from zero to its maximum value occurs during a time of 0.03 s that corresponds to one and half period of the supply voltage. In general, the reactive power surge rate can be estimated as 500 MVAr per second. In the case of the group of furnaces, the reactive power surge rate can be increased compared with one furnace.

6.4 Choice of compensating devices to reduce the voltage fluctuations

Voltage fluctuations, which occur at abruptly variable loads, are almost proportional to the reactive power fluctuations. Therefore, to eliminate the voltage fluctuations, it is necessary to apply the compensating devices, whose parameters have to meet the following requirements. They should have the operation speed, corresponding to the change in the reactive power of the initial load schedule, the sufficient enough reactive power available to compensate the variable component (the voltage fluctuations compensation) and the constant component (the power factor improvement) of the consumed reactive power. At a sharp voltage unbalance, for example, when using electric arc furnaces, a phase-wise control of compensating devices is required.

To select compensating devices at the design stage, the appropriate calculations of initial active and reactive power schedules are required. The choice of compensating devices [9] will be considered by the example of a simplified reactive power schedule, shown in Fig. *6.4.* In the original schedule, there are determined the reactive power swing ΔQ, the increase and decrease rate of reactive power ΔQ / Δt, the average value of the reactive power consumed per working cycle Q_{av}, the effective value of reactive power Q_{ef}, the rms value of the reactive power variable component. All these parameters can be calculated by the method described in [9].

Fig. *6.4,a* shows the initial schedule of the reactive power consumption Q_L and its ordered diagram with the mention of ΔQ, Q_{av}, Q_{ef} per working cycle T_1. According to the schedule of the reactive power consumption, Fig. 6.4 *b* shows the power curve of the compensating device Q_{cd} consisting of the variable and constant components for to the conditions of full ($K_{c\sim}$ = 1) and partial compensation ($K_{c\sim}$ = 0.5). Fig. 6.4 *c* presents the resulting graph of the total consumed reactive power $Q_L + Q_{cd}$ also for the conditions of full ($K_{c\sim}$ = 1) and partial compensation ($K_{c\sim}$ = 0.5). Figures 6.4 *d,e* show the graph of the reactive power constant component compensation and the graph of the reactive power, generated by the compensating device for the conditions of full ($K_{c\sim}$ = 1) and partial compensation ($K_{c\sim}$ = 0.5), respectively.

6.4.1. Special high-speed synchronous compensators

When compensating the voltage fluctuations by means of synchronous compensators, the required operation speed is achieved mainly by providing them with the thyristor excitation system with high excitation boost multiplicities (more than 10) and fast-acting regulators. The most rational reactive power regulation law of the synchronous compensator:

$$Q_{cd}(t) = K_{comp\sim}Q_{\sim}(t) + K_{comp.av}Q_{av}(t) \tag{6.20}$$

where $Q_{cd}(t)$ - power of the compensating device; $K_{comp\sim}$ - the compensation proportion of the reactive power variable component; $K_{comp\sim} \leq 1$; $K_{comp.av} \leq 1$ - the compensation proportion of the reactive power constant (average) component. The values of these coefficients can be found from the equations:

$$K_{comp\sim} \geq \frac{\Delta Q - \Delta Q_{al}}{\Delta Q} = 1 - \frac{\delta U_{t.al}\% S_{sc}}{100\Delta Q}; \tag{6.21}$$

$$K_{comp.av} \geq \frac{Q_{av} - Q_{av.al}}{Q_{av}} = 1 - \frac{tg\varphi_{al}}{tg\varphi_{av}}, \tag{6.22}$$

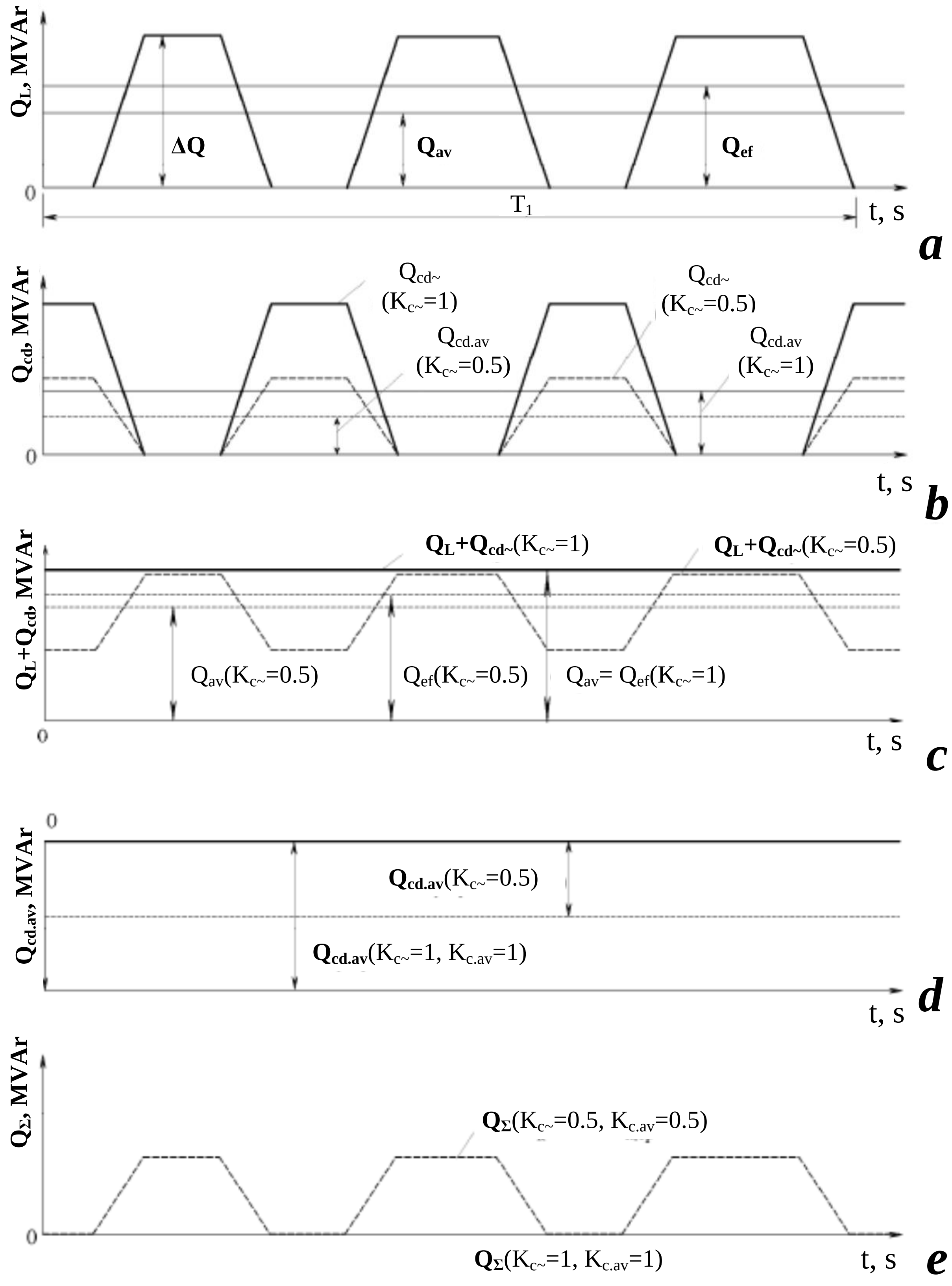


Fig. 6.4. *Reactive power compensation when applying a high-speed synchronous compensator*

where $\Delta Q = Q_{max} - Q_{min}$ – the maximum reactive power fluctuation swing according to the load graph; ΔQ_{al} – the allowed reactive power fluctuation swing, at which the voltage fluctuations are within acceptable limits; $\delta U_{t.al}$ - allowed voltage fluctuation; S_{sc} – short-circuit power at the supply network buses, where the level of voltage fluctuations should be decreased up to the normative values; $tg\varphi_{al}$ - the value corresponding to the allowed power factor.

The example of reactive power compensation with the application of synchronous compensator is presented in Fig. 6.4.

The required power of the compensating device, which provides the normative voltage fluctuations and the normative power factor, is determined from the equation:

$$Q_{cd} = \sqrt{K_{comp\sim}^2 Q_\sim^2 + K_{comp.av}^2 Q_{av}^2} \tag{6.23}$$

The required operation speed of reactive power change of the synchronous compensator is determined from the initial load curve and should be

$$Q_{cd}^{`} = K_{comp\sim} Q_L^{`} = K_{c\sim} \frac{\Delta Q}{\Delta t} \tag{6.24}$$

In practice, to reduce the voltage fluctuations, fast synchronous compensators such as SC-10000-8 with capacity of 7.7 MVAr at the voltage of 10 kV and with capacity of 10 MVAr at the voltage of 6 kV are applied. The maximum operation speed of the reactive power change (operation speed), produced to the network, according to the enterprise data, is equal to 130 MVAr / s. The short-term work with a 2-fold overload is possible. Such compensators are successfully working at some metallurgical plants, in particular, in the power supply system of hot rolling mills.

The installed capacity of a synchronous compensator at the same reactive power load graph will be less than the installed capacity of a static compensating device. This is because the synchronous compensator has a large overload capacity particular, while its installed capacity is determined by the root mean square value of the compensating power per working cycle. The synchronous compensators have all the disadvantages of rotating machines and lower operation speed compared to static compensators. In addition, the static compensating device may have phase-wise control.

6.4.2. Fast static compensating devices

Static compensating devices have several advantages compared with the high-speed synchronous compensators. The main advantage is their faster operation speed. There is also the possibility of the phase-wise control that is necessary in networks with rapidly changing unbalanced load, for example networks with furnaces. Nowadays, there are many types of static compensating devices based on controlled reactors and capacitors, in general with the use of controlled valves. In practice, the most widespread ones are the devices for direct and indirect compensation. Table 6.1 presents a qualitative comparison of high-speed synchronous compensators with static compensating devices for direct and indirect compensation.

Table 6.1. *Comparison of compensating devices*

Parameters for comparisons	**Special synchronous compensator**	**Static compensating devices of**	
		direct compensation	**indirect compensation**
Possible regulation speed, s	more than 0.06	less than 0.02	less than 0.01
Regulation	smooth	stepped	smooth
Building part	massive foundations	foundations are not required more mounting flexibility	
Service	lubrication, cooling, etc.	Service is almost not required	
The ratio of rated reactive power to the maximum reactive power, a.u.	0.5 .... 0.7, there is a possibility of 2-fold overload	1.0 Overload isnot allowed	2.0, an adjustable inductive part 1.0, capacitive non-adjustable part 1.0
Work at unbalanced load	Phase-wise control is almost impossible	Phase-wise control is carried out almost without additional costs	
Loss of the nominal power,%	2.5…4.0	0.5…1.0	1.0…2.0
The supply voltage distortion	no	no	controlled thyristor reactor is the source of the higher harmonics

Static compensating devices for direct compensation can provide the discrete control of the reactive power by switching on and off the capacitor banks or filters of the higher harmonics at the change in the reactive power of consumers (Fig. 6.5 and Fig. 6.6). To ensure the high operation speed, thyristor switches are used as circuit breakers at each stage. To eliminate transients, which will lead only to the increase in voltage fluctuations, the capacitor inclusion is performed with thyristor switches at the moment, when the voltage of capacitors and supply voltage are equal in the magnitude and polarity. The capacitors are turned off by removing the unlocking pulses from the thyristors at the moment, when the current in their circuit becomes equal to zero.

The operation speed of the device for direct compensation is generally determined by the delay in switching on or off the sections of the capacitor banks for the period of the supply voltage (0.02 s) under the condition of a continuous change in the reactive power. This delay can be reduced by implementing the special circuit designs. One of the advantages of direct compensation devices is that they do not generate higher harmonics in the network.

For the correction of the voltage fluctuations when working with abruptly variable loads, the reactive power of each step has to be equal to:

$$\Delta Q_{st} \leq \frac{\delta U_{t.al}\%}{100} S_{SC} \tag{6.25}$$

where $\delta U_{t.al}\%$ - allowed voltage fluctuations; S_{SC} – short-circuit power in the supply network point joint for the abruptly variable load and other power consumers, for which $\delta U_{t.al}$ is determined.

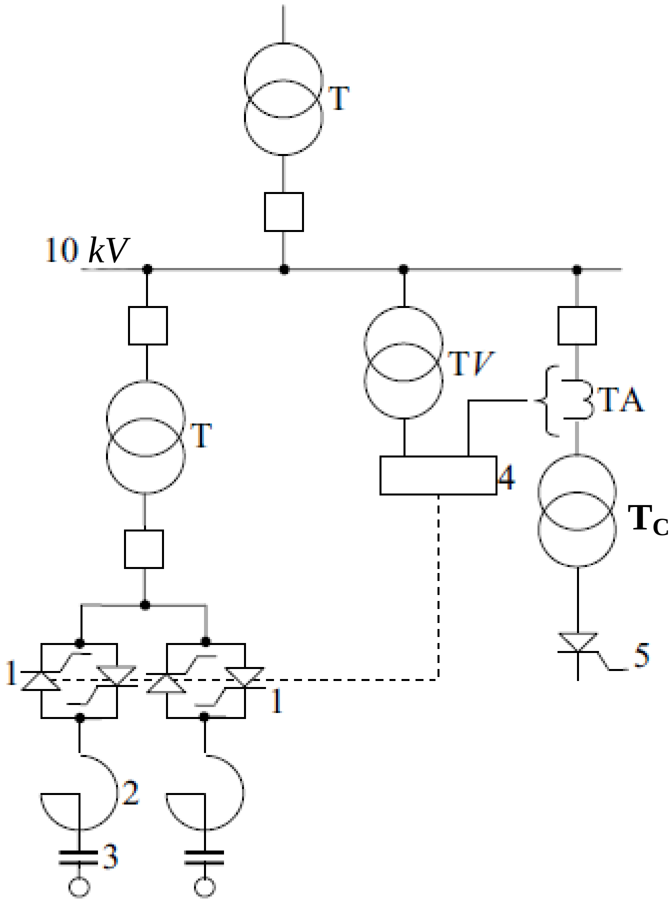


Fig. 6.5. *Schematic diagram of the compensating device with discrete CB power regulation with thyristor switches (direct compensation): 1 - thyristor switches, 2 – reactor; 3 - capacitor bank (CB); 4 - a device to control the thyristor switches; 5 - thyristor converter (load)*

The voltage fluctuations during the operation of direct compensation device are reduced to values (Figure 6.5):

$$\delta U_{t.ac} = \frac{\Delta Q_{st} \cdot 100}{S_{SC}} \%, \tag{6.26}$$

while their frequency after compensation is increased (fig. 6.6) up to the value:

$$f_{ac} = f_{eq} \cdot 2n_{st}, \tag{6.27}$$

where f_{ac} – the reactive power (voltage) fluctuations frequency after compensation; f_{eq} – the fluctuation frequency of the equivalent reactive power load swing; n_{st} – the number of reactive power steps of direct compensation.

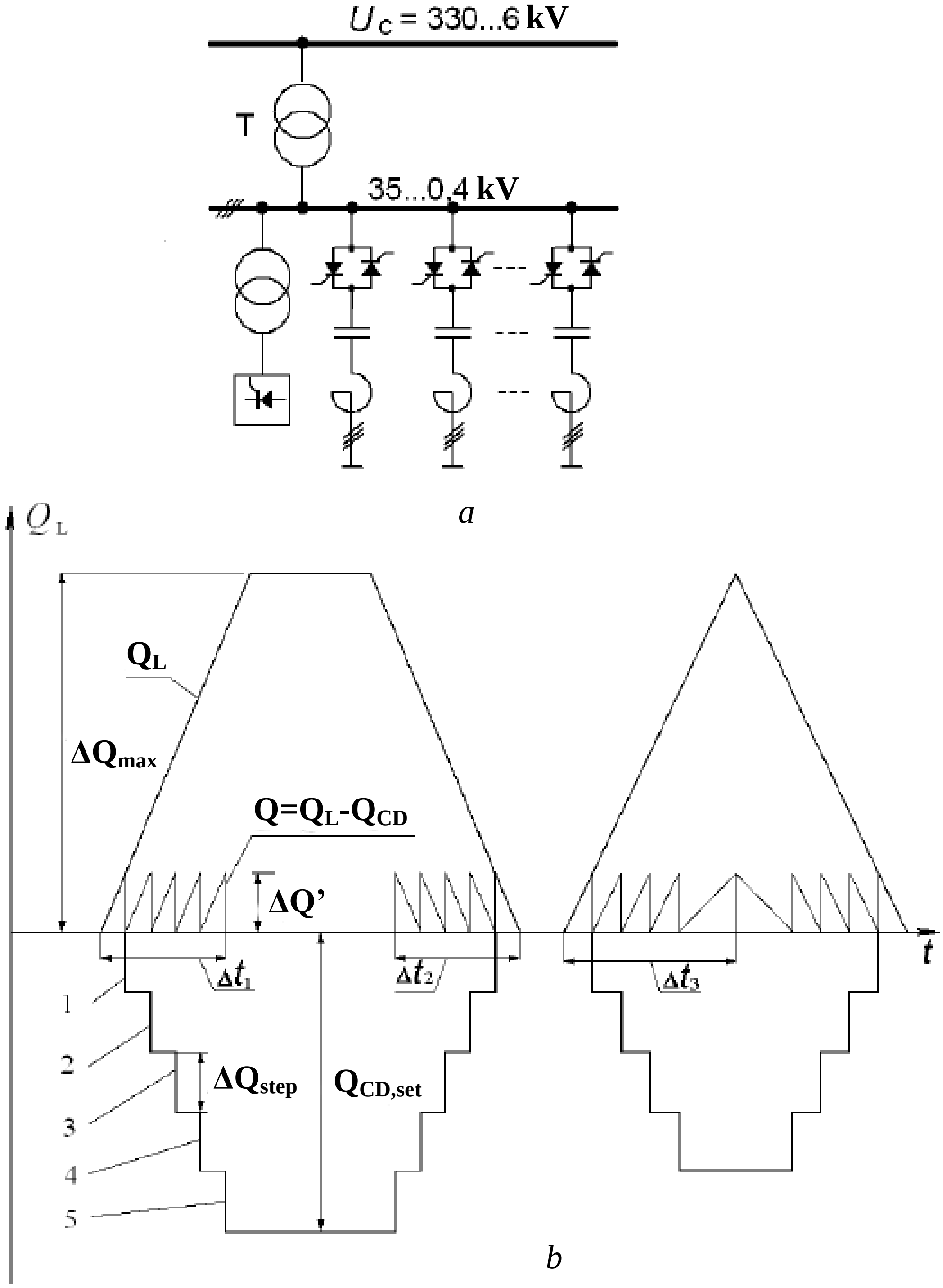


Fig. 6.6. *Reactive power compensation by the direct compensating device*

The allowed fluctuations $\delta U_{t.al}$ for different abruptly variable loads are decreased during the operation of the static compensating devices. For electric arc furnaces $\delta U_{t.al} \cong 0.5$ %, for blooming and slabbing $\delta U_{t.al} \cong 1.3$ %, for continuous hot rolling mills $\delta U_{t.al} \cong 1.5$ %.

The total installed capacity of the compensating device is determined from the equation:

$$Q_{cd\Sigma} = \Delta Q_{max} K_{comp\sim} . \quad (6.28)$$

Static compensating devices of indirect compensation (Figure 6.7) consist of two parts such as gradually regulating inductive element (reactor) for the voltage fluctuations compensation and unregulated part, which can be a capacitor bank or filters of higher harmonics [9].

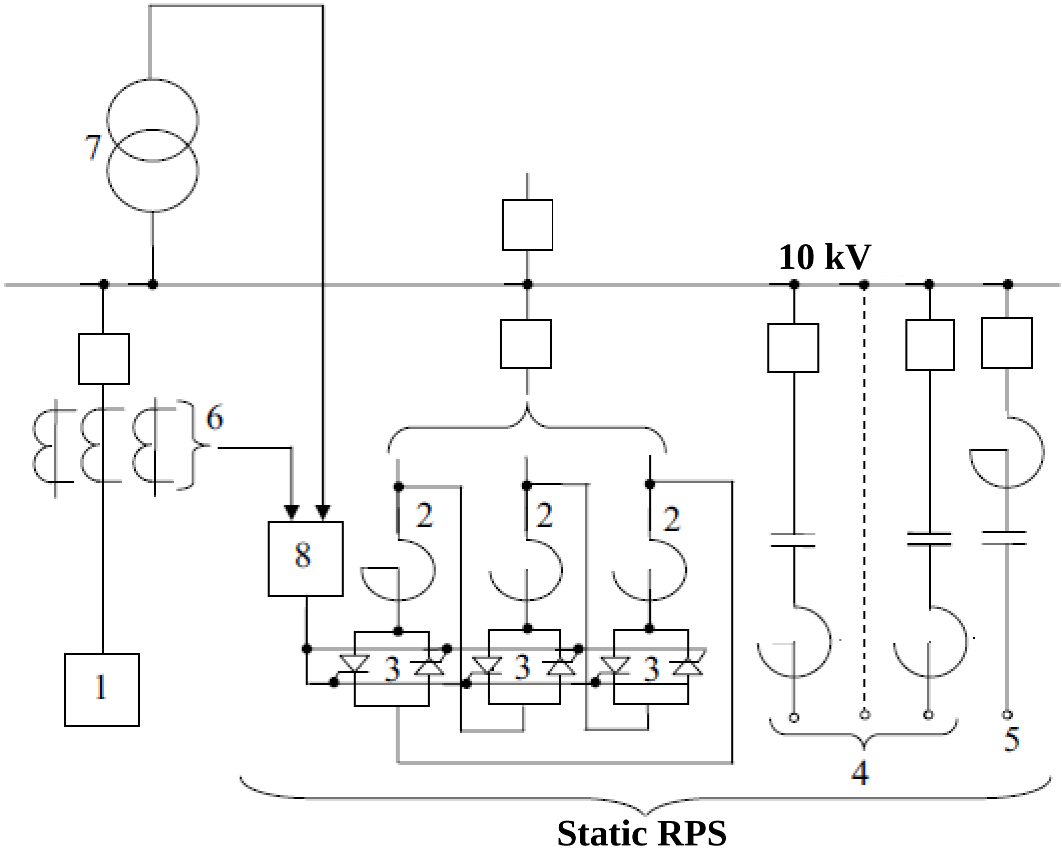


Fig. 6.7. *Schematic diagram of a static compensating device for indirect compensation: 1 - load of thyristor electric drives or electric arc furnaces; 2 - controlled reactors; 3 - thyristor switches; 4 - filters of higher current harmonics; 5 – CB for in-parallel compensation; 6 - current transformers; 7 - voltage transformer; 8 - thyristor phase-pulse control system.*

The principle of indirect compensation for reducing the voltage fluctuations is that the controlled reactor consumes the reactive power, when it is not consumed by the abruptly variable load, and vice versa (see Figure 6.8).

The reactive power (current) regulators have to also ensure the regulation to implement monitoring the front of the reactive power surge and drop (otherwise such a regulation would be ineffective). Therefore, the compensating device is required to have a fast operation speed, corresponding the front of the reactive power surge and drop for the most characteristic abruptly variable loads.

The current regulation in the reactor can be carried out in various ways. For example, some companies apply the controlled saturable reactor. However, the operation speed of such devices is possible to estimate by the delay time, which is over 0.06 (three periods of the supply voltage) and insufficient for such consumers as electric arc furnaces. Therefore, the current regulation in the reactor is currently produced by means of back-to-parallel connected thyristors (Figure 6.7). This provides smooth control of the reactive power with the time delay of 0.01s. This operation speed can be additionally increased by special schematics.

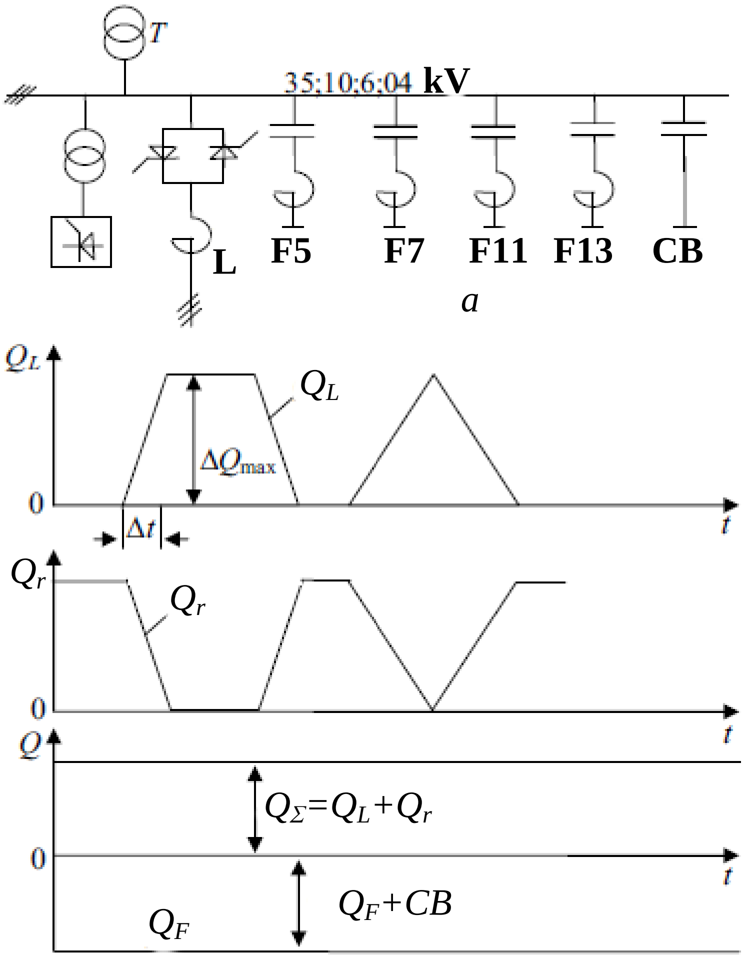


Fig. 6.8. *Reactive power compensation by an indirect compensating device: a – the circuit of a static compensating device; b - the operation principle*

The installed capacity of the reactive part compensating devices is determined based on the load graph from the equation:

$$Q_r = \Delta Q_L K_{comp\sim} . \tag{6.29}$$

The installed capacity of capacitor banks and filters of higher harmonics can be approximately determined by the formula:

$$Q_{cd.av} \geq (Q_{av} + Q_{av.reg})K_{c.av} \approx [Q_{av} + (Q_{max} - Q_{av})K_{comp\sim}]K_{c.av} \, , \tag{6.30}$$

Where $Q_{av.reg}$ – the average reactive power, consumed by the regulated element (inductance).

The parameters of the indirect compensating device for arc furnaces in the absence of consumed load graphs are recommended to define by the following formulas:

for group of same furnaces

$$Q_r \geq S_{ft}\sqrt[4]{N} - \frac{\delta U_{t.al} \cdot S_{sc}}{100}; \tag{6.31}$$

$$Q_{cd} \geq \left(S_{ft}\sqrt[4]{N} - \frac{\delta U_{t.al} \cdot S_{sc}}{200}\right) K_{av}; \tag{6.32}$$

for group of furnaces with different capacities

$$Q_r \geq S_{ft.max}\sqrt[4]{\frac{\sum_{i=1}^{n} S_{ft.i}}{S_{ft.max}}} - \frac{\delta U_{t.al} \cdot S_{sc}}{100}; \tag{6.33}$$

$$Q_{cd} \geq S_{ft.max}\sqrt[4]{\frac{\sum_{i=1}^{n} S_{ft.i}}{S_{ft.max}}} - \left(\frac{\delta U_{t.al} \cdot S_{sc}}{200}\right) K_{av}; \tag{6.34}$$

Self-test questions

1. What is meant by voltage deviations and voltage fluctuations?
2. What parameters determine the voltage fluctuations in the supply network?
3. What is determining when establishing quality standards by voltage fluctuations?
4. Name the main sources and their parameters that cause frequency fluctuations during the operation of abruptly variable loads.
5. How is the allowed active power determined based on the allowed voltage fluctuation?
6. How is the value of the voltage swings determined during the operation of electric arc furnaces?
7. What are the main provisions on the basis of which compensating devices are selected to reduce voltage fluctuations?
8. What do you know about special high-speed synchronous compensators?
9. What compensation methods using static compensating devices do you know?
10. What are the advantages and disadvantages of static compensating devices and special synchronous compensators by comparable parameters?

7. POWER QUALITY MANAGEMENT

The power quality indices (PQI) are the criteria for ensuring the electromagnetic compatibility of the operation of various technical equipment. Therefore, the norms of PQI according to GOST 32144-13 are the subject to inclusion in the technical specifications for the connection of power consumers and in contracts for the use of electrical energy concluded by the consumer with the energy supplying company. At the same time, in order to ensure the norms of the standard, it is allowed to establish more stringent norms in the technical conditions for connection of consumers, who are the culprit for the PQI deterioration, and in contracts for the use of electrical energy with them. Obviously, the power quality indices have to be constantly controlled and managed.

The power quality management is understood as the implementation of the necessary organizational and technical measures aimed at ensuring the specified requirements to PQ. Organizational activities include:

1. Application of rational power supply schemes.
   - 1.1. Selection of the optimal network configuration (radial, closed);
   - 1.2. Reducing the number of transformation steps in the network;
   - 1.3. Network partitioning;
   - 1.4. Reducing the length of networks 0.4 and 6-10 kV;
   - 1.5. Arrangement of jumpers between shop transformers at a voltage of 0.4 kV;
   - 1.6. Connecting the sources of electromagnetic interference and abruptly variable loads to individual transformers or electrically remote bus sections, as well as to split windings of transformers;
   - 1.7. Use of special connection schemes for valve converters;
   - 1.8. Uniform distribution of loads in the phases;
   - 1.9. Use of special connection schemes of the transformer windings;
   - 1.10. Use of circuit solutions leading to an increase in short-circuit power, such as combining low-voltage split windings of transformers or pairing for parallel operation of split windings.
2. The use of transformer automatic control, compensating devices, synchronous motors, valve converters, thyristor reactive power sources.
3. The regulation of the load graph and power consumption modes.
4. Operational measures to improve the PQ, reflected in the form of job descriptions, operational and repair power supply schemes, approved action plans to improve the PQ.
5. The system of economic and material incentives for businesses and employees of energy services, providing increased PQ.

The technical measures include the use of a special facilities or activities that require substantial capital investments.

The technical means for managing the steady-state voltage deviations are:

- application of on-load tap-changing transformers for both centralized and local voltage regulation;
- implementation of the deep input scheme at the enterprise;
- reconstruction of the transmission line by replacing or splitting wires,

or by using the cable transmission lines instead of aerial lines;

- installation of longitudinal and transverse capacitive compensation devices, synchronous compensators, valve-controlled reactive power sources, shunt reactors;
- replacement of a part of asynchronous motors with synchronous ones;
- the use of linear voltage regulators on power lines or on the secondary winding of a power transformer.

The technical means for managing the voltage change swing are:

- installation of transformers with higher capacity or with split low-voltage winding for connection of abruptly variable load;
- strengthening of switching equipment at distribution gears due to the need to increase the short-circuit power to reduce the negative impact of voltage fluctuations on consumers.
- use of dual reactors to separate the power supply of loads with abruptly variable and quiescent character;
- application of longitudinal-transverse compensating devices, including high-speed thyristor-based static compensating devices;
- use of special stabilizing devices operating on the principles of ferromagnetic amplifier.

The technical means for managing the voltage non-sinusoidality are:

- application of filter-compensating devices;
- application of valve converters using multi-phase rectifier circuits (6, 12, 24-phase circuits and higher);
- use of special anode transformer when connected to the network with valve converters;
- use of smoothing reactors and filters to reduce the ripple of the rectified current.

The technical means for managing the voltage unbalance are:

- use of balancing devices, consisting of capacitive and inductive elements that have electrical or electromagnetic connections through transformers or autotransformers;
- use in low-voltage networks with a neutral wire of compensation balancing devices that compensate for the current of zero or reverse, or both sequences together.

Self-test questions

1. What are the main tasks of power quality control?
2. What is meant by electromagnetic compatibility of power supply systems and electric equipment?
3. What power quality indices do you know?
4. How can you test the power quality indices in their compliance with the GOST 32144-13?
5. What is the principle of choosing points for monitoring the PQI?

6. What tasks are set for power supply organizations to ensure the compliance with GOST 32144-13 requirements and to carry out a certification of the power?
7. What tools for PQI control do you know? What are the requirements to these devices?
8. What methods of monitoring PQI do you know?
9. How do PQI affect the work of different current-using equipment?

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