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ENERGY EFFICIENT TECHNOLOGIES IN POWER SYPLY SYSTEMS

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The book shows organizational, technical measures and improvement of electricity metering, implementation of which will improve the energy efficiency of power supply systems, taking into account the following criteria: ensuring the quality of electricity at receivers and a minimum of electrical energy losses. Solutions are considered that implement the latest trends in increasing the energy efficiency of power supply systems: the use of renewable energy sources and the activity of end users of electricity. Implementation of the above measures and solutions creates conditions for the implementation of the concept of smart energy management (smart grid from the perspective of increasing energy efficiency) in power supply systems.

The textbook "Energy efficient technologies in power supply systems" is intended for training bachelors in the field of "Electricity and electrical engineering" (13.03.02).

The textbook has been prepared in Russian and English within the framework of the project “Integration of education with consumer behavior in relation to energy efficiency and climate change in the universities of Russia, Sri Lanka and Bangladesh”, implemented under the international “ERASMUS +” program.

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INTRODUCTION

Every fifth person on planet does not have access to electricity. In 2008, the UN General Assembly stepped forward with the initiative called "Sustainable Energy for Everyone." The initiative is addressed to all sectors of society: business, governments, investors, public institutes, and academic community. It aims to achieve three important interrelated goals by 2030:

- ensuring ubiquitous access to modern energy services;
- increasing the efficiency of global energy consumption by 40%;
- increase in the share of renewable energy in the world up to 30%.

Taking into consideration electric energy all-purposeness, such access must be provided through power supply systems from electric power sources. Population growth, increased access to electric energy, its wider use in all spheres of human activity leads to an increase in its consumption. Improving efficiency at the power consumption stage is essential to ensure sustainable development that contributes to better conditions and higher living standards. It is a well-known fact that a decrease in one unit of consumed energy leads to three units of unclaimed primary energy. These factors determine the world's prospect of introducing of low-cost demanded devices with extremely low power consumption to the market, which will provide significant advantages in terms of energy saving. However, as a rule, such electrical receivers are implemented on the basis of non-linear elements, which lead to deterioration in the quality of electricity, an increase in energy losses and reactive power consumption in power supply systems.

The work analyzes and shows organizational, technical measures and improvement of electricity metering, implementation of which will improve the energy efficiency of power supply systems, taking into account such criteria as ensuring the quality of electricity at the receivers and minimizing the loss of electric energy. The book also discusses solutions that implement the latest trends in increasing the energy efficiency of power supply systems: the use of renewable energy sources and the activity of end users of electricity. Implementation of the above measures and solutions creates conditions for the implementation of the concept of smart energy management (a smart grid from the perspective of increasing energy efficiency) in power supply systems.

1 Analysis of power supply systems from the standpoint of energy conservation

While preparing the materials for this module, a number of definitions should be given regarding the subject of research and presentation. Taking into account [1.1-1.6], the following definitions are most established in the training courses for specialists in the field of "Electrical Engineering and Power Engineering" in the modules: "**Power Supply**" and its component "**Energy Saving (energy conservation) Technologies for Power Supply**".

Power supply – supply of consumers with electric energy

Electricity consumer - an electric receiver a group of them, united by a technological process and located in a certain area.

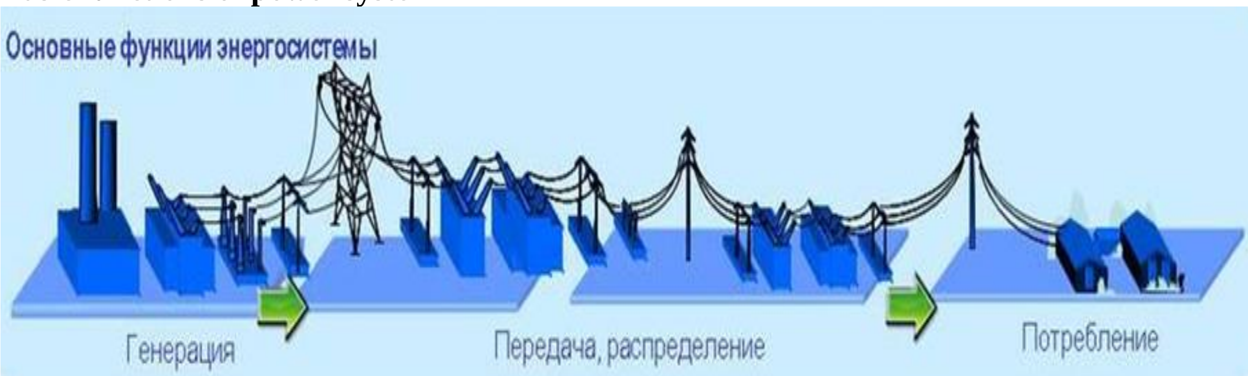
An electric power receiver (EP) is a device, apparatus, assembly, mechanism where electric energy is converted into another type of energy for its use (electric motors, electric furnaces, electric lighting installations, electrostatic and electromagnetic fields installations, etc.)

Energy efficiency refers to the characteristics that reflect the ratio of the beneficial effect of the use of energy resources to the costs of energy resources produced in order to obtain such an effect, in relation to products, technological process.

Power supply system - a set of electrical installations designed to provide consumers with electric energy

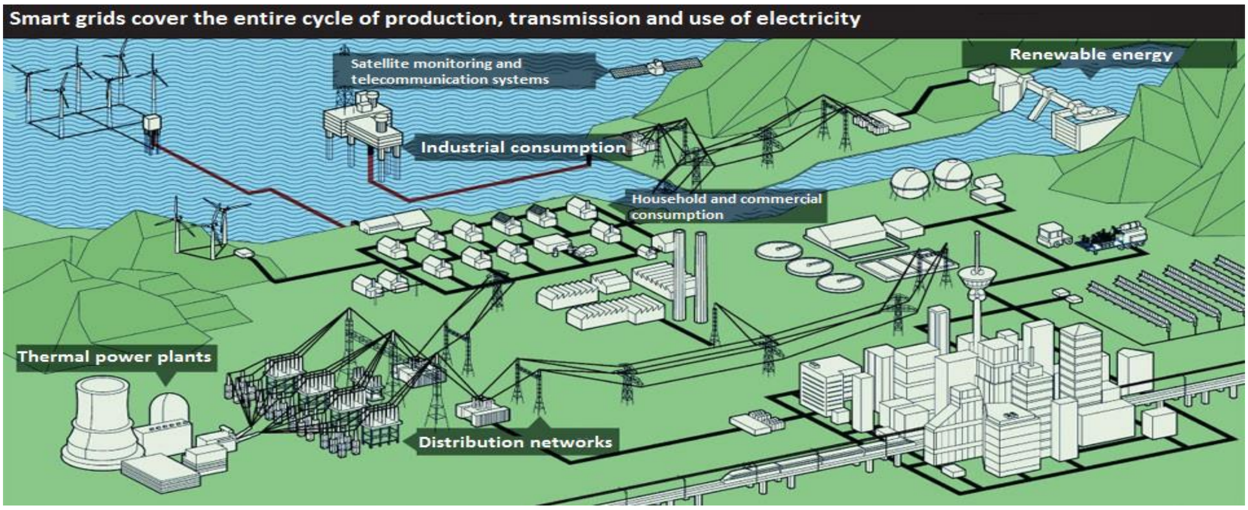
In a number of research works [1.3,1.20], the **power supply system** was defined as a set of devices for the production, transmission and distribution of electricity, which is similar to the concept of **electric power system**. According to [1.20] "**The electric power system** is the electric part of the power system and the receivers of electric energy powered by it, united by a common process of production, transmission, distribution and consumption of electric energy (Fig 1.1a).

Basic functions of power system



Generation **Distribution** **Consumption**

a)



b)

Figure 1.1 – Structure (a) and a simplified diagram of the electric power system (b)

In the courses "Power Supply", the systems of power supply for facilities that are a continuation of the power system are considered. The power supply system of the facility encompasses substations, power lines and consumers of electrical energy (Figure 1.1). As a rule, there are four main power supply systems for facilities in their area of activity, which consume the biggest amount of electrical energy (Figure 1.2).

- Power supply systems for industrial enterprises [1.1-1.3,1.6].
- Power supply systems for residential houses and public buildings, public utility facilities and organizations [1.4,1.6,1.7].
- Power supply systems for agricultural facilities [1.8,1.9,1.10,1.13].
- Power supply systems for electrified vehicles [1.11].

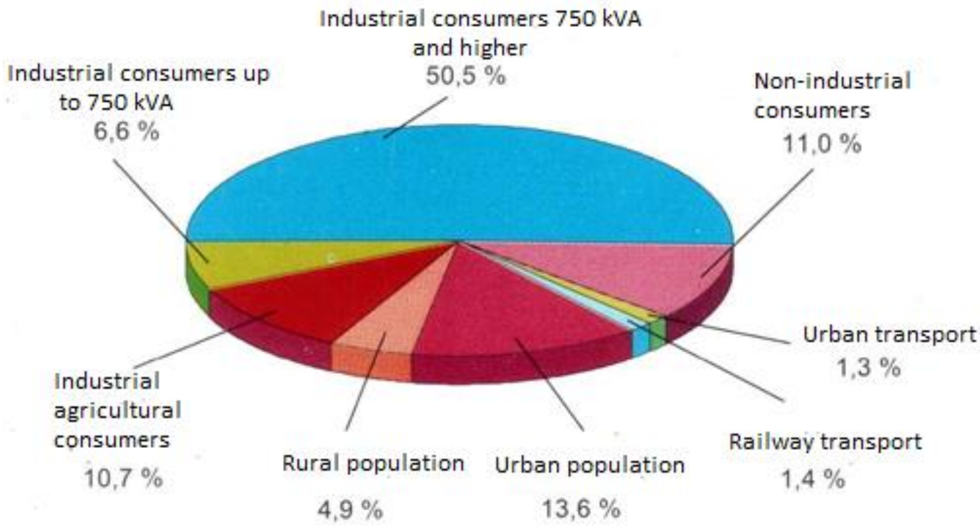


Figure 1.2 - The structure of electricity consumers in Russia

Let us consider the structures of power supply systems of objects and prospects for increasing their efficiency.

Power supply system for industrial enterprises (Figure 1.2 - 57.1%)

Depending on the installed capacity, industrial enterprises are divided into three types: small capacity enterprises (1-5 MW); medium capacity enterprises (5-75 MW) and large capacity enterprises (over 75 MW) power. The power supply system of an industrial enterprise, as a rule, has three subsystems (Figure 1.3).

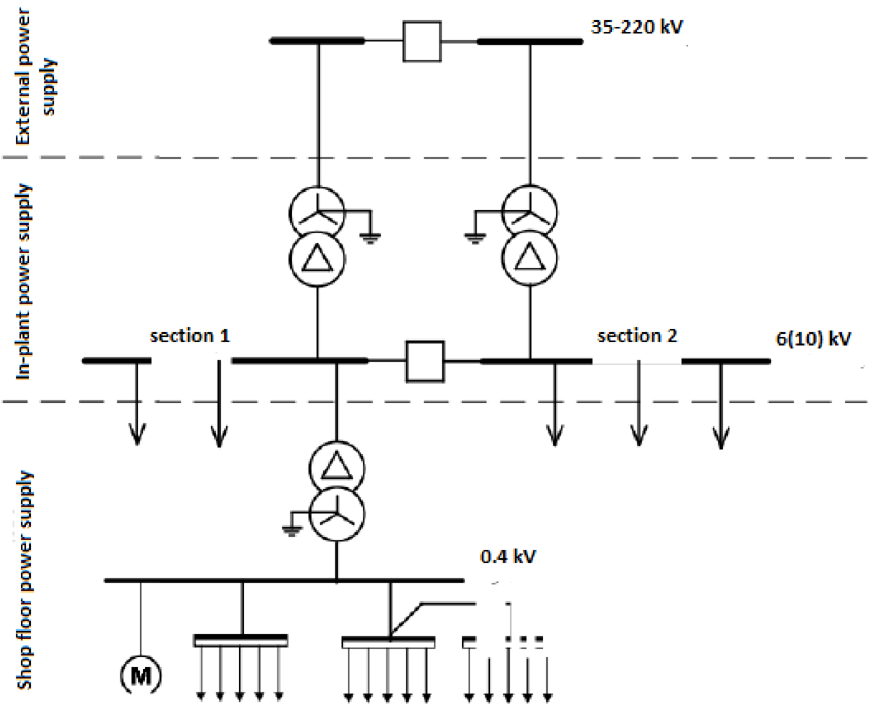


Figure 1.3 - Subsystems of the power supply scheme of an industrial enterprise

External power supply is a set of power lines with voltage up to 220 kV, connecting transformer substations of the power system with receiving transformer substations of the enterprise.

Depending on the installed capacity, enterprises are connected to the power system for voltage from 10 to 220 kV, which makes it possible to obtain the necessary power from the power system. This holds true under condition 1.1.

$$S_{K3} >> S_n, \tag{1.1}$$

where S_n – the load power; S_{K3} – short circuit power at that point in the power system to which the power supply system of an industrial enterprise is connected.

$$S_{K3} = \frac{U_H^2}{Z_{K3}}, \tag{1.2}$$

where, Z_{K3} is the resistance to a point in the power system, where the power of the power system in comparison with S_n is infinitely large.

Internal power supply of a plant is the receiving substation of the enterprise (Figure 1.4 - hydraulic fracturing) and a complex of electrical distribution networks that receives, distributes and transfers electric energy to power points (Figure 1.4-TP).

Internal power supply of plant's workshop- a complex of workshop transformer substations (Figure 1.4-TP), distribution networks, power supply points and direct power supply networks of electrical receivers with voltage up to 1,000V (Figure 1.3)

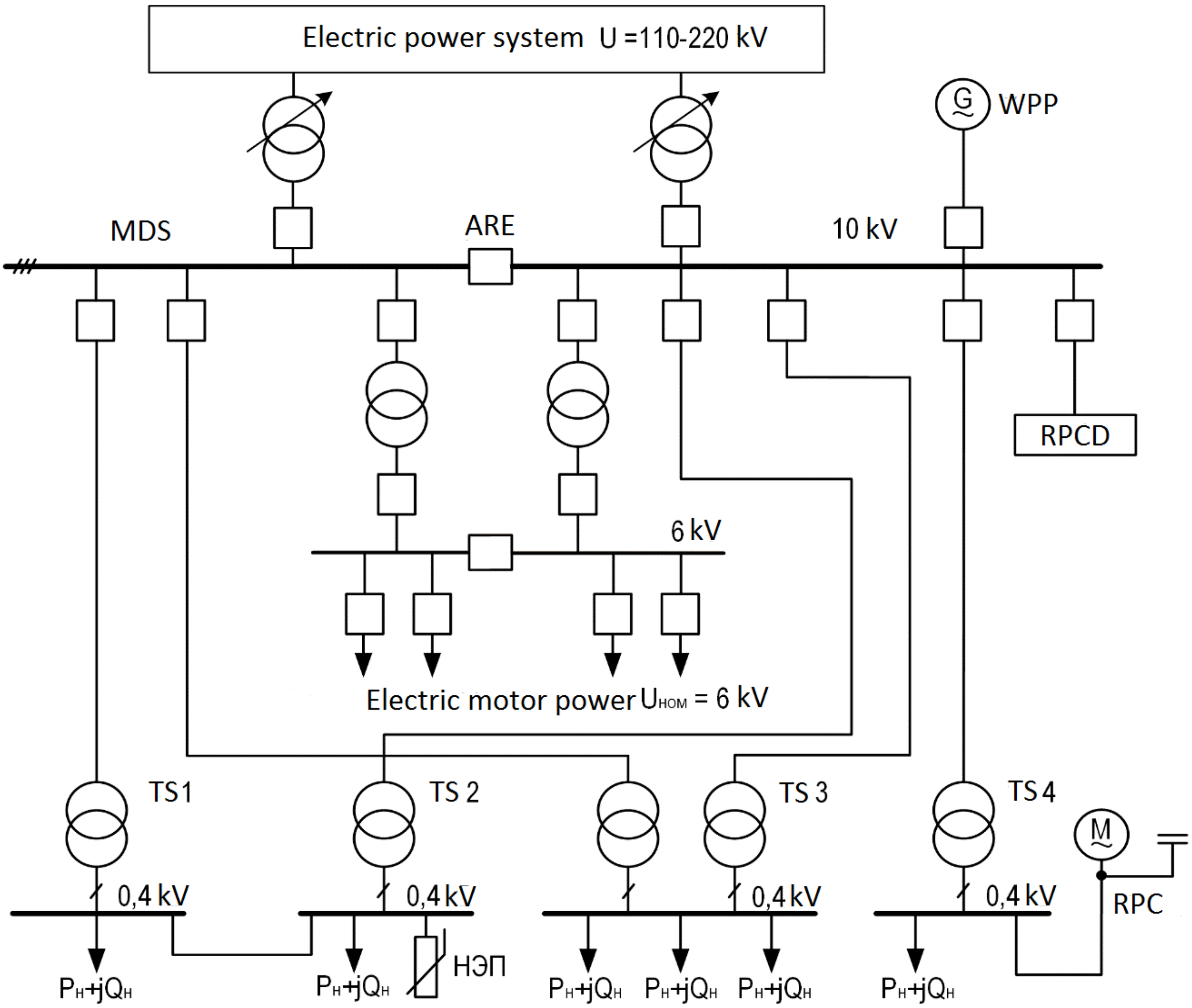


Figure 1.4 - A simplified typical power supply scheme of an industrial enterprise

Figure 1.4 shows: loads (P_H + jQ_H), including those caused by non-linear power receivers (NPR); centralized and individual installations for reactive power compensation. In recent years, power supply systems are additionally equipped with renewable energy sources: wind power plants (Figure 1.4 - wind turbines); co-generation plants, waste management companies and others. Renewables can be used for electricity and heat production, as well as for transport services. Wind and the solar electricity sources change their production depending on weather conditions. On the other hand, bioenergy, hydropower and geothermal energy are such sources that are not varying and can be accumulated and regulated. Thus, in general, this gives us reliable and uninterrupted power supply that meets demand. [1.12].

At the design stage a rational modern power supply system should fit the following technical and economic requirements:

1. Ensuring the safety of employees, reliability and efficiency of power supply;
2. The quality of electricity that meets the requirements of regulatory documents
3. Ensuring low power loss
4. The absence of harmful effects on the environment.

Industrial enterprises are characterized by the dynamism of the technological process, the readjustment of production. At the same time, new electrical technologies are used, which determine the growth of reactive power consumption and higher harmonic currents and voltages.

There is an intensive development of power supply systems, the growth of obsolete equipment. These factors often lead to lower energy efficiency of power supply systems of industrial enterprises.

Power supply systems for residential houses and public buildings, public utility facilities and organizations (Figure 1.2 - 24.6% share)

The considered power supply systems (Figure 1.5) are designed to provide electric energy to non-production facilities: residential houses, schools and preschool institutions, hotels, catering and trade facilities, consumer services and utilities and others [1.4,1.6,1.7]. They are characterized by a high density of electrical loads (from 5 to 20 MW / km2) and a large number of consumers located in a limited area, especially in the center of cities

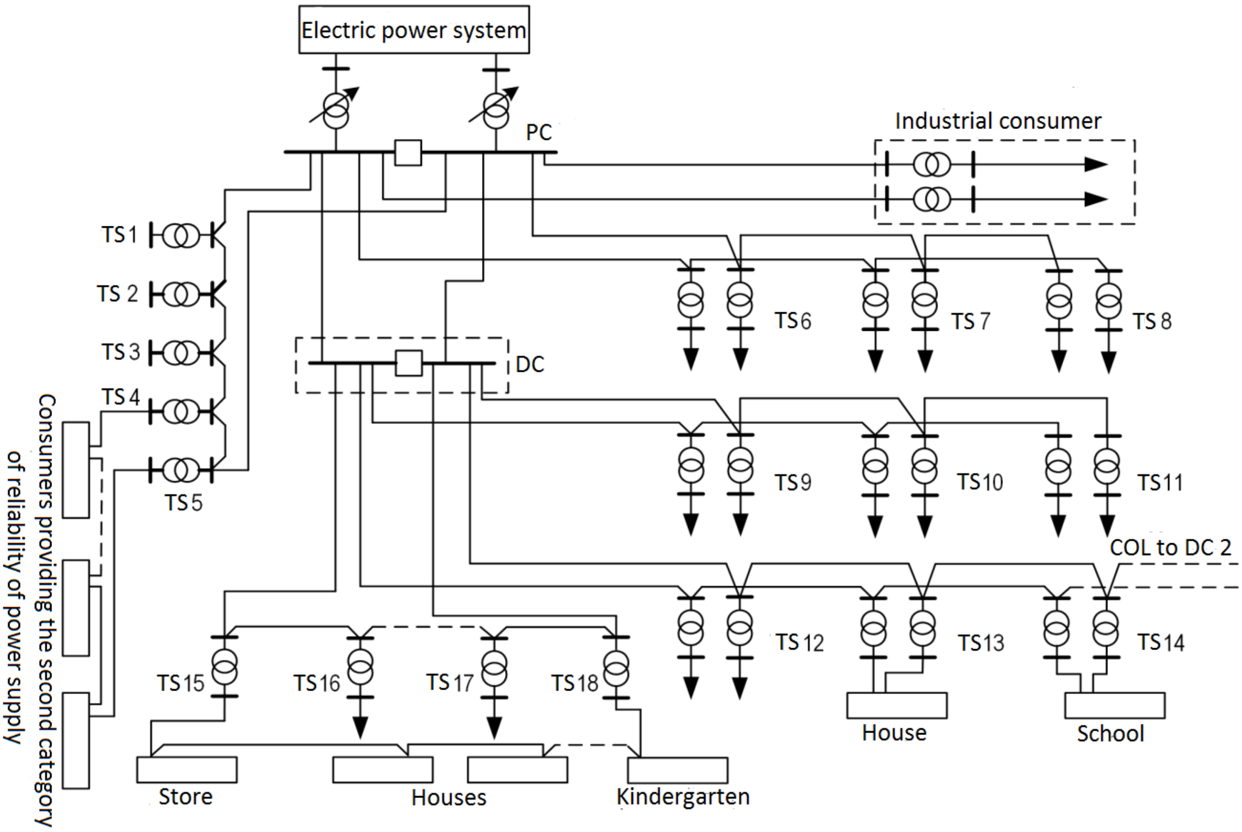


Figure 1.5 - Simplified power supply system for residential and public buildings, public utility facilities and organizations

Figure 1.5 shows: a central substation (CS) and transformer substations (TS) (with a voltage of 10-20 / 0.4 kV) which provide supply directly to consumers of electricity. In some cases, small capacity industrial enterprises are also connected to this power supply system. A features of such systems are: cable power lines; a significant number of single-phase and non-linear loads. Moreover, the growth of the latter is unpredictable. In recent years, the considered power supply systems are additionally equipped with renewable energy sources (Figure 1.1b).

Electrical supply systems for agricultural facilities (Figure 1.2 – a share of 15.6%)

Features of power supply systems for agricultural facilities of the Russian Federation are as follow: significant length and branching of power lines; a significant proportion of unbalanced loads; deterioration of equipment and more

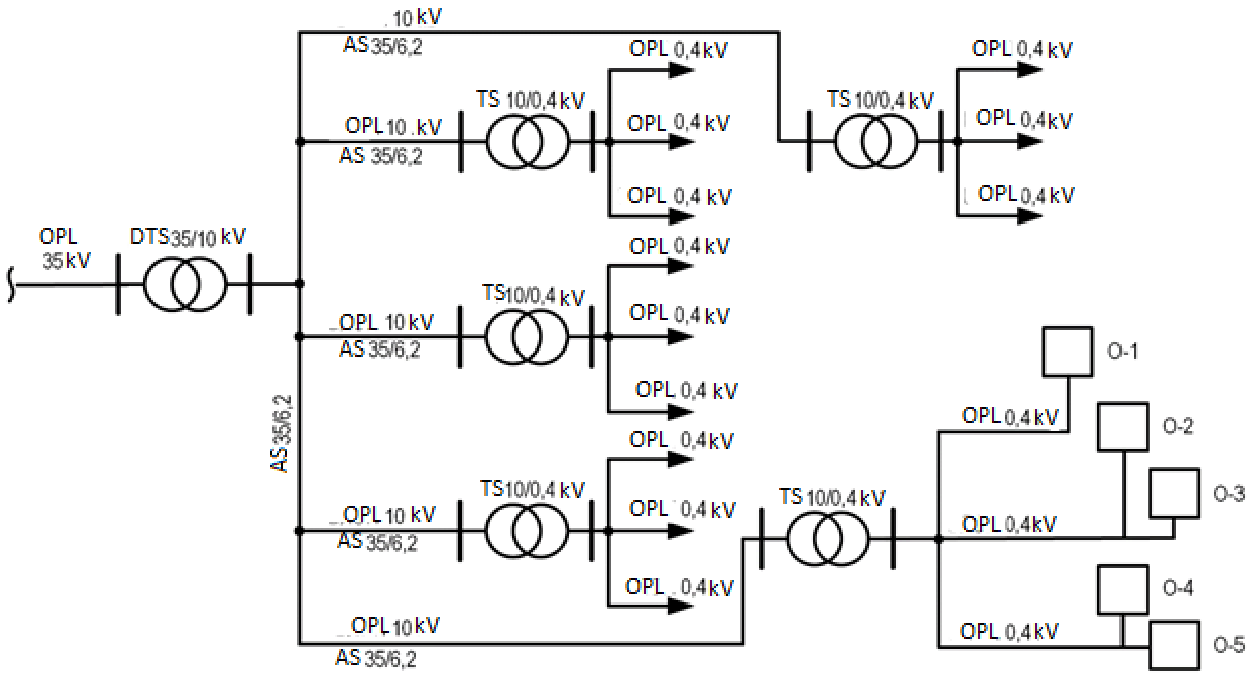


Figure 1.6 – Typical power supply scheme for agricultural facilities

The market economy has led to the appearance of power consumers with high specific power, providing the technological needs of the villager: needs for electric heating; use of household and agricultural machinery and etc. The above mentioned needs led to an increase in the installed capacity of agricultural electrical receivers. In some cases, it reached 26 - 53 kW per average villager. Existing power supply systems under conditions of a steadily increasing load and their physical deterioration are often not adapted to fulfill their purpose. In a number of rural electricity grid companies, losses of electricity reach 40%. At the same time, the amount of the same losses in the networks of economically developed countries of Europe and in Japan does not exceed 7%. A significant proportion of these losses is due to the low degree of reactive power compensation [1.8-1.10,1.13,1.17,1.22]. It should be noted that basically all agricultural power transmission lines in the Russian Federation are overhead transmission lines. This, taking into account their considerable length and loads, leads to an increase in voltage losses (Section 4). Under these conditions, the problem of modernizing rural distribution networks and increasing their efficiency is extremely urgent. Independent power plants based on renewable energy sources can provide energy supply in those places where construction of networks is technically difficult or economically unprofitable. Bioenergy, wind, solar, and geothermal plants can provide the energy needed to supply electricity, heating, cooling, domestic hot water and food preparation, and process heating to the built area [1.12].

Power supply systems for electrified vehicles (Figure 1.2 - 2.7%)

Alternating and direct current electric power systems for electrified transport are used globally. Alternating current electric power systems, as a rule, are used for statewide/federal electrified transport are not included in the scope of this course. DC power supply systems are used for the electrified transport of cities and the region. In particular, in the Kaliningrad region the following types of electrified transport are used: commuter trains; trams and trolleybuses. All of them run on direct current [1.18]. Figure 1.7 shows a standard suburban power supply system for electrified vehicles.

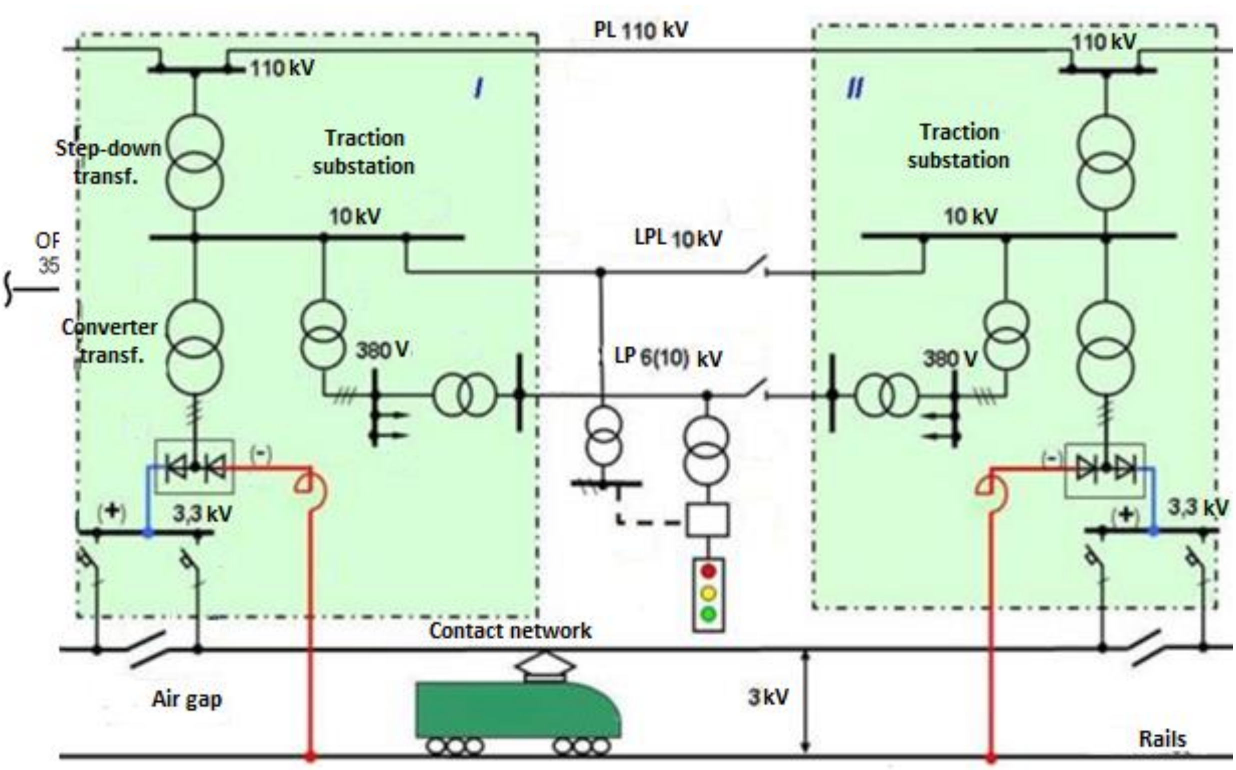


Figure 1.7 – Suburban power supply system for electrified vehicles

The basis of the regional energy system is a 110–220 kV meshed network which supplies local power plants, all consumers of the region [1.18], and also electrified vehicles belonging to public transport [1.11,1.23]. As follows from Figure 1.7, the contact network receives power from several traction substations at a constant voltage of 3.3 kV.

An uncontrollable six-phase rectifier is used at the traction substation. Traction substations of city electrified transport (trams and trolleybuses) are supplied by city network with a voltage of 10-20 kV, and the voltage on the buses of the contact network is + 600V. The main disadvantages of these systems are as follows: during operation, they generate higher current harmonics in the mains, mainly 5 and 7, consume significant reactive power, causing energy losses and affecting the quality of electricity in the mains.

Table 1.1 - Composition of current harmonics emitted into the supply network by a semiconductor converter depending on its phase

Phase	Composition of current harmonics									
6-phase	5	7	11	13	17	19	23	25	29	31
12-phase	-	-	11	13	-	-	23	25	-	-
24-phase	-	-	-	-	-	-	23	25	-	-

Below are the main approaches and measures to be implemented to improve the energy efficiency of power supply systems.

It is a known fact that, the reduction of one unit of power (1 kW) at the stage of energy consumption leads to three units (3 kW) of saved installed capacity of the power plant. Therefore, the use of the latest electrical technologies that allow the consumer to implement the technological process at lower energy costs is a determining factor in the field of energy conservation.

Consider an example of the implementation of such technology in a lighting system

In 2016 the share of electricity spent on lighting in the world was 19% of all generated electricity [1.14–1.16], which was due to the widespread use of low-efficiency incandescent lamps.

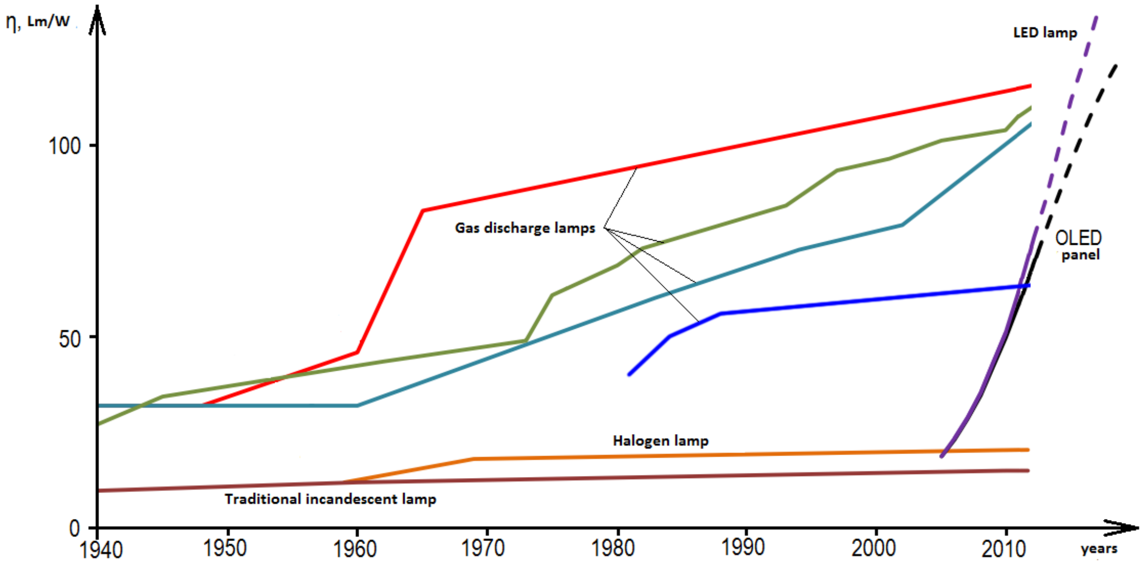


Figure 1.8 – Development of luminous efficiency of light sources (η_v)

The criteria for evaluating the effectiveness of a light source are: specific light output (lm / W); life time; environmental friendliness; the influence on the mains [1.14-1.16]. Due to above requirements, the production of incandescent lamps is prohibited by law in many countries.

Table 1.2 - Characteristics of various types of lamps

Type of lamp	Achieved output light lm/W	Theoretical light output, lm/W	Presence of harmful substances	Lifetime, thousand hours
Incandescent lamp	20	53,5	No	Up to 10
Fluorescent lamp	85	100	Hydrargyrum	Up to 25
LED lamp	**102 (for a lamp) 205 (for diode)**	**More than 300**	**No**	**Up to 100**

The use of LED lights can significantly reduce energy consumption. The disadvantages of using LED lamps are: emission into the supply network of higher harmonics of current; consumption of reactive power. It should be noted that leading manufacturers of LED lamps in recent years, by improving their design, have achieved a significant reduction in the emission of higher current harmonics into the supply network and in the level of reactive power consumption by LED lamps [1.14-1.16]

International experience in improving the energy efficiency of electric networks and power supply systems indicates the existence of common approaches to solving this critical problem, which is becoming more and more relevant every year.

These approaches are reflected in international and national regulatory legal acts and standards, industry standards, state and technical policies, regulations and rules and are based on the following basic principles.

1. Energy efficiency shouldn't be provided just by any means, but by techno-economically feasible means.
2. The energy transfer efficiency and distribution of electricity should address not only energy efficiency, but also improve the quality and reliability of electricity supply.
3. Improving energy efficiency is a long-term task, the successful solution of which should be based on: sound technical, innovative, energy and economic management policies; state support for measures to increase energy efficiency, primarily in terms of regulatory and methodological support, standardization of activities, improvement of tariff policy and economic incentives; analysis, synthesis and dissemination of advanced domestic and foreign experience

According to the International Energy Agency, the relative losses in the networks of electric power systems of industrialized countries were in the range of 4-7%, including: in Germany - 4%, Japan and France - 5%, China -6%. The relative losses of electricity in the networks of the electric power system of Russia in 2015, including the networks of industrial enterprises, Russian Railways and others that provide services for the transmission of electricity to their entities amounted to 12-14% of the electricity generated, and from distribution to the grid - up to 13-15 %

According to the minimum expert estimates, the potential for reducing electricity losses in electric grids in Russia is 20–25 billion kWh per year. The practical realization of this potential is a complex task that requires significant joint efforts of personnel of electric power companies and consumers of electricity.

Over the years, a standard procedure has been worked out in the development and implementation of energy conservation programs: setting goals and objectives for energy conservation, energy surveys, calculation and analysis, selection and implementation of organizational and technical energy-saving measures, improving electricity metering; monitoring the results of implementation and actions to further improve these results; assessment of their economic efficiency.

The high level of technical losses in the Russian electric networks is associated with a low level of reactive power compensation, 70% physical and moral deterioration of the network, a clearly insufficient solution to the problems of optimizing the operation of the power supply system, but first of all, with the unresolved problems with the quality of electric energy. The continuous increase in installed capacity of non-linear, asymmetric and rapidly changing loads is not always accompanied by the introduction of solutions aimed at ensuring the quality of electricity, even in industrialized countries of Western Europe. So, in the distribution networks of Switzerland with a voltage of 230/400. Within the period 1979-1991 the content of higher harmonics increased by 30%. Other indicators of the quality of electric energy also affect the energy efficiency of electricity transmission through electric networks, the reliability and economic indicators of the electrical equipment of the network and ultimately affect their working conditions.

A decrease in the quality indicators of electric power leads not only to a significant decrease in the energy efficiency of electric networks due to an increase in electricity losses, but also to a decrease in the service life of electric equipment, and, consequently, to an increase in capital investments in electric networks and a violation of the normal functioning of the electric power system. An expert assessment of the annual losses from low quality of electricity is based on well-known figures: modern electricity consumption in the world is approximately **20 trillion kWh, losses from non-compliance with the requirements of the quality of electricity are estimated at $ 500 billion.** To prevent such consequences or their limitations, it is necessary to organize the development and implementation of methodological, organizational and technical measures to ensure compliance with existing standards, norms and rules. First of all, these measures should be implemented in the networks of consumers of electric energy, since it is in systems of power supply that consumers in most cases are the main culprits for the deterioration of the quality of electricity [1.17].

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Recommended online video footage (free access)

1. https://youtu.be/nbPmsBmo03Y
2. https://youtu.be/fQNQKkvGQL0
3. https://youtu.be/WTIQ_xcp0sU
4. https://youtu.be/YcBgxVfD70Q
5. https://youtu.be/TQg2Y0kp2vI

Test questions

The power supply system is:

- Part of the energy system, united by a common process of production, transmission, distribution and consumption of electrical energy
- A set of electrical installations designed to provide consumers with electric energy
- A set of devices for the production, transmission and distribution of electricity

Which power supply systems account for the highest energy consumption?

- Power supply systems for industrial enterprises
- Power supply systems for small and medium-sized businesses
- Power supply systems for residential and public buildings, utilities and organizations
- Power supply system for agricultural facilities
- Electricity supply systems for electrified vehicles

What characterizes the power supply systems of residential and public buildings, public utilities and organizations?

- A large number of consumers located on a limited area
- Low density electrical loads
- Significant length

What is the ratio of the load power of the power supply system of the facility and the short-circuit power at the point of the power system to which this system is connected, that provides the electric power of the required quality:

- Short circuit power not less than 50 times greater than the load power
- Short circuit power equal to load power
- Short circuit power less than load power

At the design stage, the power supply system of the facility must satisfy the following conditions:

- The quality of electricity, in accordance with the requirements of regulatory documents
- Provide low power loss
- Ensure reliable power supply
- Cause no harmful effects on the environment
- Use technologies that provide low cost of the designed power supply system

The latest technologies implemented on non-linear elements, as a rule, are characterized by:

- Emission into the mains supply of higher current harmonics
- Reactive power consumption.
- Greater efficiency
- Lower cost

Which of the semiconductor converters has a lower level of higher current harmonics by emission to the mains?

- Six-phase
- Twelve-phase
- Twenty-four phase

What type of lamps has the highest light output?

- Incandescent
- LED
- Luminescent

2 Regulatory and legal documents in the field of energy conservation

2.1. Regulatory documents in the Russian Federation

The regulatory framework of the Russian Federation (RF) for energy conservation and energy efficiency has been developed to create conditions for energy conservation for all entities in the energy complex engaged in the production, conversion, transmission, consumption of energy resources, including waste management.

All regulatory documents can be arranged in the following order depending on their legal force:

1. The Constitution of the Russian Federation;
2. Federal laws adopted by the State Duma of the Russian Federation;
3. Decrees of the President of the Russian Federation;
4. Regulations and decisions of the Government of the Russian Federation;
5. Orders of ministries and departments of the Russian Federation;
6. Regional laws, decrees and decisions of administrations (governments) of regions;
7. Decisions and decisions of municipalities;
8. Orders and instructions of heads of enterprises and organizations of all forms of ownership.

The system of energy legislation is based on constitutional norms on guaranteeing the unity of the economic space, the free movement of goods, support for competition, and freedom of economic activity. The Constitution of the Russian Federation also divided the powers between the federal authorities and the authorities of the constituent entities of the Russian Federation. According to the Constitution of the Russian Federation, the subjects of the Russian Federation have the fullness of state power in their jurisdiction [2.1].

Among the regulatory acts in the energy sector, federal laws occupy the main place. Normative acts that do not belong to the category of laws are by-laws and are aimed at organizing the implementation of the law [2.2].

Legal relations in the field of energy supply in the electric power industry are regulated by the regulatory legal acts given in table 2.1.

Table 2.1 – Regulatory acts regulating relations in energy conservation

№	Name of regulatory act	Number	Date of adoption
	Federal laws		
1	“On the electric power industry”	№ 35- FL	26.03.2003
2	“On energy conservation and energy efficiency improvement and on amendments to certain legislative acts of the Russian Federation”	№ 261-FL	23.11.2009

Continuation of Table 2.1

№	Name of regulatory act	Number	Date of adoption
	Decisions of the Government of the Russian Federation		
1	On approval of the Rules of non-discriminatory access to electric power transmission services and the provision of these services, the Rules of non-discriminatory access to operational dispatch management services in the electric power industry and the provision of these services, the Rules of non-discriminatory access to the services of the administrator of the wholesale market trading system and the provision of these services and the Rules of technological connection of power receiving devices of consumers of electric energy, facilities for the production of electrical energy, as well as power grid facilities, owned by grid companies and other persons to electric networks "	№ 861	27.12.2004 (amended 27.12. 2019)
2	"On the procedure for creating a state information system in the field of energy conservation and improving energy efficiency and the conditions for its functioning"	№ 391	01.06.2010
3	"On the provision of subsidies from the federal budget to the budgets of the constituent entities of the Russian Federation for the implementation of regional programs in the field of energy conservation and energy efficiency and recognition of the acts of the Government of the Russian Federation as invalid	№ 754	31.07 2014
4	On approval of the State Program of the Russian Federation "Energy Efficiency and Energy Development"	№ 321	15.04.2014
	Orders of the Ministry of Energy of the Russian Federation		
1	"On approval of guidelines for the development and implementation of regional and municipal programs in the field of energy conservation and energy efficiency"	№ 916	11.12.2014

Continuation of Table 2.1

№	Name of regulatory act	Number	Date of adoption
2	"On the approval of requirements for the form of programs in the field of energy conservation and energy efficiency of organizations with the participation of the state and municipal education, organizations engaged in regulated activities, and reporting on the progress of their implementation"	№ 398	30.06.2014
3	On the approval of the methodology for calculating target values in the field of energy conservation and energy efficiency, including under comparable conditions "	№ 399	30.06.2014
4	"On approving the requirements for conducting an energy survey and its results and the rules for sending copies of an energy passport compiled from the results of a mandatory energy survey to the Ministry of Energy of the Russian Federation"	№ 400	30.06.2014
5	"On approval of the procedure for the submission of information on energy conservation and on improving energy efficiency"	№ 401	30.06.2014

The basic legislative act in the field of electric power is Federal Law No. 35-FL On Electric Power [2.3]. This law establishes the legal basis for economic relations in the electric power industry, defines the powers of state authorities to regulate these relations, the basic rights and obligations of electric power entities and consumers of electric and thermal energy.

The Federal Law "On Energy Conservation and Improving Energy Efficiency and Amending Certain Legislative Acts of the Russian Federation" [2.4] is common to all sectors of the energy industry. The main goal of this law is to create the legal, economic and organizational foundations of stimulating energy conservation and increasing energy efficiency.

According to Article 2 of the said law, **energy conservation** is the implementation of organizational, legal, technical, technological, economic and other measures aimed at reducing the amount of energy resources used while maintaining a beneficial effect.

The main provisions of the Law on Energy Saving are shown in Table 2.2.

Table 2.2 - the Main provisions of the Law on energy conservation

№	Provision of law
1	Ban on the circulation of goods with low energy efficiency.
2	Introduction of energy efficiency classes for goods
3	Requirements for the installation of electricity metering devices
4	Requirements for the energy efficiency of buildings, structures
5	Energy Efficiency Measures in the Housing Fund
6	Requirements for energy saving and energy efficiency programs of organizations with the participation of the state and organizations engaged in regulated activities
7	Requirements for regional and municipal energy saving and energy efficiency improvement programs.
8	Obligations and requirements for conducting a mandatory energy survey and its results
9	Development of the Institute of Energy Service Contracts
10	Creation of a state information system in the field of energy conservation and energy efficiency.

In accordance with Article 12 of the Law on Energy Saving, the produced, transferred, consumed energy resources are subject to mandatory metering using metering devices for energy resources used. The specified requirements apply to all facilities connected to electric networks of centralized power supply.

The Government of the Russian Federation approved the State Program of the Russian Federation “Energy Efficiency and Energy Development” [2.5]. The goal of the State Program is to reliably provide the country with energy resources, increase the efficiency of energy resources use, and reduce the anthropogenic impact of the energy complex on the environment.

The State program includes subprograms “Development and modernization of the electric power industry”, “Development of the use of renewable energy sources” in the electric power sector. The main objectives of these subprograms are: investment and innovation renewal of the electric power industry, aimed at ensuring high energy, economic and environmental efficiency of production, transmission and distribution and consumption of electric energy, development of the use of renewable energy sources.

One of the requirements of the current legislation is the development of regional and municipal programs in the field of energy conservation and energy efficiency [2.6], as well as programs of organizations with the participation of the state and the municipality and organizations engaged in regulated activities [2.7].

The regulatory and technical framework for energy conservation includes state standards, technological regulations, technical and methodological documents.

A set of regulatory and methodological documents on energy saving is given in GOST (State All-Union standard) 31607-2012 “Energy Saving. Normative and methodological support” [2.8]. This standard establishes the basic concepts, principles, goals and subjects of activity in the field of normative and methodological support for energy conservation, the composition and purpose of the fundamental regulatory, methodological documents and applies to activities related to the efficient use of energy resources, energy-consuming objects, technological processes, work, service

The technical regulation of the Customs Union "Electromagnetic compatibility of technical means" TR TS 020/2011 [2.9] regulates the relations of the parties involved in the design, creation and commissioning of electrical equipment and electrical installations related to ensuring the quality of electric energy. With the entry into force of the technical regulation on electromagnetic compatibility for the first time on a legal basis, the responsibility of consumers of electric energy for the deterioration of the quality of electric energy in electric networks arises.

2.2 Analysis of approaches to improving energy efficiency in advanced economies

In most industrialized countries of the world (USA, Germany, Japan, France, Spain, England, etc.), there are national programs aimed at improving energy conservation, developing renewable energy sources and protecting the environment. Along with national programs, a number of interstate programs to improve energy efficiency have been adopted and are being implemented.

The main measures to improve energy efficiency in advanced economies are given in table 2.3 [2.10].

Table 2.3 - The main measures to improve energy efficiency

№	Energy efficiency improvement measure
1	Implementation of energy efficiency standards, mandatory building codes, planned indicators related to the limitation of energy consumption for heating and lighting of premises.
2	The provision of state subsidies and subsidies for energy conservation
3	Providing preferential loans and guarantees for financing energy saving measures
4	Granting tax benefits
5	Introduction of a flexible tariff system
6	Control over the use of energy resources, the implementation of energy conservation standards
7	Renewable energy
8	Conducting programs aimed at promoting energy conservation among the population

The United States is one of the leaders in the use of renewable energy sources (RES). About 80 billion dollars were allocated for the implementation of the renewable energy development program in the United States, while it was envisaged to increase the share of renewable energy sources to 25% -30% and reduce emissions of harmful and dangerous substances into the atmosphere [2.11].

The country supports and subsidizes energy-saving measures, introduces discounts for consumers of energy-saving equipment, establishes tax benefits for enterprises and homeowners who have implemented energy-saving measures, and build energy-efficient houses. So US citizens living in energy-inefficient houses have the right to rely on government support as part of the Housing Energy Efficiency Program. This program provides a 10 percent tax rebate on the cost of energy-saving work and income tax benefits [2.12].

Germany, being energy-dependent on energy supplies from other countries, solves the problem of security of energy supply by saving energy and stimulating the development of alternative renewable energy sources, mainly wind and solar energy. In Germany, the regulatory framework is constantly being improved, innovation is being actively pursued, new standards are constantly being updated and developed, mechanisms are created that stimulate energy saving in all sectors of the economy [2.12].

In Germany, over € 1.5 billion has been spent on house renovations to reduce energy consumption. Moreover, homeowners wishing to renovate their houses to improve its energy efficiency are provided with tax incentives of 20% and also bank loans with a low interest rate. [2.12].

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2.4 Federal Law of November 23, 2009 No. 261-FZ (as amended on July 26, 2019 No. 241-FZ) “On Energy Saving and on Improving Energy Efficiency and on Amending Certain Legislative Acts of the Russian Federation”
2.5 Decree of the Government of the Russian Federation of April 15, 2014 No. 321 (On approval of the State program of the Russian Federation “Energy Efficiency and Energy Development”.
2.6 Order of the Ministry of Energy of Russia dated December 11, 2014 No. 916 “On approval of methodological recommendations for the development and implementation of regional and municipal programs in the field of energy conservation and energy efficiency”.
2.7 Order of the Ministry of Energy of Russia dated June 30, 2014 No. 398 “On approval of the requirements for the form of programs in the field of energy conservation and energy efficiency of organizations with the participation of the state and the municipality, organizations engaged in regulated activities and reporting on progress their implementation "
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Test questions

Accounting of which fuel and energy resources should be maintained by all legal entities in accordance with Federal Law No. 261 "On Energy Saving and Improving Energy Efficiency"

- produced
- stored
- consumed
- transported
- all of the above

How often, according to Federal Law No. 261, an organization (enterprise) should conduct an energy survey:

- annually
- once every five years
- once every ten years
- as needed
- once every seven years

Which of the government bodies at the federal level is entrusted with the supervision of the efficient use of energy resources throughout the state:

- State Duma
- Ministry of Energy of the Russian Federation
- Ministry of Economic Development of the Russian Federation
- Accounts Chamber of the Russian Federation
- To the Government of the Russian Federation

The state information system carries out information interaction at the level of

- state - a budget object;
- state - subject of the federation;
- the state - the subject of the federation - a budget object;
- state - subject of the federation - municipality - budget object;
- state - budget object

The implementation of legal, organizational, scientific, industrial, technical and economic measures aimed at the effective use of fuel and energy resources is

- efficient use of energy;
- saving of fuel and energy resources;
- energy conservation;
- economic effect
- energy efficiency

Which of the documents of the regulatory framework for energy conservation does not apply to the regulatory and technical:

- Construction norms & regulations;
- GOST (State All-Union standard)
- Rules for conducting energy surveys
- Decisions of the Government of the Russian Federation
- Terms of Reference

Which of the documents of the regulatory framework for energy conservation does not apply to the regulatory:

- Law on energy conservation
- Decisions of the Government of the Russian Federation
- Decree of the President
- GOST(State All-Union standard)
- Order

3 Organizational measures in the field of energy conservation in power supply systems

Organizational measures, as a rule, do not require significant financial resources, so it is advisable to carry them out first.

Typical organizational measures in the field of energy conservation are given in table 3.1.

Table 3.1 – Typical organizational energy saving measures

№	Name of organizational event
1	Conducting an energy survey and compiling an energy passport
2	Implementation of an energy management system
3	Continuous energy monitoring
4	Periodic verification and adjustment of energy supply contracts
5	Optimization of the structure of the power supply system
6	Compliance with the rules for the operation and maintenance of energy supply systems and individual power plants, the introduction of schedules for turning on and off lighting, ventilation systems
7	Conducting periodic "raids" to verify the efficiency of energy consumption
8	Conducting explanatory work with employees on energy conservation issues, campaigning, advanced training of those responsible for energy conservation, signs on the need to save energy
9	Development of a system of incentives for employees to reduce losses of fuel, electricity and heat, while introducing administrative measures for inefficient consumption (use) of energy resources

3.1. Energy surveys of enterprises and organizations

According to Art. 2 of Federal Law No. 261-FL, an energy audit refers to the collection and processing of information on the use of energy resources in order to obtain reliable information about the amount of energy resources used, energy efficiency indicators, identifying energy saving opportunities and improving energy efficiency, reflecting the results in the energy passport of entrepreneurs [3.1].

Energy inspection activities are only entitled to persons who are members of self-regulatory organizations in the field of energy inspection.

An energy survey is usually carried out on a voluntary basis, with the exception of organizations for which it is mandatory.

An energy survey is mandatory for the following individuals (every 5 years):

- public authorities, local authorities endowed with the rights of legal entities;
- organizations with the participation of the state or municipality;
- organizations engaged in regulated activities;
- organizations engaged in the production and (or) transportation of water, natural gas, thermal energy, electric energy, production of natural gas, oil, coal, production of oil products, processing of natural gas, oil, transportation of oil, oil products;
- organizations whose total costs for the consumption of natural gas, diesel and other fuels, fuel oil, thermal energy, coal, electric energy exceed 50 million rubles per calendar year;

- organizations conducting activities in the field of energy conservation and energy efficiency, financed in whole or in part from the federal budget, budgets of the constituent entities of the Russian Federation, local budgets.

The main objectives of the energy survey are:

1) obtaining objective data on the amount of energy resources used;
2) determination of energy efficiency indicators;
3) determination of the potential for energy conservation and energy efficiency;
4) development of a list of measures for energy conservation and energy efficiency and their valuation

The requirements for conducting an energy audit and its results and for the form of an energy passport were approved by order of the Ministry of Energy of Russia dated June 30, 2014 No. 400 "On approval of the requirements for conducting an energy survey and its results and the rules for sending copies of an energy passport compiled from the results of a mandatory energy survey" [3.2].

At the first stage of the energy survey, the processing and analysis of information obtained from the collection of information about the object of the energy survey (information survey) is carried out. Based on the analysis of the information obtained from the results of the information survey, a plan for the visual inspection and instrumental examination is determined.

The main activities and the results of the information survey, visual inspection and instrumental examination are shown in table 3.2.

Table 3.2 – Activities and results of the energy survey

№	Activities and survey results
Information survey	
1	Analysis of customer contracts with resource supply organizations
2	Analysis of the state of actually used energy supply systems
3	Determination of the structure and analysis of the dynamics of the expenditure of energy resources used in physical and value terms for the reporting (base) year and two years preceding the reporting (base) year for energy use systems in general
4	Determining the structure and analysis of the dynamics of consumption for each type of energy resources used as a percentage for the reporting (base) year and two years preceding the reporting (base) year, for energy use systems in general
5	Development of balances for each type of energy resources used for the reporting (base) year and two years preceding the reporting (base) year, for energy use systems in general.
Visual inspection and instrumental examination	
6	Calculation of the actual consumption of energy resources used separately for elements of energy resources use systems
7	Evaluation of the efficiency of energy resources use separately for the elements of energy resources use systems
8	Calculation and assessment of the unaccounted potential of used energy resources in physical and value terms separately for elements of energy resource use systems

Continuation of Table 3.2

№	Activities and survey results
9	Determination of the structure and analysis of the dynamics of consumption, consumption and losses for each type of energy resources used for the reporting (base) year and two years preceding the reporting (base) year, separately for each element of energy resource use systems
10	Drawing up a balance for each type of used energy resources for the reporting (base) year and two years preceding the reporting (base) year, separately for each element of energy resource use systems
11	Calculation of actual and standard costs of used energy resources for the reporting (base) year separately for each element of energy resource use systems
12	Calculation and assessment of energy resources use efficiency for the reporting (base) year separately for each element of energy resources use systems
13	Calculation and assessment of potential aimed at energy conservation and energy efficiency, for each type of energy resources used separately for elements of energy resources use systems

One of the most significant issues arising from energy audits is the assessment of energy efficiency. This assessment is carried out for a number of quantitative characteristics called energy efficiency indicators (indicators). The list of possible energy efficiency indicators is given in table 3.3.

Table 3.3 – Energy Efficiency Indicators

№	Energy performance indicators
1	Losses of electric and thermal energy
2	Efficiency of power plants and electric motors
3	Power factor (cos φ) of the electrical network
4	Consumption of energy resources (electricity) for own and technological needs
5	Electricity Quality Indicators
6	Exceeding the actual consumption of reactive energy of its economic value established in the contract
7	The level of means of automatic regulation of power consumption modes
8	Characteristics of active and reactive load graphs (unevenness coefficient)
9	The constant component of energy consumption, independent of the volume of production of the enterprise
10	The specific consumption of energy resources (electricity) per unit of output
11	The share of energy costs (electricity) in the cost of production
12	Number of energy efficiency certified products and services

The methodology for conducting an energy audit should not depend on the type of the organization. All actions should be carried out in a standard algorithm.

An energy audit allows you to identify priority organizational measures to reduce energy consumption without significant costs, as well as determine what needs to be done to save energy and improve energy efficiency.

3.2. Energy management. Implementation of an international standard at the enterprise ISO 50001

Energy management is a methodological science with practical tools, which includes a set of interconnected and interacting elements aimed at shaping energy policy, planning energy consumption, setting goals and objectives, developing measures to achieve them, motivation.

The purpose of energy management of an enterprise is to reduce energy costs through the systematic management of energy resources, as well as reduce environmental impact.

The guidance for the implementation of the energy management standard at the enterprise is the new international standard ISO 50001: 2011 - Energy management systems - Requirements with guidance for use [3.3].

The ISO 50001 standard provides the basis for energy efficiency for industrial enterprises in any industry. The basis of this standard is the management of people who manage resources.

The methodology of the energy management standard system can be described as follows:

- planning (plan) - conducting energy analysis and determining basic criteria, indicators of energy efficiency, setting goals, objectives and developing measures for energy conservation.
- implementation (do) - implementation of energy conservation measures;
- check - monitoring and measurement of key performance characteristics;
- action (act) - taking action to continually improve performance.

The model of the energy management system (Deming cycle) is shown in Figure 3.1

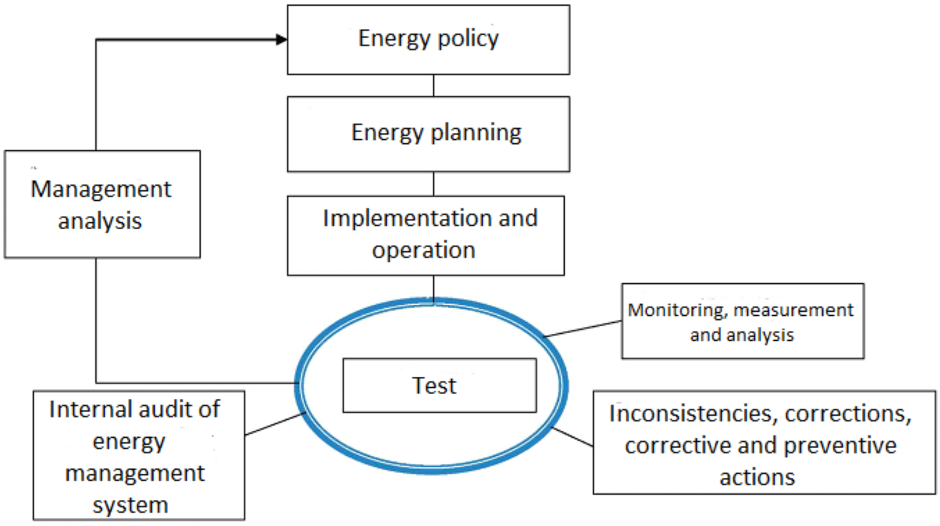


Figure 3.1 – The model of the energy management system

The energy management system includes the following elements: energy supply, measurement, documentation and maintenance of necessary reports on energy use, equipment selection and purchase.

When implementing the ISO 50001 standard, it is necessary to go through four stages [3.4]:

Stage 1. Performing a preliminary audit in the management system.

Stage 2. Development of an energy management system and its implementation in accordance with ISO 50001.

Stage 3. Pre-certification audit: performing internal audits of the company, analysis of the effectiveness of the current energy management system.

Stage 4. Certification audit (performed by the certification body according to the contract).

As a result of the implementation of the energy management system according to the ISO 50001 standard, operational management of energy consumption and reduction of energy costs by up to 15% are ensured;

The ISO 50001 standard not only provides cost savings, but it is also a tool to improve business efficiency and competitiveness. The results of the implementation of the standard are significant organizational, financial and reputation effects, as shown in table 3.4

Table 3.4 – Results of the implementation of the ISO 50001 energy management system standard

Organizational effect	Financial effect	Reputation effect
Effective energy management	Improving the financial performance of the company	Image attractiveness of the company
Improving the production cycle	Improving financial transparency and reducing costs	Reputation among business partners, the public and government
Improving manageability and optimizing business processes	Ensuring investment attractiveness and increasing the value of the company	Reputation of the company as a successful one in improving energy efficiency
Result: ensuring stable competitiveness of the company in domestic and foreign markets		

It should be noted that energy management at the enterprise works continuously, unlike energy audit, which is carried out every 5 years.

When implementing the ISO 50001 standard, it is necessary to analyze the regulatory documents of the enterprise for compliance with the requirements of the standard and adjust all business processes for energy management in the enterprise in accordance with the standard. It is recommended to analyze the existing activities of enterprise services in terms of planning, rationing of energy consumption and energy conservation, on the basis of which to form the organizational structure of energy management with the appointment of those responsible for energy conservation.

An additional advantage of the ISO 50001 standard is its integrability with the international standards ISO 14001 - environmental management, ISO 9001 - quality management and others [3.5].

3.3 Additional measures to optimize the power supply system

From the standpoint of energy saving, the efficient operation of power supply systems is ensured, inter alia, through the use of energy-efficient equipment with proper optimization of the structure and operation modes of this system. A number of organizational measures are aimed at this (table 3.1, p. 5). The applicability of one or another of them in specific conditions is an optimization problem. In addition to financial indicators (cost, profit, costs), energy efficiency indicators are used as optimization criteria (table 3.3) [3.1]. Most often it is: ***ensuring a minimum of power (energy) losses and ensuring quality indicators of the supplied electricity***. The selected option should not primarily adversely affect the safety of personnel while ensuring the necessary level of reliability of power supply to consumers. This is a feature of the tasks associated with energy conservation in power supply systems.

The approach to solving problems is standard and involves the preparation of *an objective function* on which the corresponding *restrictions and boundary conditions are imposed*.

Limitations are various technical, technological, economic, regulatory and other conditions that must be considered when solving a problem. *Example of restrictions*: if the optimization parameter is the cross section of the conductors, the restriction will be the minimum acceptable value according to the conditions of mechanical strength.

Boundary conditions - maximum permissible values of optimization parameters are set in the form of a certain range of variation of the desired variables. *An example of boundary conditions*: the permissible range of variation of the established voltage deviation in accordance with the current standard for electricity quality.

After carrying out the appropriate calculations, the implementation of the event may be recommended or rejected

3.3.1 Operational-regime measures in power supply systems

Power supply systems are mainly distribution networks of medium and low, rarely - high voltage. Consider regime events relevant to such networks from the standpoint of energy saving and loss reduction.

Перераспределение потоков электроэнергии по линиям сетей электроснабжения

In closed high-voltage networks of large industrial power supply systems, to reduce active losses, the method of optimizing open circuits is widely used, which is based on the position that their minimum level corresponds to the network mode in which the power distribution along the branches is proportional to their active resistances. To compensate the equalizing current arising due to the heterogeneity of the network (different ratios ζ = X / R), especially when connecting networks of different nominal voltages (Figure 3.1), transverse voltage regulation devices are used (longitudinal regulation is carried out by transformers). In the absence of such devices, the flow distribution changes forcibly, by choosing the location of the circuit opening in the secondary voltage network.

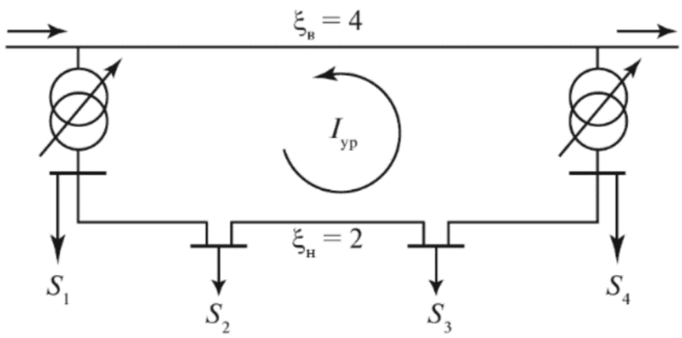


Figure 3.2 – Closed loop formed by networks of various nominal voltage [3.2]

Medium voltage networks as a rule already operate in open mode, so for them the question of finding the best place to open is considered. At the same time (Figure 3.2), the load is redistributed on the sections of the line itself and between the supply substations, which leads to a change in losses in the external network. The optimization criterion is *the minimum of total* *losses in networks of both levels*. Optimum opening points may vary for the highest and smallest loads. This is one of the most effective organizational measures to reduce electricity losses in distribution networks, especially in urban ones, with a voltage of 6-10 kV.

The operation of the network with a break of multilateral power supply (as i.e. a radial-trunk) provides a reduction in losses [3.10]. Such a mode can be provided when feeding consumers of the 1st and 2nd category in terms of reliability of power supply in medium and high voltage networks in the presence of automatic load transfer (ALT) and two or more independent mutually redundant sources (in case of an accident, the ATS includes backup power, Figure 3.3) The methodology for calculating the effect of network separation measures is given in [15].

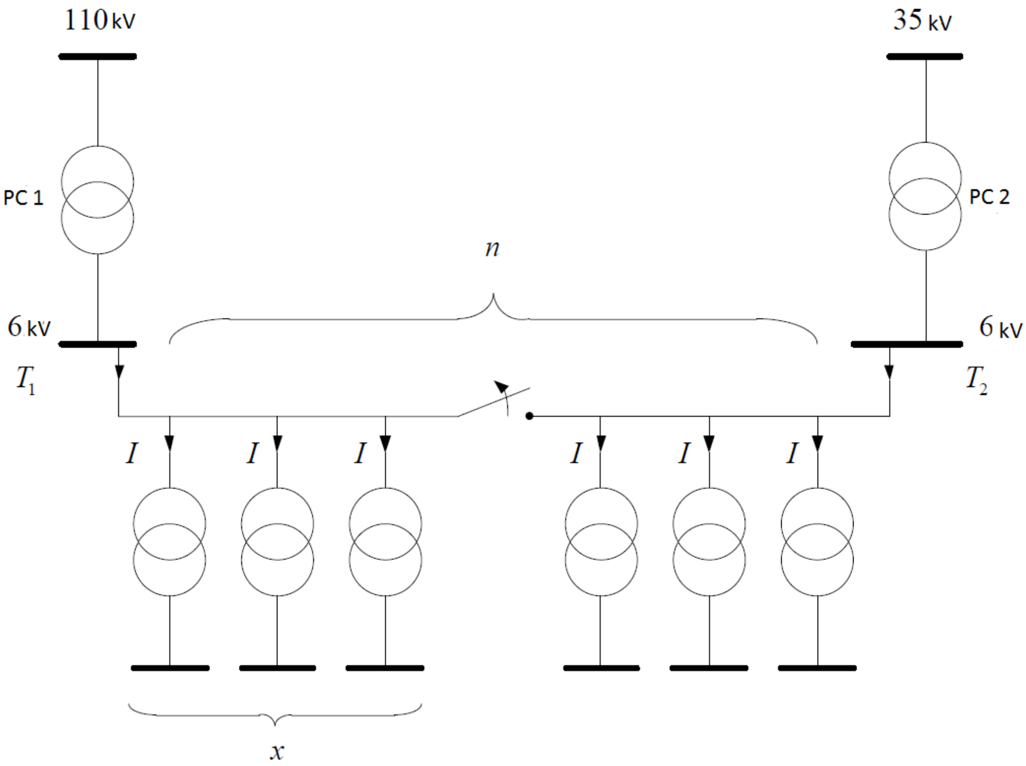


Figure 3.3 – An example of selecting the break point of a distribution network circuit

Generally, in low, medium and high voltage networks of power supply systems, there are opportunities for working on different schemes. At low voltage, switching in the circuit is possible, leading to a change in the power source, for example, from another TS. At a high voltage, substations of 110 kV can, as a result of switching, receive power over another line or network circuit, etc. Among this set of modes, it is possible to determine more or less optimal modes in terms of the level of losses. Their analysis is carried out using appropriate mathematical models.

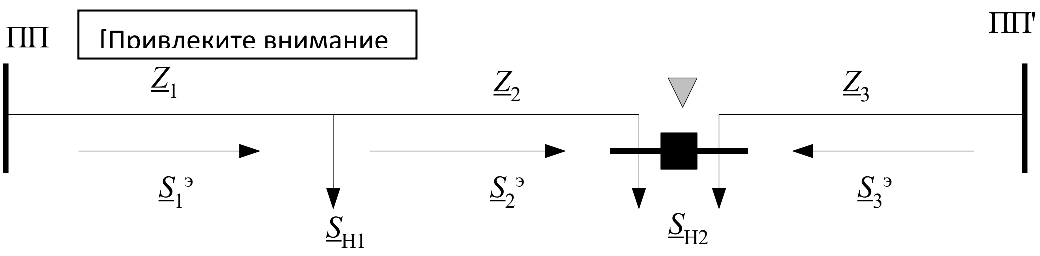


Figure 3.4 – Opening the line with two-way power

Another simplest measure from this group is the inclusion of redundant power lines under load. If the length and cross-section of the wires of the main and backup overhead lines are equal, due to their parallel operation when turned on at the same load, the losses will decrease by almost 2 times.

Voltage regulation in the power centers of networks of power supply systems, ensuring minimal loss of electricity

The measure is traditionally used in distribution networks (urban, industrial and rural power supply systems), made according to the radial principle. These are 6-20, 35 kV networks and part of 110 kV networks. Their power centers (PCs) are respectively substations of 500-35 / 6-20 kV, 500-110 / 35 kV and 500-220 / 110 kV (Figure 3.4). The criterion for regulating the voltage in the PC (if transformers with on-load tap changers are installed in the PC) or the installation of working branches of the transformers (if the latter are with PBB) is the *minimum power loss in the network with allowable voltage deviations from consumers*. The voltage regulation in the PC of the 6-20 kV network is carried out so that the voltage is maximum during heavy loads and minimum during small loads. Such regulation is called counter. An example is shown in Figure 3.5

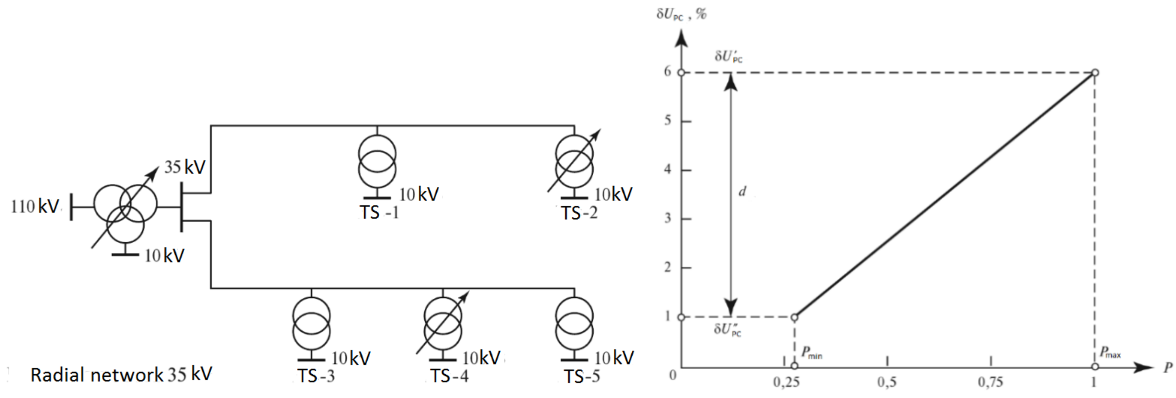


Figure 3.5 – Diagram of a 35 kV radial network and the required law of voltage regulation on the buses 6 - 10 kV of its substations [3.8]

The problem arises of finding the optimal mode in the permissible region of their existence, satisfying the conditions of voltage regulation, but differing in its parameters and magnitude of power losses. To solve it, a mode optimization program or a simple enumeration of obvious options can be used. A detailed description of the measures and the calculation of the effect of their application is given in [3.7,3.9,3.15].

It is recommended that transformers with on-load tap changers be installed in the PC, but in their absence, the selection of branching of the off-load tap changers is made at least twice a year for characteristic (seasonal) changes in loads, for each of them its efficiency is calculated separately.

Energy efficient transformer operation

At the voltage level of 10(6)/0.4 kV, in networks made mainly by cable lines (which is typical for industrial and modern urban power supply systems), no-load (XX) transformers prevail in the overall loss structure and their reduction is of paramount importance. When the transformer is fully loaded or overloaded, the load losses are greater than the XX losses, and vice versa, in the underload modes, the XX losses exceed the load losses. For substations with the same type of transformers of the same power with a load factor $k_з$:

1. When the load increases, connecting the (n + 1)-th transformer is advisable when:

$$k_З \geq \sqrt{\frac{n+1}{n}} \cdot \sqrt{\frac{\Delta P_{ХХ} + k_Э \cdot \Delta Q_{ХХ}}{\Delta P_{КЗ} + k_Э \cdot \Delta Q_{КЗ}}} \quad (3.1)$$

2. When reducing the load, it is advisable to turn off one of the transformers when:

$$k_З \geq \sqrt{\frac{n-1}{n}} \cdot \sqrt{\frac{\Delta P_{ХХ} + k_Э \cdot \Delta Q_{ХХ}}{\Delta P_{КЗ} + k_Э \cdot \Delta Q_{КЗ}}} \quad (3.2)$$

where n is the number of transformers turned on, ΔPxx are the passport idle losses of the transformer, kW; ΔPкз - passport losses of short circuit of the transformer, kW; $\Delta Q_{xx} = S_н \frac{I_{xx}}{100}$ - reactive idling power of the transformer, kVar; $\Delta Q_{кз} = S_н \frac{U_{кз}}{100}$ – short-circuit reactive power, kVar; Sн - rated power of the transformer, kV · A; Uкз - short circuit voltage,%; Ixx - open circuit current,%; $k_э$ - loss factor, kW / kVAr (table 3.5).

$$\Delta P = n \cdot (\Delta P_{xx} + k_э \cdot \Delta Q_{xx})$$

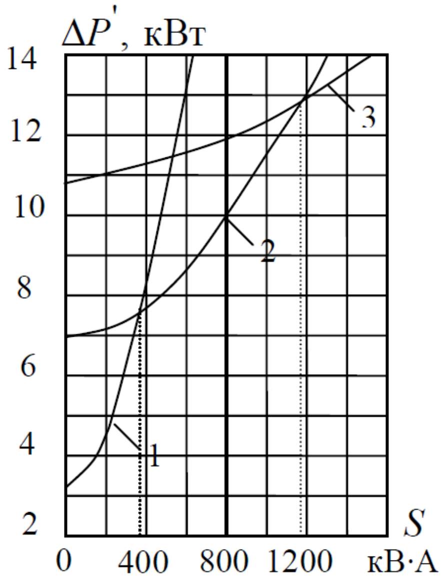
If the transformers at the substation have different rated power, the curves of the dependence of the total power losses as a function of their load are built by the equation:

$$\sum \Delta P = n \cdot (\Delta P_{ХХ} + k_Э \cdot \Delta Q_{ХХ}) + \frac{1}{n} (\Delta P_{КЗ} + k_Э \cdot \Delta Q_{КЗ}) \cdot k_З^2 \quad (3.3)$$

Table 3.5 – $k_э$ values depending on the installation location of transformers [3.11].

№	Characteristics of a transformer and power supply system	$k_э$, kW/kVar	
		During ES max load hours	During ES min load hours
1	Transformers powered directly from ES buses	0,02	0,02
2	Mains transformers powered by power supply ES	0,07	0,04
3	110/35/10 kV step-down transformers powered by district networks	0,1	0,06
4	Step-down transformers 10-6/0,4kV, powered by district networks	0,15	0,1

Example: Three identical transformers with a capacity of 630 kVA each are installed at the substation. From the graphs of the reduced losses (Figure 3.5), we determine the optimal mode of their operation.



1 - isolated operation of the transformer 630 kV · A;

2 - parallel operation of two transformers 630 kV · A;

3 - parallel operation of three transformers 630 kV · A.

Figure 3.5 - Given losses determine the economically feasible mode of operation of transformers 630 kV·A, 10 kV

- at loads from 0 to 380 kV·A, turn on one of the transformers;

- when the load increases from 380 to 1180 kV·A, connect a second transformer;

- at loads of more than 1180 kV·A, parallel operation of all transformers is advisable.

In rural electric networks, the main part of 10/0.4 kV transformer substations are single-transformer and this approach is not applicable. But they can meet seasonal loads: various mines, recreation camps, gardening societies that work only in the summer. For the remainder of the year, their transformers may be disconnected.

Loss reduction allows the exchange of overloaded and underloaded transformers. Due to the high cost, the purchase of new, energy-efficient transformers may not give the desired economic effect, then, in the presence of a large fleet of transformers, the most appropriate measure might be their exchange (especially triple or more) between several substations and, possibly replacing some of them with modern ones. Comprehensive reduction of losses in general for substations involved in the replacement of transformers can reduce the payback period of a new transformer.

The use of new, energy-efficient transformers, the main advantages of which are discussed in detail in the fourth section of this course, can generally make the above-mentioned measures meaningless due to the very low magnitude of the effect obtained, but they are justified in existing power supply systems before reconstruction.

Consolidation of the load schedule of consumers

Alignment of the load schedule of consumers also leads to a decrease in losses in the power supply system and is carried out by applying incentive measures to consumers that ensure that part of the load is transferred to the hours of nightly failure of the daily schedule and to reduce consumption during peak hours (in the morning and evening hours). The effect is positive for the power system as a whole. Until recently, the method was used for large industrial consumers, but with an increase in the level of intellectualization of networks, it is becoming increasingly promising for urban and agricultural power supply systems. Methods of this kind of stimulation are discussed in more detail in the fifth chapter of this course.

Reducing the loss of electrical energy from the implementation of this measure can be determined by the formula:

$$\delta W = \Delta W_{н}\left(1 - k_{ф2}^{2}/k_{ф1}^{2}\right) \tag{3.4}$$

where the indices 1 and 2 denote the coefficients of the shape of the graph before alignment and after it; ΔWn - load losses in the network with a coefficient of form $k_{ф1}$.

According to [3.7], taking into account that Tmax1 and Tmax2 are the number of hours of using the maximum load before alignment and after, we can write:

$$\frac{k_{ф2}^{2}}{k_{ф1}^{2}} = \left(\frac{1090/T_{max2} + 0{,}876}{1090/T_{max1} + 0{,}876}\right)^{2} \tag{3.5}$$

Phase load balancing in 0.4 kV networks

Electric networks of 0.4 kV are mainly three-phase, four-wire. The symmetric mode of such a network is the most optimal in terms of the magnitude of power and energy losses. Urban and rural networks contain a large number of single-phase EPs. At the design stage, they strive to distribute them evenly, but consumers turn on and off independently of each other, so the current phase loads differ in current and power factor. Over time, new EPs appear in subscribers and the level of asymmetry increases. The bulk of it is contributed by the load, and the proportion associated with the parameters of the elements of the power supply network itself is negligible.

According to the method of symmetrical components, asymmetric currents can be represented as the sum of the currents of the forward, reverse and zero sequences (Figure 3.6). A quantitative characteristic of the asymmetry level is the voltage asymmetry coefficients in the reverse and zero sequence.

There are systematic asymmetries in which the average values of the loads in different phases and the probabilistic or random, caused by intermittent, changes in the loads caused by random factors (intermittent load) are not the same. Systematic asymmetry is more characteristic of urban and rural electricity supply networks and can be reduced by periodic (1-2 times per year) redistribution of loads between phases. Probabilistic is typical for industrial consumers (arc welding, metal smelting) and is eliminated by special high-speed devices based on semiconductor converters. Their installation relates to technical measures to reduce losses.

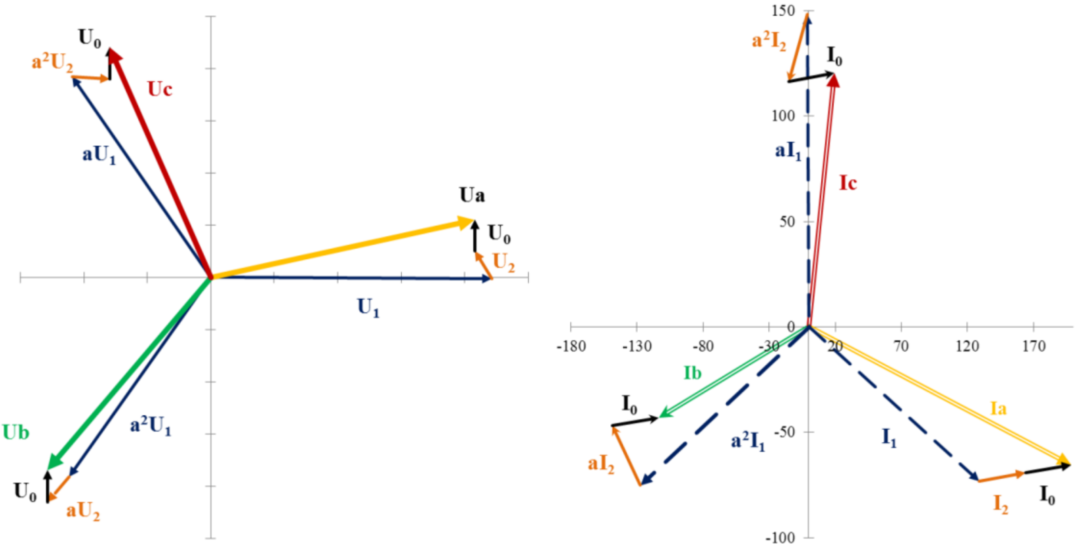


Figure 3.6 - An example of the application of the method of symmetrical components for voltages and currents of phases A, B, C [3.14]

To evaluate the level of reduction of electricity losses due to this measure in a specific 0.4 kV network according to [3.7], you can use the formula:

$$\delta W = 0{,}7\frac{W}{100}k_{\tau 1}\left(k_{\text{Нер1}}\Delta U_{max1} - k_{\text{Нер2}}\Delta U_{max2}\right) \tag{3.6}$$

where $k_{\text{Нер1}}$ and $k_{\text{Нер2}}$ are the unevenness coefficients for the initial phase load distribution and their distribution after leveling; ΔU_{max1} and ΔU_{max2} - voltage losses in the network,%, before load balancing and after; *W* - supply of electricity to the network.

Coefficients of unevenness can be determined by the formula:

$$k_{\text{Нер}} = 3\frac{I_A^2 + I_B^2 + I_C^2}{(I_A + I_B + I_C)^2}\left(1 + 1{,}5\frac{R_N}{R_\Phi}\right) + 1{,}5\frac{R_N}{R_\Phi} \tag{3.7}$$

where Ia, Ib, Ic are the measured current loads of the phases; R_N/R_Φ - the ratio of the resistances of the zero and phase wires

3.3.2 Optimization measures in the design (reconstruction) of the power supply system

The main objective of such events is to ensure the necessary quality of electricity and the level of reliability of power supply to consumers in new construction and during renovations. Loss reduction is a concomitant effect in them.

Placement of transformer substations providing power supply to consumers in electric load centers

When designing power supply systems, the important issue is the optimal location of the power source of electricity consumers. The same question arises during the reconstruction of existing networks, if the possibility of moving power centers, for example, workshop power substations, is considered. The most optimal location of the power source (main step-down substation, central substation, workshop substations, etc.) from the point of view of minimum technical and economic costs is the point at which the center of electrical loads is located [3.12].

The center of electrical loads (ELC) is the point at which the dispersion indicators of electricity consumers in the power supply system are of the least importance.

The task of choosing the location of substations has to be addressed at various levels of the power supply system. The location of the load in a particular territory, city, agricultural region, industrial enterprise at each level is judged by a special plan - *a cartogram of loads.* Their analysis is carried out by various methods, we consider the most popular of them - *the center of mass method.*

The degree of intensity of the load distribution of consumers is presented in circles. Their centers are the coordinates of the locations of electricity consumers, and the radius of the circle characterizes the estimated power of the electricity consumer. The coordinates of the center of mass of the resulting "circle" determine the optimal location of the substation. Each circle can be divided into sectors corresponding to different types of load, for example, power and lighting load. Sometimes loads up to and above 1 kV are shared. All this gives an idea of their structure. An example of a cartogram of active loads for the territory of an industrial enterprise is shown in Figure 3.7.

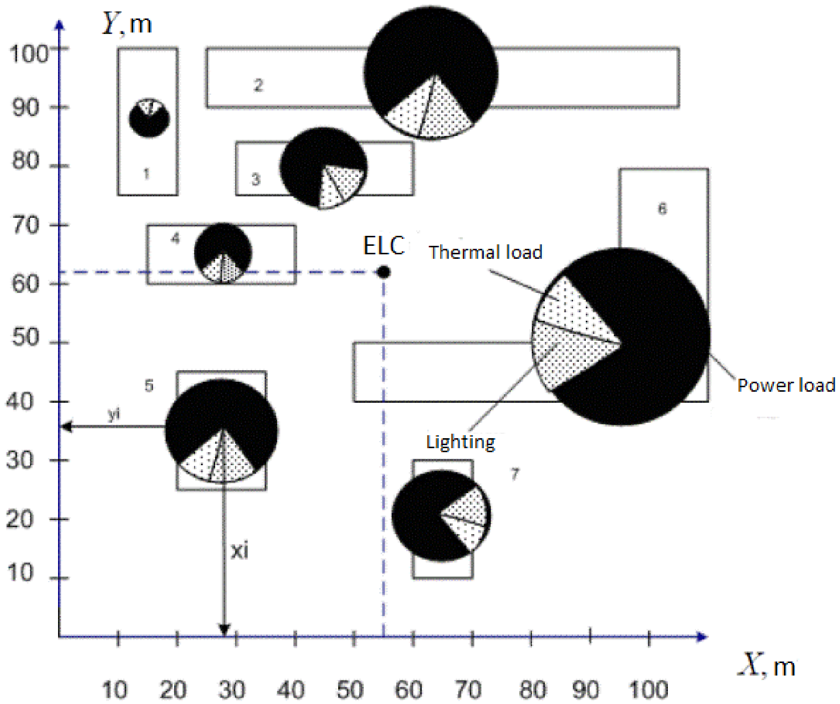


Figure 3.7 – Cartogram of the active loads of the shops of the enterprise (1-7) on its plan

The initial data for the calculations are: a coordinate system tied to a plan of the territory; location coordinates of consumers; the total power of the consumer; the value of the consumer power factor (or the value of the active and reactive power of the consumer); sometimes - the category of the consumer and the daily schedule of his load. The coordinates of the center for placing the power source of the next level of the power supply system can be determined by the formulas:

$$x_0 = \frac{\sum P_i x_i}{\sum P_i} \; ; \; y_0 = \frac{\sum P_i y_i}{\sum P_i} \qquad (3.11)$$

where P_i is the active load of the i-th consumer; x_i and y_i - coordinates of the location of the consumer on the plan of the enterprise or workshop.

If there are multi-storey buildings and the location of power receivers at various elevations, you can enter the third coordinate [3.13].

The method is simple, visual, easily implemented on a computer. The calculation error does not exceed 5-10% and is determined by the accuracy of the source data, but in the general case it does not provide a minimum of the reduced network costs. CEN is defined as a certain constant point on the territory plan, but in reality it is shifted due to changes in the consumption power according to the load schedule (at the design stage it is known approximately, but at the operation stage it constantly changes), shift and other socio-economic conditions, development of the territory. Therefore, a real CEN describes in time on the territory plan a complex shape figure and it would be more correct to talk about a certain scattering zone. To account for this, additional adjustments are made to the method. In a similar way, the placement of reactive power compensation devices can be optimized, for which reactive load cartograms are separately constructed.

Converting networks to a higher voltage

The magnitude of the active power losses in the distribution network in a first approximation depends on the square of the network voltage. When designing new facilities, the nominal voltage levels of the power supply system affect the structure of this entire system, therefore, their selection is made simultaneously with the choice of power supply scheme. The problem is solved on the basis of a feasibility study, taking into account the consumption of the object, its remoteness from the power source, source voltage, quantity and unit power of high voltage power consumers, etc. Even with small economic advantages (5-10%) of the low voltage option, preference should be given to a higher one. The high voltage source is brought as close as possible to the CEN. In a situation when the load of the networks has reached the limit values for the existing nominal voltage and an increase in their throughput is required, consider the possibility of transferring the network to a higher level of rated voltage. This is one of the most effective, but also expensive events. Structurally, it is associated with an increase in the level of phase isolation, an increase in interphase distances, possibly, replacement of wires and reconstruction of substations of the power supply system [3.16]. Reducing energy losses can be significant, but this is a concomitant effect.

Example: Suppose that on a section of a network line of rated voltage Unom1 = 35 kV with phase wire resistance $r_{ф}$= 1 Ohm, the power $S_{НГ}$ = 20 MV · A is transferred to the load. Let us determine how the losses of active power will decrease after the network is switched over to the rated voltage Unom2 = 110 kV while maintaining the cross-section of the conductors.

1. Power losses at a voltage of 35 kV will be:

$$\Delta P_1 = {S_{НГ}}^2 \cdot \frac{r_{ф}}{U_{ном1}^2} = (20 \cdot 10^6)^2 \cdot \frac{1}{(35 \cdot 10^3)^2} = 326 \text{ кВт}$$

2. Power losses at a voltage of 110 кВ will be:

$$\Delta P_2 = {S_{НГ}}^2 \cdot \frac{r_{ф}}{U_{ном2}^2} = (20 \cdot 10^6)^2 \cdot \frac{1}{(110 \cdot 10^3)^2} = 33 \text{ кВт}$$

In the given example, network losses decreased almost 10 times.

In general, energy savings in a network section when translating it to a higher voltage class are determined by the formula, kW · h:

$$\Delta Э = 0{,}003 \cdot \rho \cdot L \cdot t \cdot \left(\frac{I_1^2}{F_1} - \frac{I_2^2}{F_2}\right) \quad (3.12)$$

where L is the length of the network section on which the nominal voltage is increased, m; I is the average value of currents in each wire of the network, respectively, at lower and higher voltage, A; p is the resistivity of the wire material at 2000 ° C; F_1 and F_2 - section of the network wires at the lower and higher voltage, mm^2 (when carrying out activities without replacing the wires $F_1 = F_2$); t is the estimated time period, h

This approach is especially relevant for urban electricity networks. In areas of new urban development, a voltage of 10 kV is mainly used. The main advantage of a voltage of 10 kV over 6 kV is a higher line capacity with almost the same design. Practice has shown the possibility of successful operation of cable and overhead lines, current transformers, insulators and switching equipment with a voltage of 6 kV in a network of 10 kV. Therefore, the existing 6 kV network (more than 60% of the entire city network) is gradually transferred to a voltage of 10 kV. Such work usually lasts several years and includes the following stages: engineering support; preparatory work; direct transfer of the network from 6 kV to 10 kV; the initial period of operation of the network, converted to a voltage of 10 kV.

Disaggregation of distribution lines 0.4-35 kV

The disaggregation of low and medium voltage power lines can reduce the length of the lines and thereby reduce losses in the transmission of electricity, improve the reliability and quality of power supply to consumers. The essence of the method is to build a branched network of 0.4 - 35 kV with small feeder lengths for networks with a fixed load distributed across the territory due to the reconstruction of existing long, overloaded feeders with appropriate load redistribution [3.10].

Reducing the loss of electrical energy here is also a concomitant effect, however, it can be quite large. Example: on the head section of the line, lay the second circuit and transfer one of the nearest branches from the highway to a new line. When transferring half the load to a parallel circuit with the same wire, the losses in the reconstructed section of the line are reduced by almost 2 times [3.16].

The use of new energy-saving equipment in electrical networks of power supply systems

Cost-effective operation of power supply systems is impossible without the use of modern equipment. Its nomenclature is widely represented in the market of electrical products and its use is limited only by its high cost. Replacing obsolete equipment is an expensive undertaking and is carried out when physical wear and tear and the need to increase the network bandwidth determine the need for its reconstruction. Reducing the loss of electrical energy is a concomitant effect. Let's look at a few examples.

Use of self-supporting insulated wires (SIW) on low voltage lines and protected wires on medium voltage lines

SIW are used at voltages less than 1 kV, the so-called lines with insulated wires. Insulated wires at voltages above 1 kV (6-35 kV), including wires of the SIW-3 brand, are lines with protected wires .

The effect of the use of SIW to a small extent directly affects electrical losses and consists of the following components: a sharp decrease (up to 80%) in operating costs; reduction of voltage losses in the line; a significant reduction in unauthorized line connections. These factors reduce operating costs, prevent theft of electrical energy and reduce the loss of electrical energy.

For some overhead transmission lines of 10 (6) -35 kV, sheathed wires with NEXANS brand cross-linked polyethylene insulation are used, as well as insulated wires of foreign and domestic production SIW -3, ZALP, PZV, PAS, SAX. The advantages of overhead lines with protected wires are associated with a significant reduction in operating costs and voltage losses, as well as a small decrease in electric energy losses as a result.

Use of cables with cross-linked polyethylene insulation (XLPE insulation)

Although the loss of electrical energy in insulation of such cables is several times lower than conventional cables with paper-oil insulation (POI), their total share in the loss structure is relatively small and the effect of use is due to other indicators, a more complete comparison of which for cables made of crossed linked polyethylene and POI are given in table 3.6:

Table 3.6 – Comparison of parameters XLPE and POI cables [3.17]

Parameter Name	The relative value of the parameter The relative efficiency of the parameter			The relative value of the parameter The relative efficiency of the parameter		
	Three-core cable for voltage 10 kV					
	POI type		CLP type	POI type		CLP type
	ABB	TsASB	APvP	ABB	TsASB	APvP
Minimum cost of building and operating cable lines	1,0	1,0	1,3/1,06	1,0	1,0	0,77/0,943
Maximum reliability ¬ work (MTBF)	1,0	1,0	10,0	0,1	0,1	1,0
Minimal impact on the environment	1,0	1,0	0,5	0,5	0,5	1,0

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Test questions

How often, according to Federal Law No. 261, an organization (enterprise) should conduct an energy audit:

- annually
- once every five years
- once every ten years
- as needed
- once every seven years

Calibration of electric energy meters is conducted:

- annually
- after 2 years
- after 3 years
- after 10 years

An energy survey does not include:

- verification of the design documentation;
- preparation of an energy passport;
- collection and processing of information on the use of energy resources in order to obtain reliable information about the amount of energy resources used;
- calculation of energy efficiency indicator.

What is the minimum amount an organization should consume energy resources to be subject to a mandatory energy audit?

- 1 million rubles;
- 10 million rubles;
- 50 million rubles;
- 100 million rubles.

A survey of consumers of fuel and energy resources in order to establish indicators of the effectiveness of their use and the development of economically sound measures to increase them is called

- energy marketing;
- power plant;
- energy audit;
- efficient use of energy resources.

What is energy saving potential?

- the amount of energy savings after the implementation of the recommended energy-saving measures;
- the difference in energy consumption real and in the transition to an energy-efficient building;
- the difference in energy consumption is real and in the transition to the standards established in the city.

Who is responsible for the implementation and implementation of the energy management system at the enterprise?

- deputy Head of Energy Management Enterprise
- Chief Power Engineer
- head of enterprise
- a working group of service specialists: energy, technological, financial and labor protection

Which standard is the international standard for energy management?

- ISO 9001
- ISO 50001
- ISO 18001
- ISO 14001
- ISO 28000

What are the main stages of certification of an enterprise for compliance with ISO 50001?

- preliminary audit, development and implementation of the system, performance of internal audits, certification audit
- assessment audit, planning, system development, system implementation.
- creation of a set of regulatory documents, creation of a technical base, information support for activities.
- planning, development and implementation, the creation of a separate unit.

The level of losses in the distribution overhead line with a rated voltage of 10 kV, which feeds the active-inductive load from the power center with constant line and load parameters, will be minimal when:

- at rated voltage in the power center
- at a voltage in the power center 5% higher than the nominal
- at a voltage in the power center 5% lower than the nominal

The minimum losses of active power in a closed distribution network correspond to a mode in which:

- power distribution along the branches in proportion to their active resistances
- power distribution along the branches in proportion to their inductive resistances
- power distribution along the branches in proportion to their impedances

The main reason for switching power supply systems to high voltage is:

- consumer use at a higher voltage level
- power reduction of reactive power compensation devices
- increasing the capacity of the lines of the power supply system

When the transformer is fully loaded or overloaded, load losses in the transformer:

- higher transformer idle losses
- lower transformer idle losses
- equal to transformer idle losses

Causes of asymmetry in 0.4 kV networks:

- a large number of single-phase power consumers
- the presence of balancing devices
- a large number of reactive power compensation devices

Types of asymmetry in 0.4 kV networks:

- probabilistic asymmetry
- systematic asymmetry
- transposition asymmetry
- all of the above

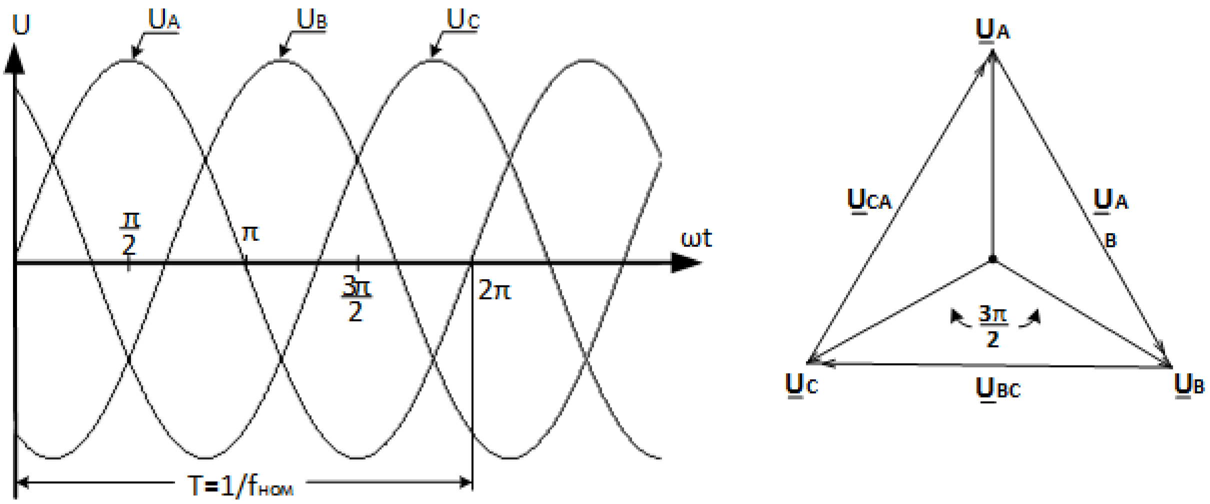
Why is a cartogram of the active loads of an industrial enterprise built?

- to determine the optimal locations for power supplies
- to determine the value of the total load of the enterprise
- to select locations for reactive power compensation devices

4 Technical measures in the field of energy conservation in power supply systems

4.1 Ensuring the quality of electricity in power supply systems

Electricity, like any product, has quality. Power supply systems, as a rule, receive electricity from a power supply organization using a three-phase voltage system. Ideally, electricity should be supplied to the power receiver under the following conditions. The frequency of the current should be equal to the nominal value: in the Russian Federation and the European Union it is 50 Hz. Phase and linear voltages are equal to the nominal values and change according to a sinusoidal law (Figure 4.1 a), and their vectors respectively have a shift of 3π / 2 (120°) (Figure 4.1b).



а) б)

Figure 4.1 – Graph of instantaneous values of phase voltages (a) and vector diagram of voltages (b) of a three-phase symmetric system at fnom = 50Hz

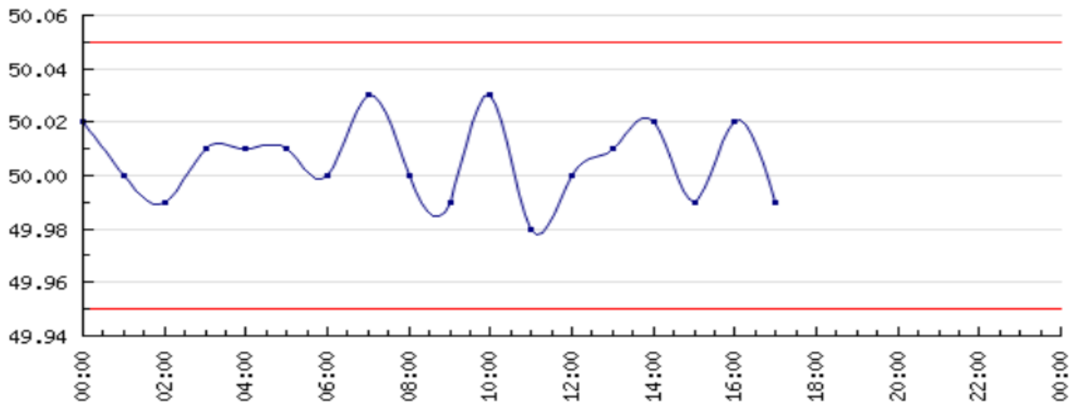
Moreover, in all operating modes, the operation of the power receiver is ensured. In reality, there is a deviation from the above indicators of the quality of electricity at the point of connection of the power receiver to the electric network. It is obvious that the energy supplying organization cannot guarantee the ideal parameters of electric energy during the operation of the power receiver. Therefore, there are international, national standards for permissible deviations of the quality parameters of electric energy. The scientific and practical aspects of the development of international EMC standards are addressed by: technical committee No. 77 “Electromagnetic compatibility of equipment, including electrical networks”, International Electrotechnical Commission (IEC); European Commission Technical Committee TK11O (EMC) (CENELEC), the results of which form the basis of international, European and national standards for electricity quality. In Russia, GOST 32144-2013 is in force, which regulates electric power quality indicators and permissible deviations [4.1] in power supply systems, and the EN50160 standard [4.2] in the European Union. Table 4.1 shows the main indicators of the quality of electricity in force in the Russian Federation and the European Union.

Table 4.1 – Main indicators of the quality of electricity in Russia and the EU

Indicator	ГОСТ 32144-2013 (State Standard)	EN 50160:2010
Frequencies deviation	In synchronous systems: ± 0.2 Hz (95% of the time of the week) ± 0.4 Hz (100% of the time of the week) In isolated systems: ± 1 Hz (95% of the time of the week) ± 5 Hz (100% of the time of the week)	In synchronous systems: ± 1% (99.5% of the season) + 4 / - 6% (100% of the time) In isolated systems: ± 2% (99.5% of the time of the week) ± 15% (100% of the time)
Voltage deviation	Positive - no more than 10% Negative - no more than 10%	In synchronous systems: ± 10% In isolated systems: + 10 / -15%
Coefficient of voltage non-sinusoidality	no more than 8% (Unom = 0.38 kV) no more than 5% (Unom = 6-25 kV) no more than 4% (Unom = 35 kV)	no more than 8% (Unom = 0.38-35 kV)
Asymmetry coefficient	reverse and zero sequence no more than 2% (95% of the time of the week) no more than 4% (100% of the time of the week)	no more than 2% of the direct sequence component
Voltage fluctuations	Short-term flicker dose (Pst) not more than 1.38 continuous (Plt) no more	Long Flicker Dose (Plt) no more than 1 (95% of the time)

It should be noted that the manufacturer guarantees the operation of the power receiver, provided that the power indicators do not go beyond the acceptable values (table 4.1). However, even when these requirements are met, significant losses of electricity occur, and the energy performance of the power receiver deteriorates from a decrease in the quality of electricity in power supply systems. Next, we consider the main indicators of the quality of electricity for power supply systems, and their impact on the loss and performance of power receivers, and ways to ensure the quality of electricity in power supply systems.

Network frequency. This indicator is a system-wide, regulated by the system operator. In view of the large installation capacities of the energy associations of the Russian Federation and the European Union, the frequency change in the energy associations is very insignificant (Figure 4.2)



http://so-ups.ru/

Figure 4.2 – Graph of current frequency change at on 01.01.2020 in IPS/UPS interconnection

Deviations (slow changes) of voltage regulated by the value of negative δU (-) and positive δU (+) voltage deviation from the nominal value (4.1, 4.2).

$$\delta U_{(-)} = [(U_{nom} - U_{(-)}) / U_{nom}] \cdot 100\% \quad (4.1)$$

$$\delta U_{(+)} = [(U_{(+)} - U_{nom}) / U_{nom}] \cdot 100\% \quad (4.2)$$

$U_{(-)}$, $U_{(+)}$ – power supply voltage values, smaller and larger thatypo Unom, respectively;
Unom – voltage equal to the standard rated voltage Unom.

Consider the effect of voltage deviations on the characteristics of an induction motor, consuming more than half of all the electricity generated in the world. So, developed on the shaft of an induction motor, the electromagnetic moment (M) is in a quadratic dependence on the input voltage (Fig. 4.3)

$$\mathrm{M} = \frac{pm_1 \cdot \frac{r_2'}{S}}{\omega_1 \left[\left(r_1 + c_1 \frac{r_2'}{S} \right)^2 + (x_1 + c_1 x_2')^2 \right]} \cdot U^2, \qquad s = \frac{\omega_1 - \omega_2}{\omega_1}, \quad (4.3)$$

where r_1, r_2', x_1, x_2' are the parameters of the equivalent circuit; m1 is the number of phases; s - slip, ω_1, ω_2 – respectively, the rotation speed of the electromagnetic field of the machine and the rotor.

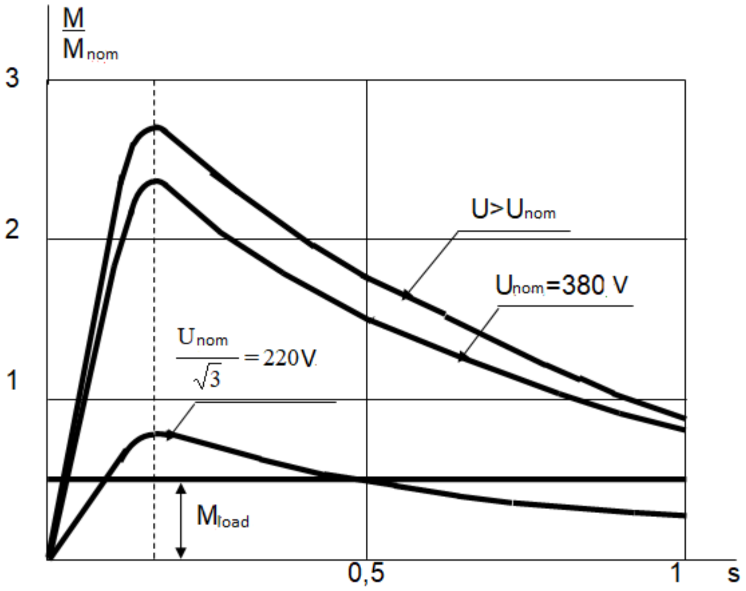


Figure 4.3 – Mechanical characteristic of an induction motor

When the voltage decreases, but while maintaining the load moment unchanged (Loads, Fig. 4.3): the current consumed from the network increases; efficiency, (cos φ_1) decreases; sharply reduced stock asynchronous motor stability. With increasing voltage, the no-load current increases, losses in steel, the efficiency and cos φ_1 decrease. As a result, losses in the power supply system increase [4.3].

The deviation of the supply voltage at the terminals of electrical energy receivers in excess of the established norms is mainly due to the voltage drop in the power line from the receiver (s) to the point in the power system where the load will not have such a noticeable effect that it is satisfied under condition 4.4.

$$S_{кз} \gg S_n, \tag{4.4}$$

where S_n is the load power; $S_{кз}$ – short circuit power at that point in the power system to which the general-purpose system is connected.

$$S_{кз} \gg \frac{U_н^2}{Z_{кз}}, \tag{4.5}$$

where $Z_{кз}$ is the resistance to a point in the power system, where the power of the power system is infinitely large compared to S_n.

Using the simplest electric circuit as an example (Figure 4.4a), we consider the main factors affecting the change in voltage (U_2) at the terminals of an electric power receiver. The voltage at the terminals of the receiver can be determined by 4.6.

$$\underline{U_2} = \underline{U_1} - \left[\frac{P_n r_{12} + Q_n x_{12}}{U_{ном}} + j\frac{P_n x_{12} + Q_n x_{12}}{U_{ном}}\right], \tag{4.6}$$

where r_{12} and x_{12} are the active and inductive resistances of the electric circuit, respectively.

It should be noted that the inductive resistance of the power supply system, which includes power step-down transformers, is significantly higher than the active resistance. Next, using the equivalent circuit, we construct vector diagrams for two cases:

1) $S_н=P_н+jQ_н$ (Fig. 4.4б);

2) $S_н=P_н+j(Q_н-Q_{КУ})=P_Н$,

when due to the full compensation of the reactive power of the load, the current I_{12} contains only the active component I_{2R} (Fig. 4.4 c).

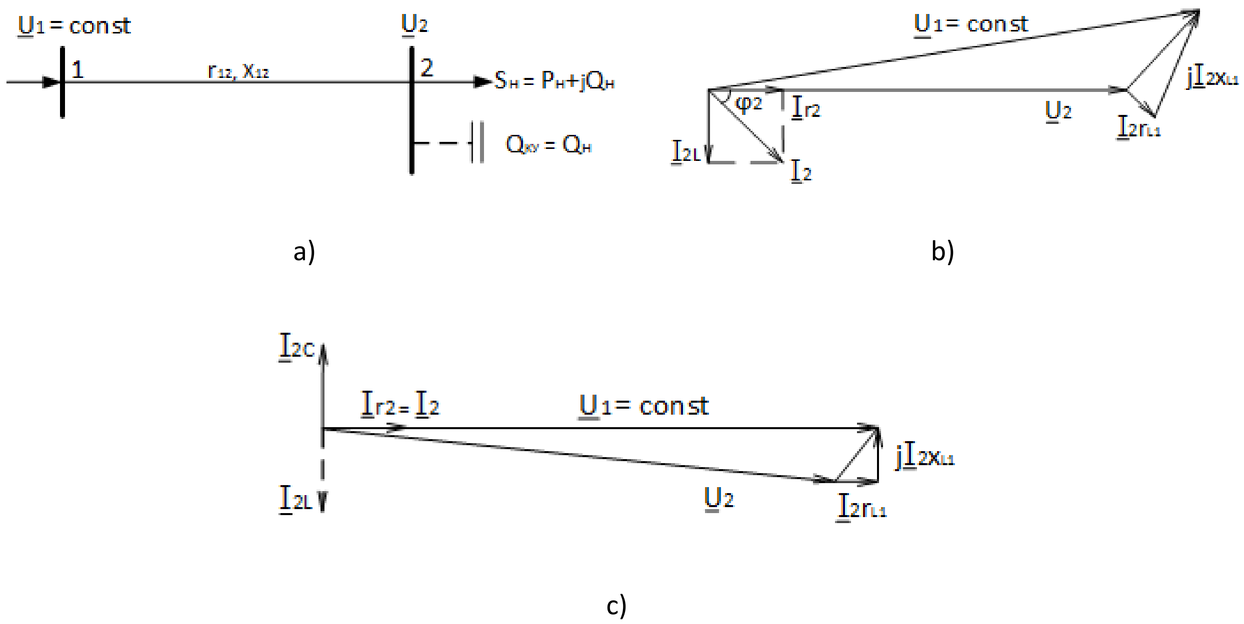


Figure 4.4 – The effect of reactive power compensation on the voltage level of the consumer

An analysis of the results shows that the reactive load of the electric power receiver QH and the inductive reactance of the line (especially air) and transformers (Fig. 3.4c) have a significant effect on the voltage deviation at the receiver. Application of transverse reactive power compensation (4.4 c); the use of short (mainly cable lines); connecting transformer substations to higher voltage networks, as well as voltage regulation are the main ways to reduce the deviation of the supply voltage at the client.

Non-sinusoidality of voltage. It is regulated by two indicators:

1. The coefficient of non-sinusoidality of the voltage curve (the value of the total coefficient of harmonic components of the voltage) K_U, % at the point of transmission of electrical energy (4.7).

$$K_U = \frac{\sqrt{\sum_{n=2}^{40}(U^2{}_{(n)})}}{U_{(1)}} \cdot 100\% \tag{4.7}$$

where $U_{(n)}$ is the amplitude value of the nth voltage harmonic; $U_{(1)}$ is the value of the amplitude of the 1st harmonic of the voltage.

2. Coefficients of harmonic voltage components $K_{U(n)}$ as a percentage of voltage of the main harmonic component $U_{(1)}$ at the point of transmission of electrical energy (4.8).

$$K_{U(n)} = \frac{U_{(n)}}{U_{(1)}} \cdot 100\% \tag{4.8}$$

The appearance of higher harmonics (SH) in electrical networks is mainly due to two reasons:

- non-sinusoidal voltage curve of the power source of the network in question,
- the presence of a nonlinear element in the network.

The level of higher harmonics emitted into the network by power sources, for example, synchronous generators, is insignificant and does not exceed 1.5% [4.4].

If there is a nonlinear element in the power supply system, it can be considered as a source of harmonics of the current to the supply network [4.5,4.6]. So, as an example, the composition of current harmonics (N) emitted into the supply network by a rectifier of an asynchronous electric drive with frequency regulation (Figure 4.5) is determined by expression 4.9. Since the rectifier in this scheme (figure 4.4) is six-phase, then 5, 7, 11, 13 and so on current harmonics are generated in the mains supply (table 1.1).

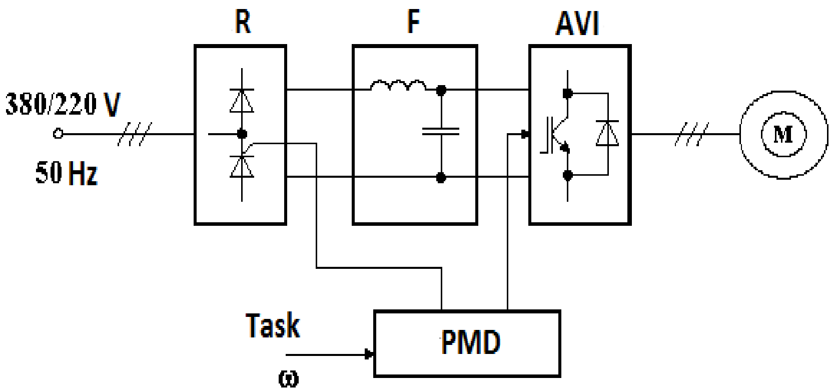


Fig 4.5 – Functional diagram of a variable frequency drive

$$N = 6 \cdot p \pm 1; \qquad I_n \approx I_1/N, \tag{4.9}$$

$p - 1,2 \ldots n$; I_1 и I_n – respectively, the first and N harmonics of the current.

As a result, at each point of the considered electric network, the voltage will be determined: by the voltage supplied from the supply network (network), and by the sum of the voltage drops from the entire spectrum of higher harmonics of the current emitted by nonlinear power receivers [4.5,4.6].

$$u = u_{\text{сети}} + \sum_{n=2}^{15} i_n \cdot z_n \tag{4.10}$$

z_n – harmonic resistance of the circuit at a frequency f_n.

The main forms of SH exposure to power supply systems are [4.5,4.6]:

1) decrease in the efficiency of transmission and use of electrical energy;
2) an increase in harmonics currents and voltages due to parallel and series resonances;
3) aging of insulation of electrical equipment and the reduction of its service life as a result;
4) false operation of equipment and others.

Ways to reduce the level of harmonics of current and voltage can be divided into three groups: a) regulatory; b) circuit and technological solutions; c) the use of filtering devices.

Regulatory measures. As the analysis of foreign regulatory documents on electromagnetic compatibility shows, tough measures are applied there directly to electrical equipment. These requirements are reflected in the standards for the permissible level of harmonics and other electromagnetic interference that generate electrical equipment manufactured by firms.

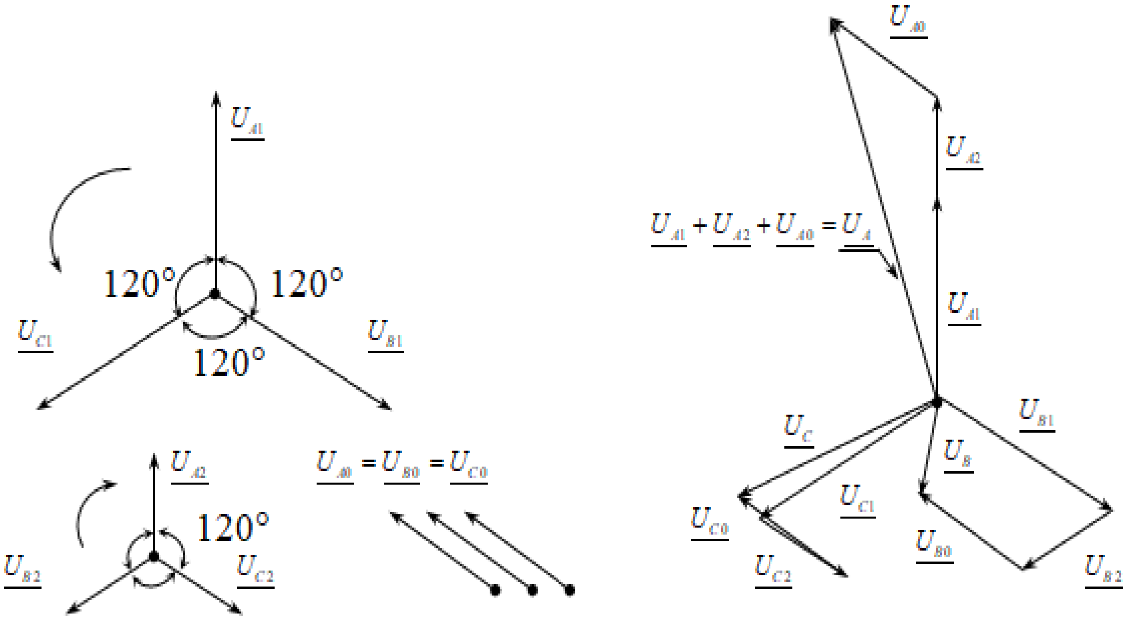
Technical system scheme solutions:

- allocation of non-linear loads on a separate bus system;
- increase in the phase state of semiconductor converters (Table 1.1). Currently, six-phase converters that generate a high level of VH current are mainly used; increasing the phase transducers to 12, and in some countries to 24 and 48 dramatically reduces the level of VH current;
- connecting a non-linear load to a system with a higher short-circuit power $\boldsymbol{S}_{кз}$.

Voltage asymmetry in three-phase systems [4.1]

The EU standard [4.2] proposes a different approach: **supply voltage imbalance supply voltage unbalance**. Regardless of the wording, the essence of this phenomenon does not change. The asymmetry of the three-phase voltage system is due to asymmetric loads of consumers of electric energy or asymmetry of the elements of the electrical network. As is known, any asymmetric voltage system, emf and currents decomposed into three symmetric systems: direct (U_1), reverse (U_2) and zero sequence (U_0).

$$\underline{U}_A=\underline{U}_{A1}+\underline{U}_{A2}+\underline{U}_{A0}; \quad \underline{U}_B=\underline{U}_{B1}+\underline{U}_{B2}+\underline{U}_{B0}; \quad \underline{U}_C=\underline{U}_{C1}+\underline{U}_{C2}+\underline{U}_{C0} \qquad (4.11)$$



Picture 4.6 – Symmetric components of three-phase voltages

It should be noted that in a symmetric three-phase system, only the direct sequence voltage takes place. Indicators of the quality of electricity related to voltage asymmetry in three-phase systems are: voltage asymmetry coefficient in the reverse sequence K_{U2} voltage asymmetry coefficient in the zero sequence K_{U0}, determined by the expressions.

$$K_{U2} = U_2/U_1 \cdot 100\%; \qquad (4.12)$$

$$U_{2(1)i} = \sqrt{\frac{1}{12}\left[\left(\sqrt{3}U_{AB(1)i} - \sqrt{4U^2_{BC(1)i} - \left(\frac{U^2_{BC(1)i} - U^2_{CA(1)i}}{U_{AB(1)i}}\right)^2}\right)^2 + \left(\frac{U^2_{BC(1)i} - U^2_{CA(1)i}}{U_{AB(1)i}}\right)\right]}$$

where U_2 is the effective voltage value of the reverse sequence of the fundamental frequency; U_1 – the effective value of the voltage of the direct sequence of the fundamental frequency.

$$K_{U0} = U_0/U_1 \cdot 100\%; \qquad (4.13)$$

$$U_{0(1)} = \frac{1}{6}\sqrt{\left[\frac{U^2_{CB(1)} - U^2_{AC(1)}}{U_{BA(1)}} - 3\frac{U^2_{B(1)} - U^2_{A(1)}}{U_{BA(1)}}\right]^2 +}$$

$$\overline{+\left[\sqrt{4U^2_{CB(1)} - \left(\frac{U^2_{CB(1)} - U^2_{AC(1)}}{U_{BA(1)}} + U_{BA(1)}\right)^2} - 3\sqrt{4U^2_{B(1)} - \left(\frac{U^2_{B(1)} - U^2_{A(1)}}{U_{BA(1)}} + U_{BA(1)}\right)^2}\right]},$$

where U_2 is the effective voltage value of the zero sequence of the fundamental frequency.

The negative sequence voltage has an extremely adverse effect on AC electric machines. This is due to the fact that AC machines have low resistance to the negative sequence Z_2.

$$Z_2 = r_2 + jx_2, \quad (4.14)$$

where r_2, x_2 are the active and inductive resistances of the reverse sequence, respectively.

Therefore, even with small values of the negative sequence voltage in the AC machines, significant negative sequence currents I_2 arise. These currents create a magnetic field in the air gap, rotating in the direction opposite to the rotation of the direct sequence field. In this case, in the windings of the rotor an emf and currents of double frequency, braking moments, noise. This leads to additional losses, the service life of electric machines is reduced. S_0, with K_{2U} within normal limits, the service life of asynchronous machines is reduced by 10.8%, synchronous machines by 16.2%; power capacitors by 20%, transformers by 4%.

The zero sequence voltage in networks with a grounded neutral determines the zero sequence current. These currents flow through grounding conductors and significantly dry the soil, increasing the resistance of the grounding devices. This is unacceptable in terms of relay protection.

Asymmetry-reducing factors:
1) equalization of phase loads in power supply systems at a voltage of 0.4 kV;
2) reducing the network resistance to currents of the reverse and zero sequences;
3) connection of unbalanced loads (S_n) to the node with a high value of $S_{\text{КЗ}}$.

At $\frac{S_{\text{КЗ}}}{S_{\text{н}}} \geq 50$ the coefficient of voltage unbalance in the reverse sequence does not exceed 2%. If asymmetry cannot be reduced, then balancing devices must be used.

An effective means of reducing the voltage of the zero sequence is the use of 6-35/0.4 kV transformers in the distribution networks with the group of connection of the triangle / star windings with a zero wire or a triangle / zigzag with a zero wire.

The EN5160 standard only evaluates the voltage of the negative sequence because this sequence [4.2].

Voltage fluctuations and flicker [4.1] (Quick changes (fluctuations) in voltage [4.2])

The source of voltage fluctuations in modern power supply systems are powerful power receivers, characterized by a pulsed, nonlinear and very variable nature of the consumption of active and reactive power. For such electrical receptors, the following is characteristic. Their power supply is usually carried out from busbars with voltage from 0.4 to 35 kV. During the work of these consumers, significant changes are observed in the active (0,1-1,3) P_{nom} consumed by them, and especially reactive power with a high speed during the day. In priority order according to the degree of impact on electric power quality indicators; these receivers can be positioned as follows: arc steel-smelting furnaces (chipboard); ore thermal furnaces; induction furnaces; resistance welding machines; converters of electrolysis plants; synchronous motors; drives of pumps and compressors in distribution networks. As a result, in power supply systems there is an increase in electricity losses, the reliability of power receivers. When the voltage fluctuates, the magnitude of its change δU_t is calculated by the formula 4.15

$$\delta U_t = \frac{|U_i - U_{i+1}|}{U_{ном}} 100\% , \quad (4.15)$$

where U_i, U_{i+1} are the values of the extrema that follow one after another and the horizontal section of the envelope of the rms values of the main frequency voltages determined on each half-period of the main frequency (Fig. 4.7).

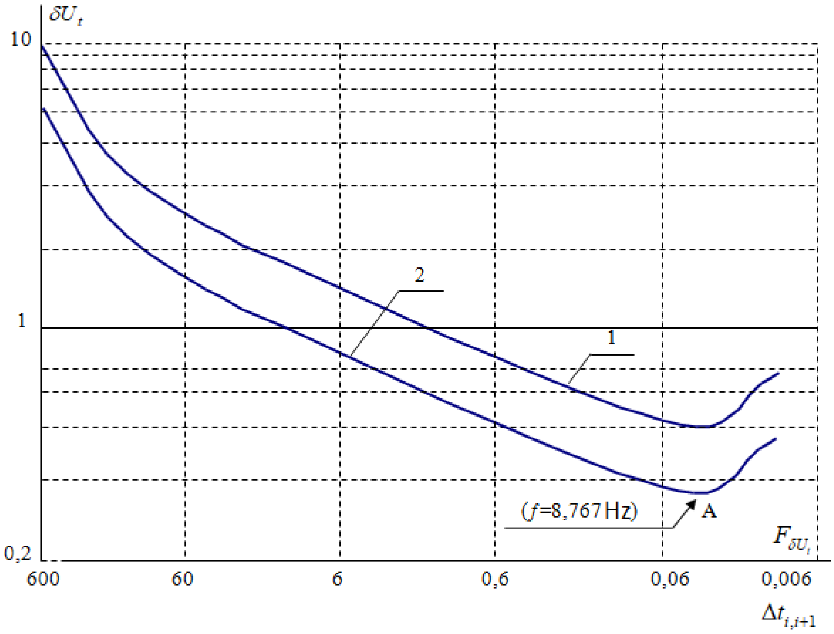


Figure 4.7 – The maximum allowable range of voltage changes depending on the frequency of oscillations $F_{\delta U_t}$ and $\Delta t_{i,i+1}$.

The frequency of repetition of voltage changes $F_{\delta Ut}$ (s^{-1}) during periodic voltage fluctuations is calculated by the equation 4.16.

$$F_{\delta U_t} = \frac{m}{T}, \tag{4.16}$$

where m is the number of voltage changes during time T.

For the load in the node of the power supply system, the range of voltage fluctuations can be determined by the:

$$\delta U_t \approx 10\frac{\Delta Q_H x_{K3}}{U_H^2} \approx 10\frac{\Delta Q_H}{S_{K3}}, \tag{4.17}$$

where ΔQ_H is the magnitude of the reactive power load.

In electrical systems, the propagation of voltage fluctuations occurs towards the low voltage busbars with virtually no attenuation, and toward the high voltage busbars with amplitude attenuation. Thus, arising at some point in the electric network and propagating through it, voltage fluctuations have a negative effect on consumers sensitive to them, mainly on lighting networks. Voltage fluctuations lead to fluctuations in the brightness of lighting devices (flicker). Voltage fluctuations lead to fluctuations in the brightness of lighting devices (flicker) [4.7]. It has been experimentally proved that fluctuations in the brightness of lighting devices cause unwanted effects on the human brain. The most unfavorable vibrations occurring at a frequency of 8.767 Hz, coinciding with the frequency of oscillations of nerve cells in the brain. Therefore, the value of the maximum allowable range of voltage measurements in the figure. 4.7

at this frequency is minimal. The technique for measuring the flicker dose using LED lamps was developed by the authors of [4.7].

To reduce voltage fluctuations, the following measures are recommended:

1) Load sharing. In this case, the oscillation source is connected to the network through a separate transformer, or to one of the transformer windings with a split winding, or through a dual reactor.

2) The use of a static thyristor compensator.

3) Connecting loads to the node of the power supply system with a high value of S_{K3}.

4.2 Reactive Power Compensation

In recent years, reactive power (RP) has been increasing in power supply systems. This is due to the fact that along with traditional consumers of RP: asynchronous electric motors, power transformers, power receivers use electric receivers based on new energy-saving technologies. Next, we consider the RP consumed by the largest group of power consumers: asynchronous electric drives, lighting devices, transformers.

The reactive power consumed by asynchronous electric drives under various operating conditions can be calculated taking into account the operating characteristics of an asynchronous electric motor (Fig. 4.8) using expression (4.18) or based on catalog data [4.8,4.9].

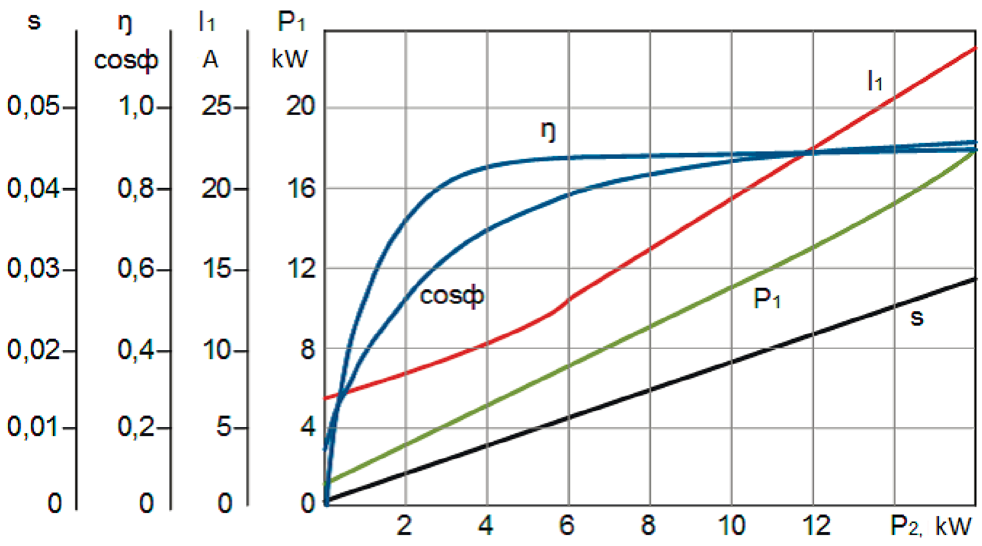


Figure 4.8 – Performance of an induction motor

$$Q_1 = \frac{K_з \cdot P_{2н}}{\eta_1} \cdot cos_{\varphi}, \quad (4.18)$$

where Q_1 –consumed by the PM induction motor at a given load factor $K_з$and efficiency η_1.

The calculation of reactive power according to the catalog data is carried out taking into account the refined equivalent circuit of the asynchronous machine according to the expressions [4.19 and 4.20].

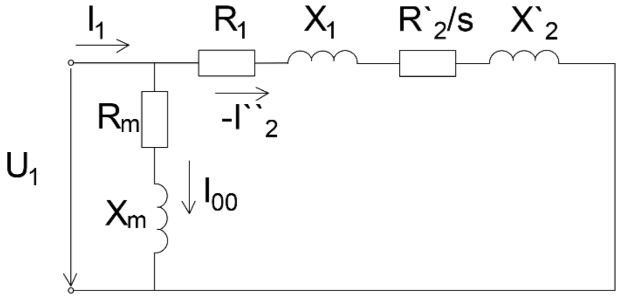


Figure 4.8 – Refined electrical equivalent circuit of an asynchronous machine

$$\dot{I}_{00} = \frac{\dot{U}_1}{R_m + jX_m} = const \quad (4.19)$$

$$-\dot{I}_2'' = \frac{\dot{U}_1}{\left(R_1 + \frac{R_2'}{s}\right)^2 + X_K^2}\left[\left(R_1 + \frac{R_2'}{s}\right) - jX_K\right] \quad (4.20)$$

$$Q_{\mu} = 3I_{oo}^2 \cdot x_{\mu`} \quad (4.21)$$

$$Q_{\delta 1} + Q_{\delta 2} = 3(I_2^{``})^2 \cdot x_k \quad (4.22)$$

$$Q_1 = Q_{\mu} + Q_{\delta 1} + Q_{\delta 2} \quad (4.23)$$

where Q_{μ}, $Q_{\delta 1}$ и $Q_{\delta 2}$ are, respectively, the reactive power consumed from the network and causing the creation of the main mannitic flux, the magnetic dissipation fields of the primary (stator) and secondary (rotor) windings of the induction motor.

It should be noted that the PM of electrical receivers depends on the mains voltage [4.9].

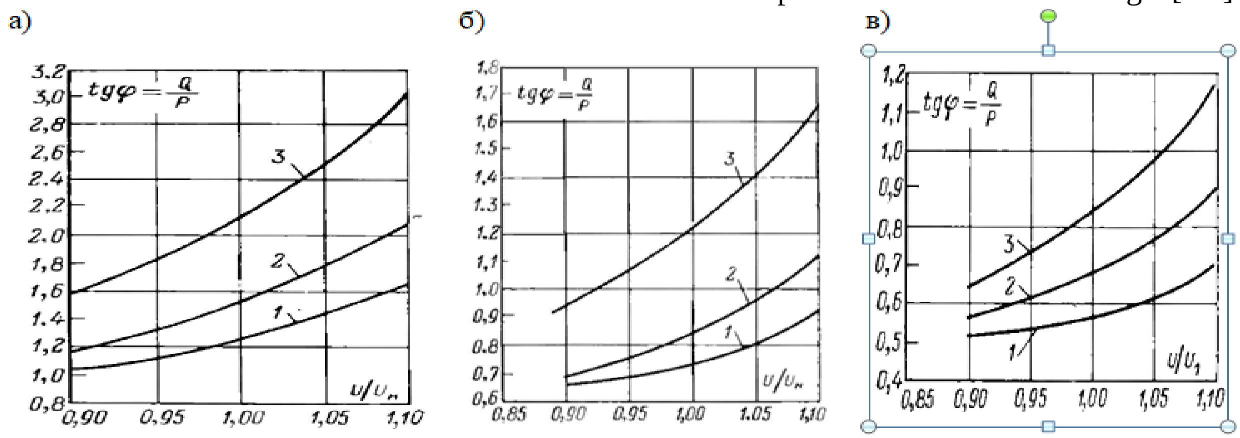


Figure 4.9 – The dependence of tgφ= Q/P on the mains voltage for various load factors of asynchronous electric motors: a) P_{nom} = 1 kW; b) P_{nom} = 20 kW; c) P_{nom} = 2000 kW. Curves 1, 2, 3 are given for load factors β = 1, 0.75, and 0.5, respectively

Incandescent lamps do not consume RP. LED lamps (table 4.2), depending on the manufacturers, have a range from 0.17 to 0.95. Moreover, the dependence of the RP of LED lamps on voltage is also traced (table 4.3) [4.10].

Table 4.2 – Energy parameters of LED lamps

Data	Passport data					Calculations
Maker	P, W	$U_{ном}$, V	$I_{ном}$, mA	F, lm	Life time	$Q^{P}_{экв}$, var
Melitec	2,5	230	70	115	25 000	14,3
Xavax	9	230	52	806	15 000	7,3
Philips	6	230	40	470	15 000	5

Table 4.3 – Ikea 6.3 W LEDs cosφ voltage dependencies

U (V)	100	150	200	250
P(W)	6,3	6,3	6,3	6,3
cosφ	0,97	0,91	0,85	0,77

As you know, from power plants to power receivers, electrical energy is transformed from 5 to 7 times. Therefore, the total consumption of reactive power in transformers and autotransformers reaches significant values. The RP value consumed by the transformer can be calculated on the basis of its passport data [11] by expression.

$$Q_{\text{Т}} = S_{\text{ном,Т}} \frac{I_0\%}{100} + S_{\text{ном,Т}} \frac{U_{\text{К}}\%}{100} K_3^2, \tag{4.24}$$

where $I_0\%$ is the open circuit current of the transformer,%; $S_{nom,\text{Т}}$ – rated power of the transformer; $U_{\text{К}}\%$ – short-circuit voltage of the transformer%; $K_3 = S/S_{\text{ном}} = \beta$ – load factor of the transformer.

As you know, the balance of reactive power in power supply systems mainly determines the voltage level in its nodes:

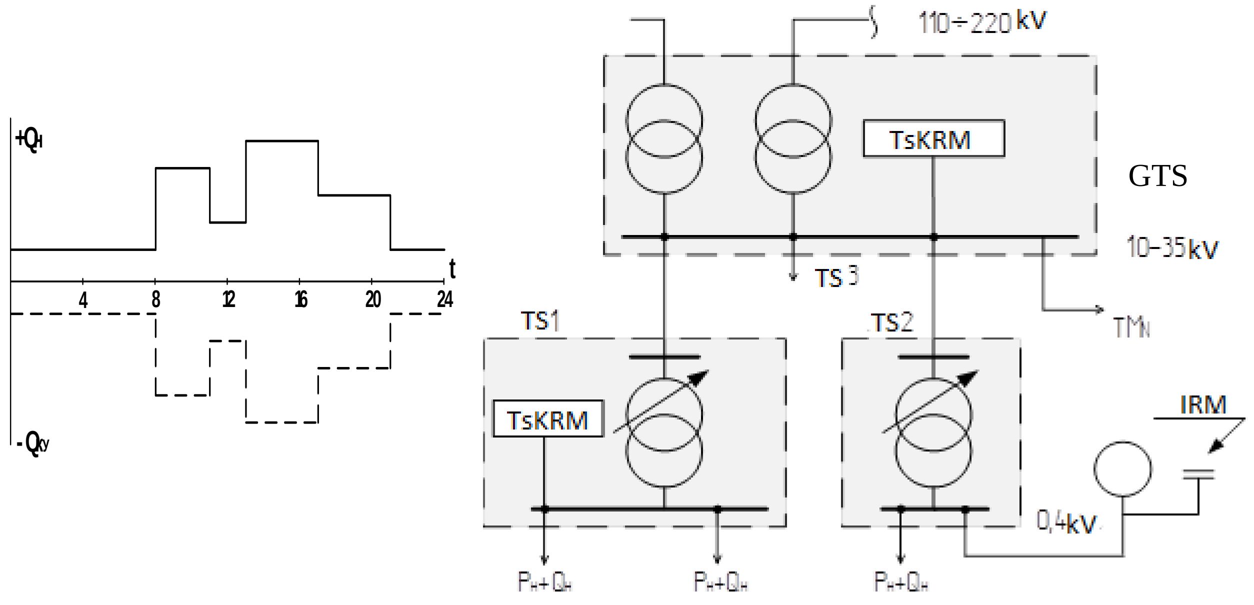
$$\Sigma Q_{\text{г}} = \Sigma Q_{\text{П}} \tag{4.25}$$

where $\Sigma Q_{\text{г}}$, $\Sigma Q_{\text{П}}$ are, respectively, the total values of the generated and consumed RP in the power system.

As shown above, the RP of electrical receivers is largely dependent on voltage. RP flows in power supply systems in some cases exceed active power flows. A low level of reactive power compensation in the RF power supply systems, first of all, leads to high values of technical losses, which are 2.5–3 times higher than in countries with high gross domestic product (USA, Germany, etc.) [4.12].

$$\Delta P = \frac{P^2 + Q^2}{U^2} \cdot \Sigma r \tag{4.26}$$

Also, voltage losses in electric networks increase, which leads to a decrease in voltage at the terminals of power receivers (expression 4.6). The reliability of the power supply system is reduced. In power supply systems, the most widely used are individual and centralized RP compensation systems (Figure 4.11).



a) b)

Figure 4.10 - Reactive load (a) and reactive power compensation systems (b) of an industrial enterprise

CRPCS – centralized reactive power compensation systems (on fig. 4.10 - TsKRM);

IRPCS – individual reactive power compensation system (on fig. 4.10 - IRM).

Individual reactive power compensation system

This RP compensation system [4.8] is used for high-power asynchronous electric drives operating at shared loads. In this case, the capacitor unit is connected directly to the terminals of the induction motor (Figure 4.11). Engine manufacturers recommend that for large engines the power of a paired capacitor bank should not exceed 20-25% of the engine power. If the capacity of the capacitor bank exceeds the recommended value, then a check should be made to ensure the electromagnetic stability of the system in question [4.13].

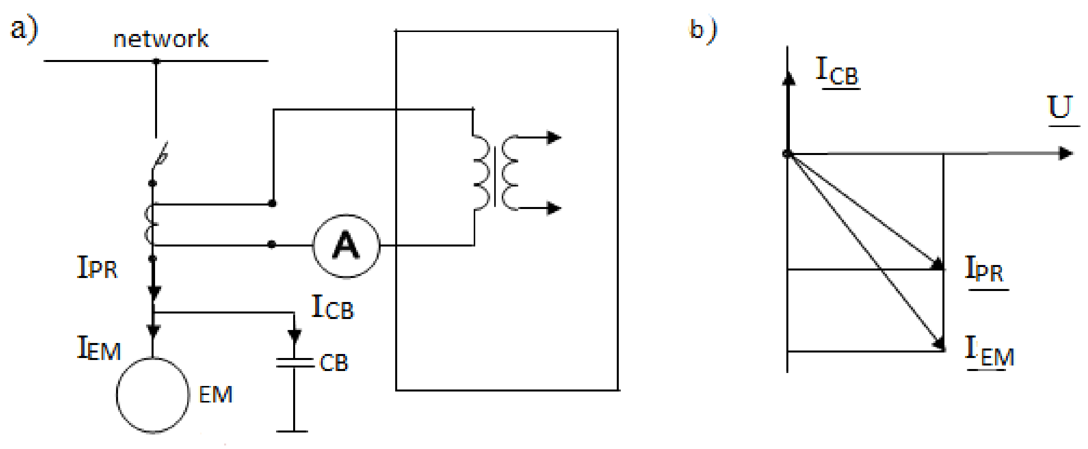


Figure 4.11 – Single-line circuit diagram (a) and vector diagram (b) of an asynchronous electric drive with individual RP compensation system current of the drive I_{ED} (electric drive)

Connecting a capacitor unit to the terminals of an induction motor reduces the amount of current consumed by the electric motor at the same active power on the shaft. Therefore, the protection (QF1) and the drive operation control system (SU1) must be adjusted to the new rated current of the drive (IEP) (Figure 4.11).

$$I_{ЭП_{ном}} = \frac{P_{2H}}{\eta_H \cdot \sqrt{3} \cdot U_H \cdot cos\varphi_{ЭП_{ном}}} \quad (4.27)$$

$$\cos\varphi_{ЭП_{ном}} = \frac{P_{1H}}{\sqrt{P_{1H}^2 + (Q_{1H} - Q_{КУ})^2}} \quad (4.28)$$

Centralized reactive power compensation system

Organizations pay the energy supply organization for the consumed electric energy according to the readings of the active and reactive energy meters. Figure 4.10 shows the most widely used power supply scheme for an average industrial enterprise. Calculations for reactive energy are carried out according to the readings of two counters, one of which records the consumed reactive energy, and the other generated reactive energy. The boundary between the power supply organization and the consumer passes along the high or low side of the main transformer substation (GTS) of the enterprise. Discounts (surcharges) from electricity tariffs for consumption and generation of reactive energy are set on the basis of the Energy Supervision instruction. Surcharges are charged for the consumption of RP and (or) energy, exceeding economic values in the contract, and for the generation of reactive energy into the network. For the consumption of RP and (or) energy in the range from zero to economic value, surcharges are not provided. In order to ensure compliance with the requirements for PM consumption and generation regimes at enterprises, a centralized method of PM compensation is widely used, when a complex capacitor installation, usually with automatic control, is connected to the substation buses to the high or low sides of the enterprise substation, depending on the meter connection (Figure 4.11) [4.21]. Based on the measurement of reactive power or current, the automatic control system (Figure 4.11, ACS), according to a given algorithm, connects or disconnects power capacitors from the network (Figure 4.11), providing almost complete compensation for PM.

This leads to a decrease in power loss in the supply network (formula 4.26) and voltage drop (formula 4.6 and figure 4.4) in the supply network.

However, when switching capacitors with the network through contactors, significant inrush currents occur.

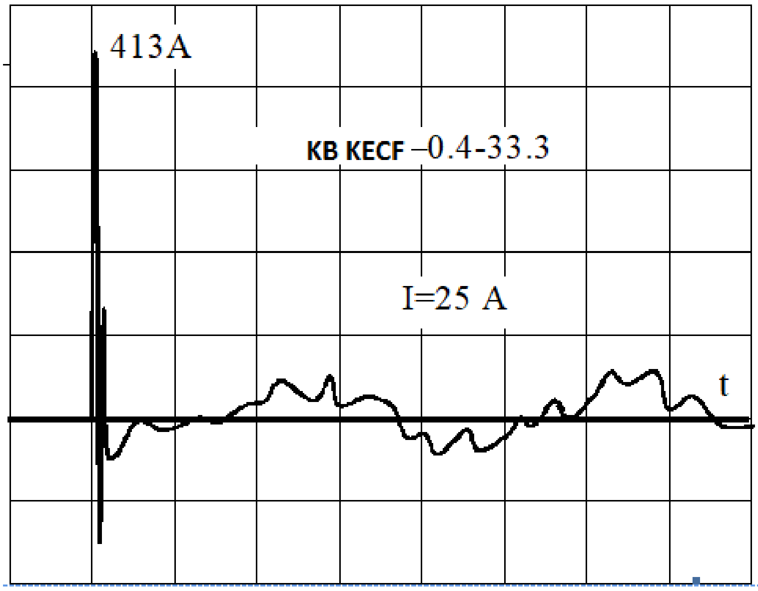


Figure 4.12 – The process of switching a capacitor bank to the network through contactors [4.14]

The use of thyristors instead of contactors eliminates inrush currents [15].

The centralized compensation system of the Republic of Moldova showed high efficiency in its application both at the main substation (GTS) and at the substations of the shops (TS1 and TS2) of the enterprise (Figure 4.10).

4.3 Energy Saving Transformers

Power transformers are classified by power range and voltage class. A significant part of power transformers of 1-3 dimensions is used in power supply systems. It should be noted that power transformers of 1-3 dimensions make up about 99% of the entire fleet of power transformers.

Table 4.4 – Classification of power transformers in size

Dimension number	Power range, kVA	Voltage class, kV
I	**Up to 100**	**up to 35**
II	**More than 100 up to 1000**	**up to 35**
III	**More than 1000 up to 6300**	**up to 35**
IV	More than 6300	up to 35
V	Up to 32000	More than 35 to 110
VI	More than 32000 up to 80000	up to 330
VII	More than 80000 up to 200000	up to 330
VIII	More than 200000	More than 330

Currently, the world mainly uses power transformers with a magnetic circuit based on electrical steel. As is known, power losses (ΔP) in transformers have two components: losses in the windings ($K^2_{load} \cdot P_K$) and in the magnetic circuit (no-load loss – P_0) [4.11].

$$\Delta P = P_0 + \beta^2 \cdot P_к \quad (4.30)$$

where β is the load factor of the transformer; RK - short circuit loss.

In power supply systems, electrical energy is transformed from one to several times, so the assessment and regulation of losses in transformers are important. It is customary to evaluate the efficiency of a transformer in the Russian Federation based on an analysis of its parameters regulated by GOST 52719-2007. It should be noted that in the Russian Federation there are no standards governing the energy efficiency of transformers. For European manufacturers of distribution transformers, the standards HD428 and 538 (three-phase distribution transformers from 50 to 2500 kVA with a voltage of no higher than 36 kV and a frequency of 50 Hz) are regulated by energy efficiency indicators: norms of open-circuit loss and short circuit (Table 4.5) [4.16].

Table 4.5 – Loss rates of European power distribution transformers

nominal rated power	load loss (short circuit)				stand-by loss			
	Oil cooled (HD428) up to 24kV			Dry type (HD538)	Oil cooled (HD428) до 24кВ			Dry type (HD538)
	List A	List B	List C	12 kV Basic	List A’	List B’	List C’	12 KV basic
kilovolt-ampere	W	W	W	W	W	W	W	W
50	1100	1350	875	No data	190	145	125	No data
100	1750	2150	1475	2000	320	260	210	440
160	2350	3100	2000	2700	460	375	300	610
250	3250	4200	2750	3500	650	530	425	820
400	4600	6000	3850	4900	930	750	610	1150
630	6750	8700	5600	7600	1200	940	800	1370
1000	10500	13000	9500	10000	1700	1400	1100	2000
1600	17000	20000	14000	14000	2600	2200	1700	2800
2500	26500	32000	22000	21000	3800	3200	2500	4300

It should be noted that these indicators do not include idling current (I_0). In our opinion, this indicator is very important for assessing the quality of transformers, since the open-circuit current largely determines the amount of reactive power (ΣQ) consumed by the transformer (formula 4.24 and the level of higher harmonics emitted by the transformer into the supply network [4.27].

Despite the high requirements for energy efficiency standards for power transformers, the share of their losses in electric power systems is about 30% of all electric power losses in these systems [4.16].

The most promising way to reduce losses in transformers is to use magnetic cores made of amorphous alloys.

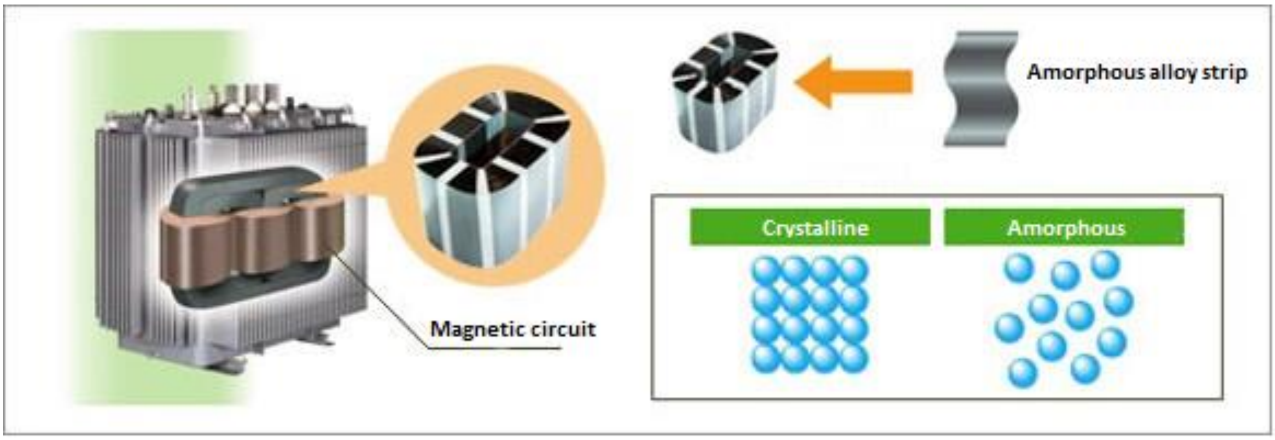


Figure 4.13 – Transformer with a magnetic circuit made of amorphous alloys

Despite a number of drawbacks of the amorphous alloy magnetic circuit: working induction is less than 1.45 T; filling of the cross section 0.8 and another, which complicates the assembly of the magnetic circuit, firms in the USA, Japan and other countries are actively working in this direction. In particular, the company General Electric [11] has been producing a series of transformers with a capacity of 10 to 2500 kVA with a core of amorphous alloys for more than 15 years (tables 4.6, 4.7).

Table 4.6 – Technical data for TM-25 transformers and General Electric firms of similar power (S_H = 25kVA, voltage 10/0.4 kV)

Parameters	P_0, W	P_K, W	I_0, %	U_K, %	Mass, kg	Noice, decibel
TM-25	130	600	3,2	4,5	380	-
"General Electric"	16	322	0,14	2,45	441	≤33

Table 4.7 – The dependence of the efficiency of transformers TM-25 and the company "General Electric" on the load factor

Load factor	0,25	0,5	0,75	1,00
TM-25	96.7	97.8	97.8	97.08
"General Electric"	99.1	98.23	98.69	98.65

As it follows from the data (tables 4.6, 4.7), the use of transformers with a core made of amorphous alloys, as well as for increasing the cross section of the primary and secondary windings, allowed us to reduce power losses in distribution transformers from 8.7 times at idle to 2.23 times nominal mode compared to losses in transformers of old technologies. There is no need to compensate for the PM transformer; emission of higher current harmonics into the supply network is practically eliminated. Due to the low idle losses, the transformer with a core on amorphous materials has a very high efficiency factor for shared transformers. Since the cost of these transformers is two times higher than usual, manufacturers are guided by the minimized cost, which consists of the price of the transformer and the cost of losses for 30 years of operation. The reduction of energy losses in transformers made of amorphous alloys, as follows from a consideration of the thermal state of the transformer (expression 4.31), leads to a decrease in its heating, therefore to an increase in the life of insulation, the possibility of rejecting a number of cooling systems.

$$\Delta P \cdot dt = C \cdot d\theta + A \cdot \theta \cdot dt\,; \tag{4.31}$$

where $\Delta P \cdot dt$ is the thermal energy released in the transformer; $C \cdot d\theta$ is the energy used to heat the transformer; A – heat transfer of the transformer.

After simple transformations, the steady-state temperature rise of the transformer over the environment $\theta_{уст}$ is determined by the expression 4.32.

$$\theta уст = \frac{\Delta P}{A} \tag{4.32}$$

Currently, the main manufacturers of amorphous alloys in the world are: USA; China; India. In Russia, a number of organizations are working on the development of transformers with a core made of amorphous alloys, and have begun to produce the first products. It should be noted that the world's leading companies are developing transformers with a capacity of more than 2.5 mVA from amorphous alloys [4.17].

4.4 Frequency drive

The main link in the electric drive system is an electric motor, which can be used as electric machines of direct or alternating current. It is known that the use of the latter increases the reliability of the electric drive (especially when using asynchronous motors with a squirrel-cage rotor), and also reduces capital and operating costs. These advantages, all other things being equal, determine the preference for using an AC electric drive. The main consumers of electric energy are electric drives of various technological equipment. Since the cost of electric energy consumption by an electric motor over a year often amounts to more than 10 times the cost of the electric motor itself, the problem of its energy efficiency is a key issue in assessing the energy saving of equipment.

A very effective way to control the speed of induction motors is frequency regulation, in which the frequency and voltage of the motor can vary in accordance with the established ratio independently, for example, the so-called control laws U / f - magnetic flux constant, U2 / f2 - critical critical constant moment, etc. When these control laws are implemented, the speed of the induction motor changes in proportion to the frequency and by changing the frequency, the rotor speed can be smoothly and widely controlled. n this case, the slip (the difference between the speeds of the magnetic field of the stator and the rotation of the rotor) changes insignificantly and, therefore, losses proportional to the magnitude of the slip also change insignificantly. This important advantage of the frequency control of an induction motor allows energy-saving technologies to be implemented both for motors with a phase rotor and squirrel-cage.

From the above it follows that for a variable frequency asynchronous drive, an AC source with an adjustable frequency and voltage is required. Only with the advent of static semiconductor frequency converters based on IGBT transistors did it become possible to create frequency-controlled industrial electric drives based on a frequency converter and induction motor

The structure of a modern frequency-controlled asynchronous electric drive, which is optimal in terms of energy and regulatory and mechanical characteristics, is based on a frequency converter with an intermediate DC link. Such a structure is shown in Fig. 4.5, and consists of a frequency converter control device, a rectifier with an inductive-capacitive constant-voltage filter and an autonomous voltage inverter built on power transistors of the IGBT type and forming the main harmonic output voltage by pulse width modulation.

An adjustable electric drive, the power part of which is based on the structure shown in Figure 4.5, has a number of advantages:

- a wide range of speed control (D = 30 ... 60 and more);
- high efficiency (without taking into account the engine, it reaches 0.98);
- high power factor (up to 0.98);
- high reliability and compactness of the converter, as no bulky mechanical elements.

The main recommendations for energy conservation for electric drives of any technological installations may include:

- careful selection of engines for power in accordance with the consumed load;
- Engines that operate unnecessarily must be turned off, preferably in automatic mode;
- the possibility of installing a variable drive should be considered
- rotation speed using frequency converters for various operating modes;
- use of energy efficient motors with high efficiency;
- failure to operate faulty or poorly repaired engines.

Consider the use of a frequency converter as one of the most effective means to significantly reduce the cost of electricity consumption of equipment that uses performance regulation by creating a mechanical obstacle through the so-called gate valves. Figure 4.14 shows all the possible ways of regulating the performance of pumps.

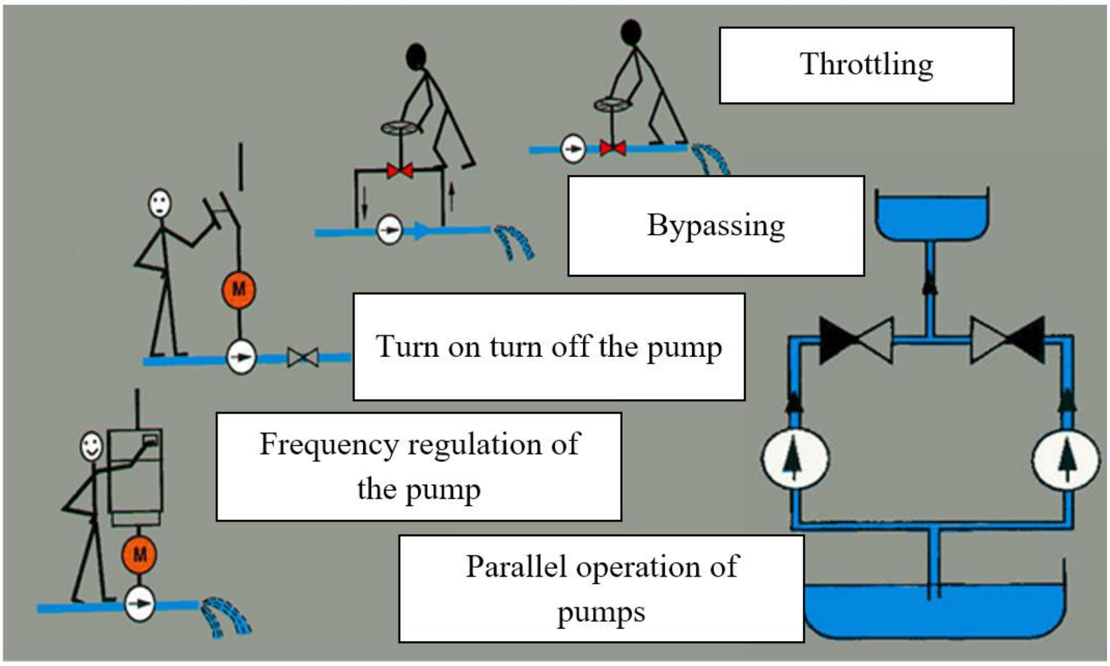


Figure 4.14 – Methods for regulating the performance of pumps

The frequency converter in this case allows you to automatically provide not only the required flow rate Q, pressure P by changing the speed of the induction motor, but also reduce the consumption of electric energy compared to an unregulated electric drive. This statement can easily be proved from the well-known dependence for determining the motor power P of centrifugal pumps and fans, where the flow rate Q is proportional to the rotational speed of the drive motor, the pressure H is the square of the rotational speed, the power consumption of the motor P is the frequency cube [4.18,4.19].

$$P = \frac{H \cdot Q}{\eta_{\text{нас}}} \quad (4.33)$$

Figure 4.15 shows the dependence of the consumed active power P of the centrifugal fan motor or pump on the relative flow Q taken in relative units with the performance regulation by a throttling valve with a constant speed of the asynchronous electric motor drive (line 1) and with the valve fully open with a variable speed of the drive electric motor (curve 2).

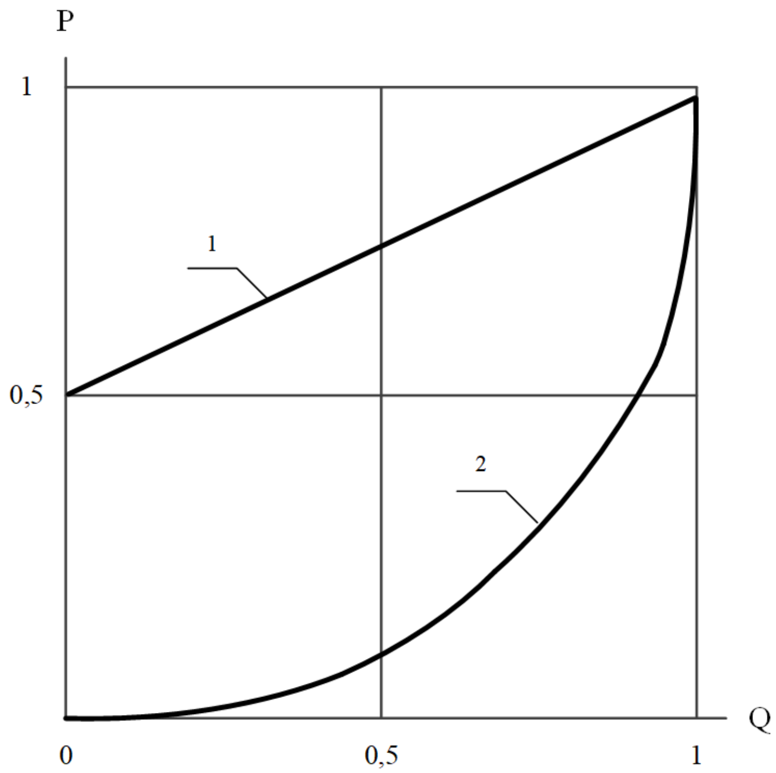


Figure 4.15 – The dependence of the relative consumed active power P of the fan motor or pump on the flow rate Q

From this figure it follows that, for example, at 50% flow rate Q, the active power consumption P during throttling is 75%, while controlling the engine speed and the same flow rate, the active power consumption will be only 12.5%. It can be seen from here that the energy savings can be 62.5% or reduced by almost five times.

Saving energy and water consumption can also be obtained in water supply systems with automatic pressure maintenance in the system. Figure 4.15 shows the typical H-Q head-to-feed characteristics when the asynchronous pump motor is operating directly from the mains (characteristic 1) and from a frequency converter with speed control of the drive asynchronous motor (characteristics 2, 3). Point A corresponds to the rated operating mode of the pump. To obtain a comfortable pressure H_{nom} during operation of the pump without speed control, it is necessary to change the resistance of the line from characteristic 4 to characteristic 5 by bypassing. It should be noted that at a working point B comfortable pressure pump flow will exceed the nominal 1.5-2 times. The required pump power will correspond to the $OH_{nom}BQ_B$. area.

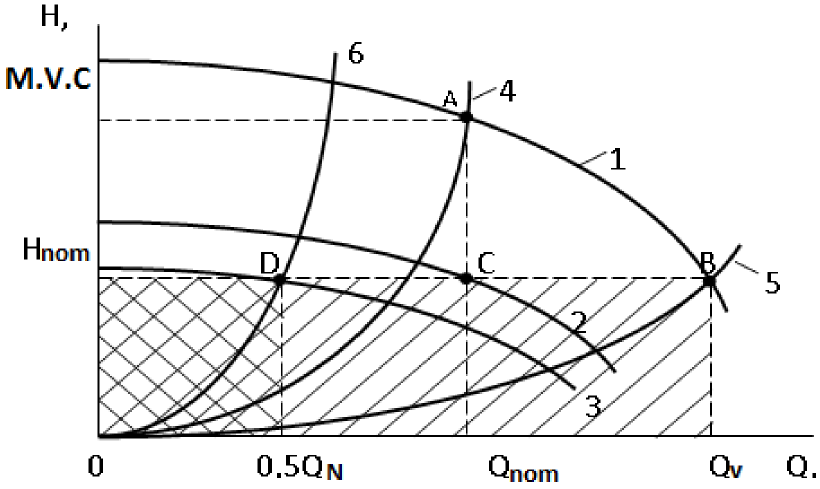


Figure 4.16 – Typical characteristics of the head-supply of the H-Q pump during operation of the asynchronous pump motor directly from the mains and from the frequency converter

When adjusting the pump capacity by changing the speed, the head-flow characteristic of the H-Q pump will move from 1 to 2 characteristic. Operating point C will correspond to the nominal pump flow Q_{nom}. With a further decrease in flow, the operating point will move closer to the ordinate axis, for example, for half feed, it will be at point D. Here, the power consumption by the pump will correspond to the 0-H_{nom}-D-0.5Q_n region shaded in the cell. As can be seen from the graph, this power can be several times lower than in an unregulated pump drive, since there is no energy consumption for creating excessive pressure or pumping water through a bypass line.

Figure 4.17 shows a comparison of power consumption for various methods of regulating pump performance, calculated by the above method for the options shown in Figure 4.14.

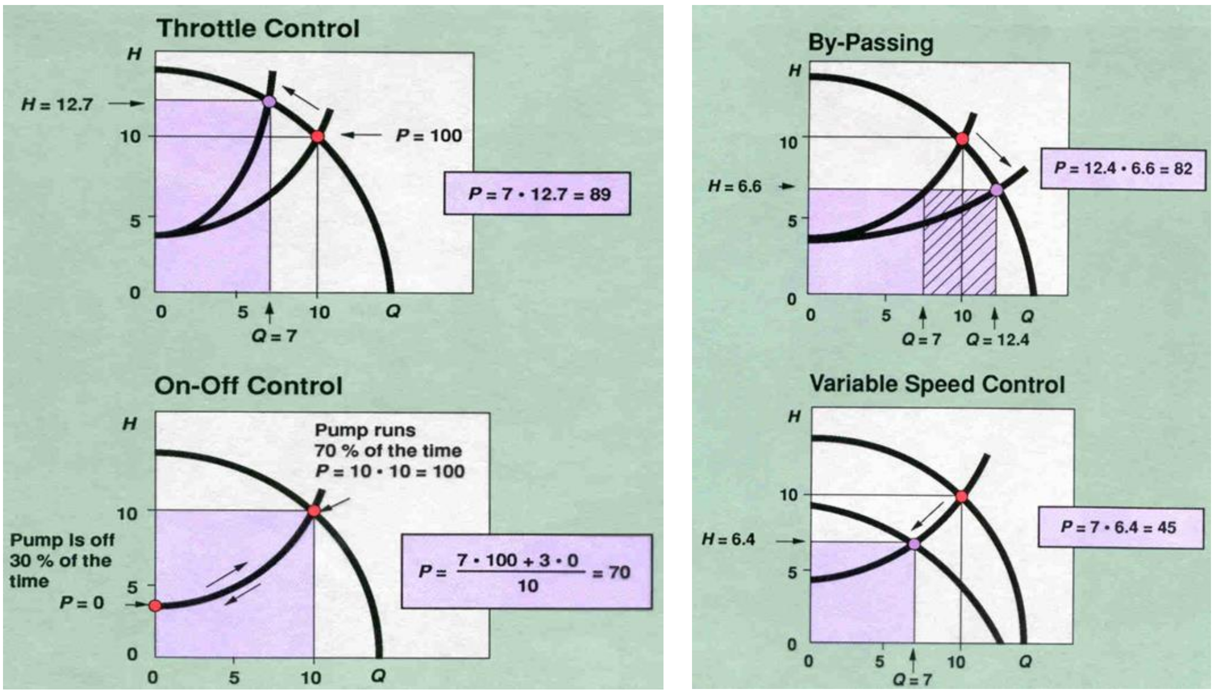


Figure 4.17 – Comparison of power consumption for various methods of regulating pump performance

Of these considered options for regulating the performance of pumps during throttling, bypassing, on / off and frequency regulation of pump performance, the power consumption was the smallest in frequency regulation.

Figure 4.18 shows, according to the data of NPO Promtehservice, a block diagram of the efficiency, which clearly shows the main ways of the economic and operational-technical effect of the introduction of frequency converters in variable frequency drives [4.20,4.21].

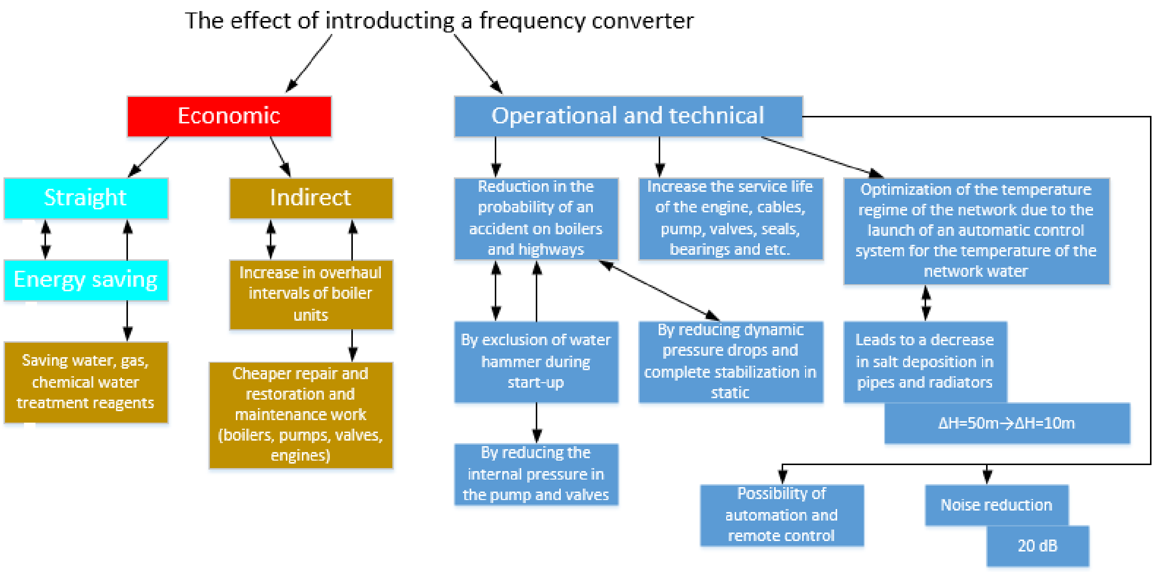


Figure 4.18 – A block diagram of the effect of the introduction of frequency converters

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Test questions

The appearance of higher harmonics of current and voltage in electrical networks is due to:

- non-sinusoidality of the voltage curve of the power source of the electric network;
- the presence of a nonlinear element in the electrical network;
- the presence of a linear element in the electric network;
- single-phase loads.

Ways to reduce the harmonics of current and voltage in the electrical network are:

- circuit and technological solutions;
- use of filtering devices;
- regulatory decisions;
- maintaining the rated voltage value in the electric network.

An effective means of reducing the voltage of the zero sequence is the use in distribution networks:

- transformers 6-35/0.4 kV with a group of connection of the delta / star windings with a neutral wire;
- transformers 6-35/0.4 kV with a group of connection of star / star windings - a zigzag with a zero wire;
- transformers 6-35/0.4 kV with a group of connection of star / star windings with a neutral wire.

At what load does the induction motor have the smallest cos φ?

- when idling;
- when working with rated load;
- at 50% load.

Requirements for the reactive power limit established by the enterprise by the energy supplying organization allows to fully implement:

- management system for centralized compensation of RP installed at the main substation of the enterprise;
- centralized compensation management systems for RP installed in the shop substations of the enterprise;
- individual compensation of individual electric drives.

The most important indicator characterizing the efficiency of the transformer is:

- transformer idle loss;
- transformer short circuit loss;
- heating of the transformer;
- life time.

Advantages of transformers based on amorphous alloys:

- low idle losses;
- working induction less than 1.45 T;
- increased insulation life due to low heating of the magnetic circuit and transformer windings.

An energy-saving way of regulating the performance of pumps (fans) is (choose one option):

- throttling;
- bypassing;
- on-off;
- frequency regulation.

The power consumption of centrifugal pumps (fans) depends on the speed of the drive (choose one option):

- quadratically
- proportionally;
- cubically;
- does not depend on any of above.

Indicate the advantages of frequency converters (you can choose several options at the same time):

- high generation of higher current harmonics;
- regulation of speed above nominal;
- high efficiency;
- high reactive power consumption.

Efficiency of the introduction of a frequency electric drive is (you can choose several options at the same time):

- saving energy consumption;
- increase the service life of equipment;
- low cost;
- possibility of automatic and remote control.

5 Consumer behavior relevant to energy efficiency in electrical power supply systems

5.1 General information and history of the electricity consumers behavior management problem in Russia

In order to keep the system frequency within the specified limits at any moment in the steady-state of the power system, power plants must produce the amount of active power equal to the consumption and cover active losses in the network - a balance must be maintained between active power produced and consumed [5.1]:

$$\Sigma P_G = \Sigma P_C = \Sigma P_L + \Sigma \Delta P, \tag{5.1}$$

where ΣP_G — net power plants generated power (except auxiliary power for own needs); ΣP_C — total active power consumption; ΣP_L — total power consumed by the loads; $\Sigma \Delta P$ — total active power losses.

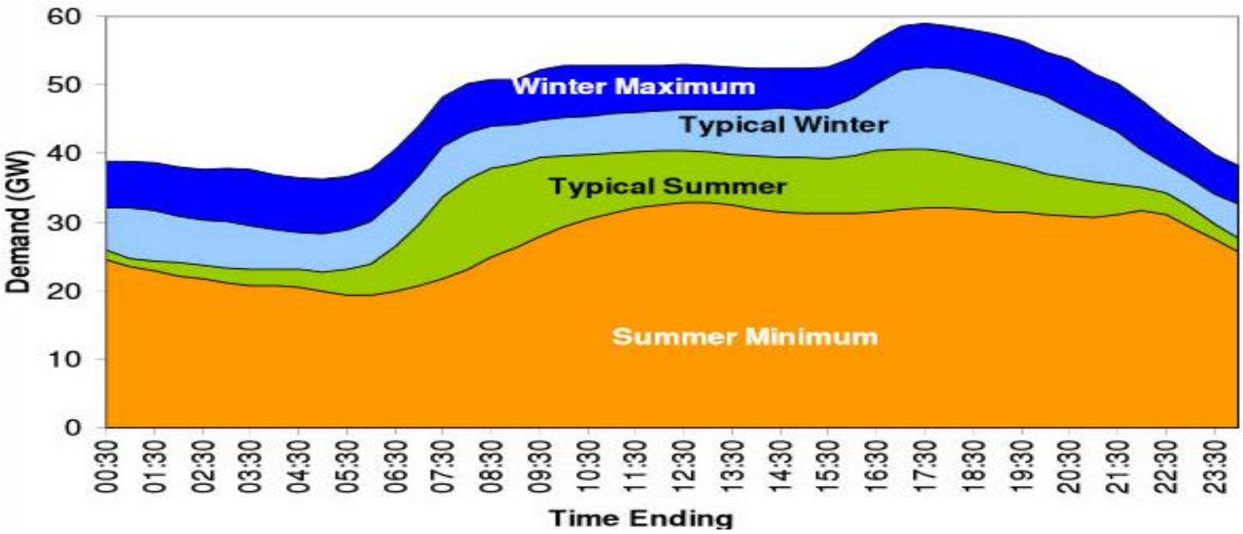


Figure 5.1 – England energy system load profiles for 2010-1011

Historically, as active side, providing such a balance were operating the traditional power plants, which changed their production following the power system load profile (Figure 5.1). With the increase of renewable energy sources penetration in the energy system, such as wind and solar, it becomes necessary to compensate for the unbalance caused by fluctuations of such sources and their low forecast accuracy on the spot [5.2]. To provide the desired level of the power system control and operational performance, new opportunities are being sought to keep up such a balance [5.3]. On the supply side they are: power plants with high maneuverability and new storage systems, on the demand side - consumer behavior management programs [5.4].

System automatic, as a form of consumer behavior control management, are important part of the energy system from the beginning. It maintains the system stability during significant imbalances of electrical energy production and consumption by automated disconnection of pre-defined consumer equipment. *Thus, consumers are involved in preventing the development of a system failure at an early stage of the system fault situation [5.2].*

In normal operating modes of the electrical energy system, the idea of consumer behavior management is also not new. The very concept of a “consumer-regulator” designed specifically to comply with the load profile of the energy system [5.5] first described in Russia in 1935 [5.6]. By the 1980s the level of automation only allowed to work successfully with some large consumers, whose technological process allowed flexible control of the load on the spot [5.7].

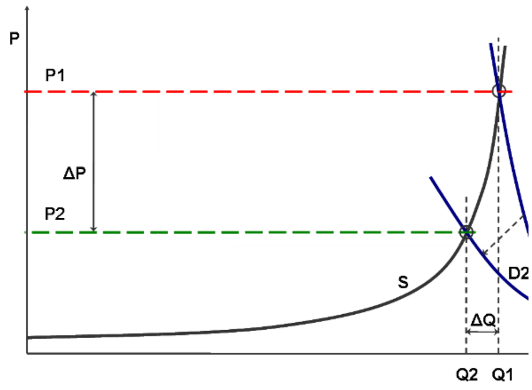
The main goal was to shave the load picks in the energy system to cut the total national economic costs [5.8].

Since the USSR collapsed and the competitive relations in the electricity market in Russia were introduced, elements of market demand management have been discussed. Historically, consumers had not had the practical ability to affect the supply and demand balance. Under such conditions, the price of electricity is almost entirely determined by producers. In order for electricity demand to depend on market prices and to decrease consumption with rising prices, special stimulus measures are needed.

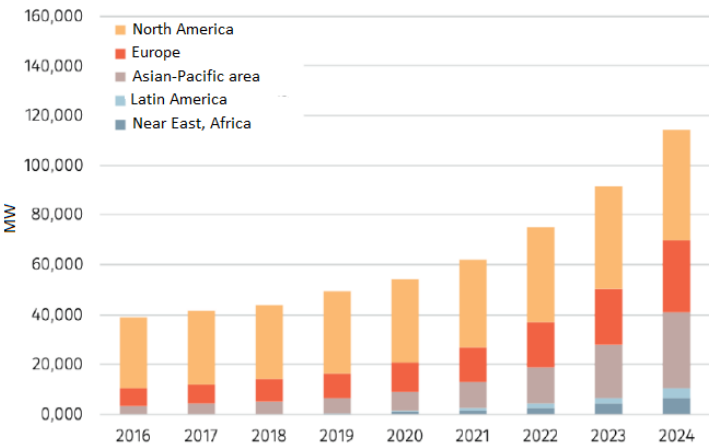
Such measures and approaches to consumer behavior management in the energy sector are summarized by the general concept of *"Demand Response" – changes in electric usage by demand side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized.* Demand response (DR) can lower electricity prices in the wholesale market and, as a result, in the retail market [5.9]. For the consumer, the compensation received is a way to increase its power consumer's operation economic efficiency and the power supply system efficiency.

Figure 5.2a explains the principle of consumer participation in demand management. The smooth growth of the supply curve S replaced by a sharp increase at the end with the use of the most expensive generators (such as gas turbine power plants). A reduction in peak hours from Q1 to Q2 leads to the shift of the demand curve D1 to curve D2 and a drop in the electricity price by ΔP.

Programs to motivate consumers to take part in economic and emergency demand management are very well developed in the world and are actively used in the USA (since 1999), the European Union, Australia, New Zealand, China, and other countries. System operators of wholesale markets in developed countries (PJM - USA, IESO - Canada, etc.) can manage consumer resource capacity from 2% to 6% of peak demand, which is 0.7-14 GW [5.10, 5.11]. Due to the economic effect, these capacities can grow by 3.5 times, up to 144 GW by 2025 (Figure 5.2, b) [5.12].



a)



b)

Figure 5.2 - The principle of consumer participation in demand management and forecast of global technology use until 2025 [5.9].

In each country, such programs have their distinctive features, because of the differences of the electricity market organizational principles, the presence of a capacity market, the possibilities for consumers to take part in it, and the differences in the demand management program's goals and the degree of their practical implementation.

In Russia, the concept of voluntary load restriction, which idea was to pay consumers for the possibility of reducing their load with the command from the system operator, was discussed back in 2007-2008, but was never implemented [5.2]. Since 2017, a price-dependent program to reduce electricity consumption and capacity level in the wholesale market has been running. The participants are consumers with at least 5 MW real capacity, market entity with 2 MW least amount of load reduction. The program is not really working, today, only Rusal aluminum company takes part in it with a total load capacity of 64 MW (1% of the company consumption and 0.1% of the peak demand of the wholesale market 2nd price zone, the number of operating cycles is much lower than expected). The total costs of the energy system have not yet been compensated by the total systemic effects [5.10], but the experts assess the program as promising.

Demand response is not one independent technology. This is a set of different practices and measures that have an economic effect — more complex use of generating and network capacities, reducing the need for new generation capacities investments, and technological — a new regulatory tool for the system operator that helps to stabilize the frequency and ensure higher reliability of energy supply and power quality.

In relation to energy efficiency in power supply systems, the greatest potential is in the retail consumer demand management programs, which are consumers who are not wholesale electricity market entities.

5.2 Active consumer concept

Today we can witness an explosive development of digital technologies that allow real-time processing of big data and the energy sector already offers relatively cheap technologies to manage the load on the retail consumer side. The aim is to change the retail consumers' electricity consumption from their normal load profile according to price signals or direct market commands covered by respective compensation.

The problem of demand management for retail consumers cannot be solved using the technologies available in the traditional energy system. To develop such practices, the concept of an intelligent energy system (IES) is used, where operate the so-called **"Active consumers"** [5.13].

Active consumer is a participant of the consumer electricity market, which, based on the existing regulatory framework, having the technical and technological capabilities, and taking into account its needs, can choose:

- its energy consumption mode, which complies with the need to fulfill its production plans or household electricity supply needs, optimizing electricity costs from foreign markets;
- the level of additional service provision, which includes the active and reactive consumer power control available for the system operator;
- conditions for operating its own capacity (if any) to form a participant application for the purchase / sale of electricity in the wholesale and retail markets.

Key organizational principles of active consumer demand management systems are.

- equal participation of consumers: stimulating the participation of consumers of all types and sizes in the energy and power market (or the market of system services / reliability) giving them equal rights with the producers.
- Flexible measurement and payment system. Measurement system should be acceptable to both, consumers and their contractors, to take into account the timeliness of the reaction based on the results of the system operation and financial compensation calculations.
- Legislative and regulatory control. Single Regulatory Information Agreement: Consumer agreements must be confidential and under strict regulatory control, with regulators working together to overcome barriers for the implementation of the demand management system.

These principles motivate the active behavior of the retail consumer. Using them, a range of load control mechanisms has been developed in the world, some of which are already being successfully implemented, including Russia. Possible classification is given in table 5.1 [5.14]. Consumers, as participants in the considered programs, can be classified in terms of their activity level (Figure 5.4) [5.14,5.15].

The simplest approach to formalize the aim of active consumer costs minimization is given in [7]. For this, the minimization of the criterion is considered:

$$\min\left(\text{C}_p P_{max} + \sum_{k=1}^{K} C_{ek} E_{nk}\right) \tag{5.2}$$

where C_p – unit cost of one kW of daily maximum load; C_{ek} – unit cost of one kWh of electrical energy; P_max – maximum consumer load, kWh; E_{nk} – total electrical energy consumed per day, kWh; K – the number of parts into which the daily load profile is divided.

The criterion reflects the general case of the consumer's payment for both the consumed electricity and the maximum load, which is, for the moment, typical for industrial consumers. For domestic consumers, as a rule, only the second component is taken into account, which integrally considers both power and energy.

The following are considered as limitations when minimizing criterion (5.2):

$$E_{nk} \geq E_{nk\ \text{min}}, \quad k = \overline{1, K}; \tag{5.3}$$

$$0 \leq P_r \leq P_{r\ \text{max}} \tag{5.4}$$

Formula (5.2) capture possible restrictions on electricity consumption in the interval k of the daily load (technological minimum taking into account special conditions of production technology, such as technological reservation).

The inequality shows restrictions on the maximum total power of regulated power consumers, the transfer of which to a different zone of the load schedule is acceptable to the consumer. At the same time

$$P_r = \sum_{i=1}^{n} P_{ri}, \tag{5.5}$$

where P_{ri} – capacity of a single regulated power consumer; n – the number of consumer regulated electrical power receivers.

When solving the optimization problem (5.2) - (5.4), it should be taken into account that the limiting values of the regulated electric load $P_{r\ \max}$, as well as the possibility of its transfer to other areas of the day load curve, should be determined by the consumer's staff who are well aware of its technological features and the ability to adapt to consumption changes.

Table 5.1 - Types of demand management programs [5.14]

Elements of the demand management program	Modern state	Future state
Direct demand management	The consumer, at his discretion, switches the equipment on or off during the minimum/maximum tariff hours according to the tariff menu.	Consumer equipment has devices for remote shutdown at peak moments and switching on at minimum prices.
Load Requirement (Offer) or Buy-Back Program	The consumer, at his discretion, switches the equipment on or off during the minimum/maximum tariff hours according to the tariff menu.	The consumer, on the basis of spot information on the state of the market, may abandon consumption at a given time and sell the capacity
Tariff, differentiated by time of day	The consumer, at his discretion, switches the equipment on or off during the validity of the zonal tariffs	Voluntary and compulsory programs based on the mandatory participation of all consumers.
Commercial/industrial versions of the programs		
Interruption programs	Forced shutdowns in force majeure situations	Disconnection with the consent of the consumer, giving the possibility to cut payments to the supplier using the price modification system
Load reduction programs	Forced load reduction in force majeure situations	Reduction of the load with the consent of the consumer, giving the possibility to cut payments to the supplier using the price modification system
Real-time charging	Real-time operation in the balancing wholesale electricity and power market	Real-time operation on the balancing wholesale electricity and capacity market as well as on the end-user level on the retail consumer market
Load Requirement (Offer) or Buy-Back Program	The industrial consumer at its discretion loads the capacity according to the operation mode, depending on the tariff or the terms of a long-term contract	The consumer, based on current market information, can cut consumption at a given time and sell capacity as one of the following options: variable percentage of wholesale prices, constant percentage of wholesale prices, constant or variable price, determined by competitive selection of consumers.

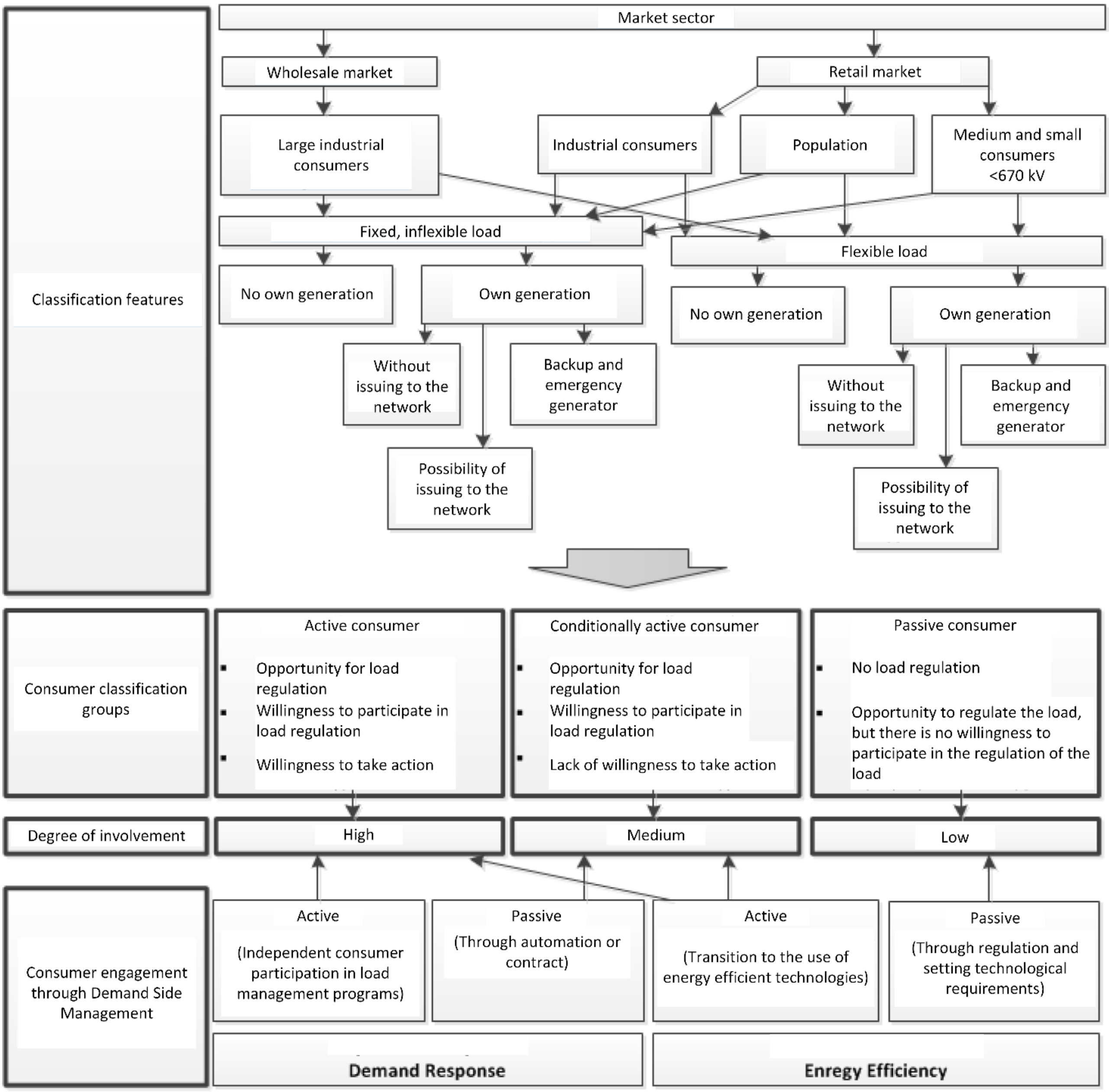


Figure 5.4 – Classification of consumers in terms of ability to take part in demand management programs [5.15]

The most of electricity consumers in the retail market do not have legal (regulatory framework), technical (power flow control, smart meter system) and marketing (dynamic pricing, tariff modification) opportunities for direct participation in organized power and energy markets. To ensure their access to demand management programs, special organizations are used - demand management aggregators [5.9].

5.3 Load aggregation concept

Demand management aggregators (DMA) – organizations, that purchase services from retail consumers, combine their ability to change consumption and convert it into goods and services in the capacity, power and system services markets, as well as send part of the effect obtained in the wholesale market to consumers. Demand management aggregators:

- searches for consumers, with the possibility to change their consumption without compromising their total production, and evaluates them;

- develops optimal algorithms for participation in demand management programs, equips consumers with necessary technical solutions;
- acts as an agent in the wholesale market - takes on the interaction with the infrastructure of the wholesale market, undergoes complex admission procedures;
- provides for the wholesale market a resource of consumer group changing load in the form of a single load, is responsible for the fulfillment of obligations.

The retail consumer gets the opportunity to influence the supply and demand balance in the wholesale market, without becoming its entity, with no understanding of the market rules, without complicated regulation of interaction with commercial and system operators.

March 20, 2019 Decree of the Government of the Russian Federation No. 287 [5.16] was signed, which defines the new demand management mechanism operation rules. In 2019, the mechanism was launched in pilot mode to test the technology on a limited amount of services. DMA can become a part of the electric power industry, it could be a power supply company (guaranteeing supplier) or a consumer, that has signed a contract with consumers in the retail electric energy market for the load change service provision. It is necessary to go through the competitive selection process and sign an agreement with JSC “SO UES” following the rules approved by Decree of the Government of the Russian Federation of March 3, 2010 No. 117. Decree No. 287 amends it accordingly [5.9]. Based on the results of the pilot projects, a framework for aggregators' work on the wholesale market will be developed.

The priority retail customers that the DMA should deal with on the first place are those whose load can be sufficiently reduced in the short term (or "shifted" in time) without affecting the main production cycle. These include facilities in which the main contribution to the load is made by ventilation and air conditioning systems, refrigeration and pumping equipment, electric heating, electric water heaters. Those are industrial enterprises and commercial real estate, such as shopping and entertainment centers, office centers, logistics infrastructure (warehouses, container terminals, sorting centers), sports facilities (ice palaces) [5.9]. At the same time, the following can be used as a resource for changing consumption: own generation, technological capabilities for changing consumption, energy storage devices (Figure 5.5).

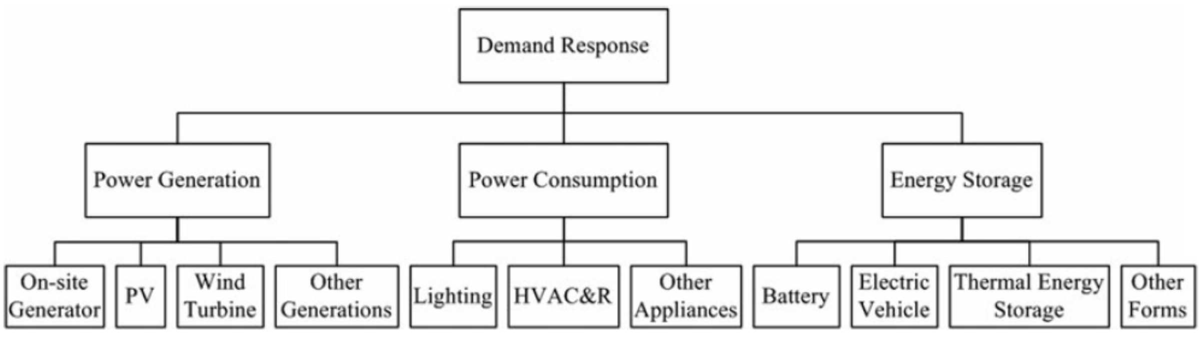


Figure 5.5 - Classification of retail consumers as part of demand management programs [5.5.17]

The place and role of DMA in the chain of interacting agents, providing representation of retail consumers on the wholesale market are shown in Figure 5.6. In addition to the energy and capacity market, it can operate in auxiliary services markets, such as the system reliability services market. The structure of such markets varies greatly from country to country, e.g. there are no explicit capacity reserve markets in Russia.

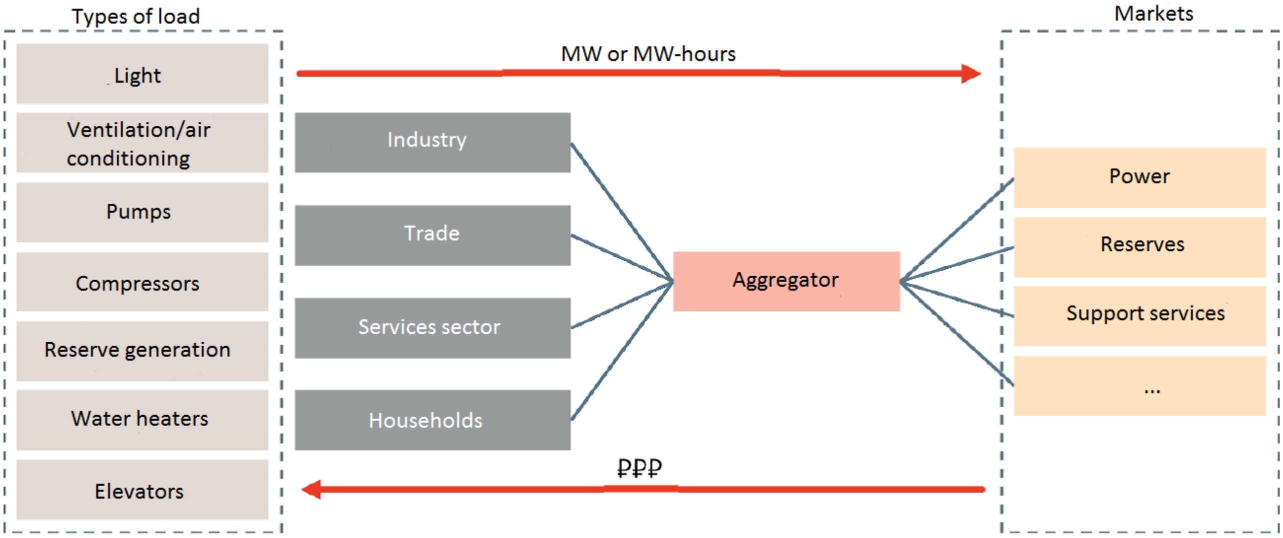


Figure 5.6 – The role of demand management aggregator [5.9]

A large number of different aggregation mechanisms have been developed, tested worldwide (Figure 5.7). Their basic principle - change in load should be considered as equal change in a generation. In contrast to generation, the change in the consumer load cannot be measured directly and should be calculated. Estimation of demand management resource effect assumes a comparison of observed load with theoretical load, which would take place without regulation.

Payment for DMA services is calculated using the information about the consumer participation effects, and is adjusted with the use of interception of control or an unsuccessful remote control information. In this case, the behavior of consumers can be blocked at the time, then DMA is operating.

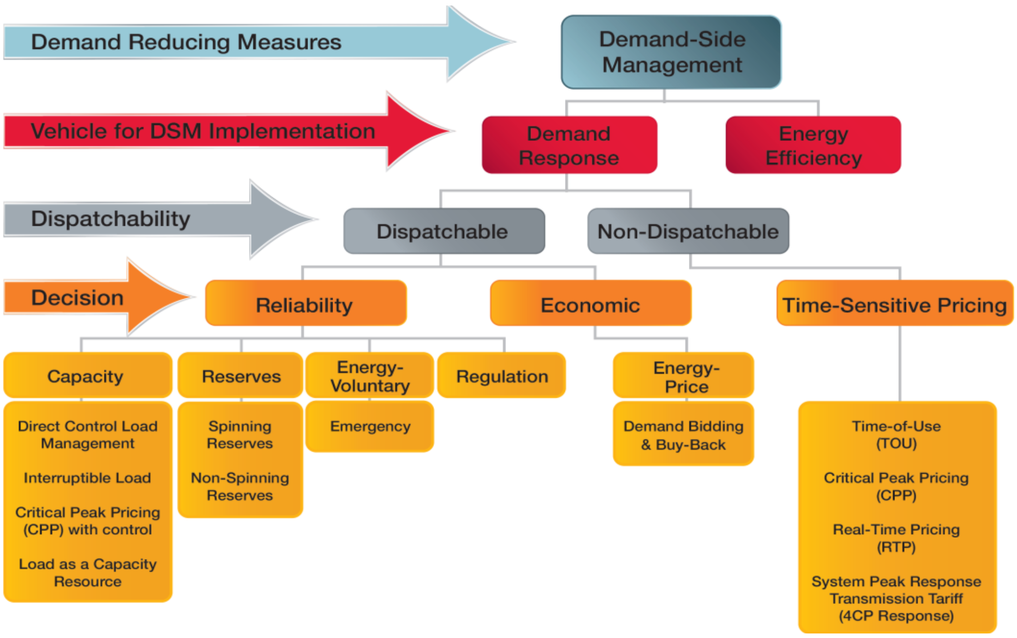


Figure 5.7 – Classification of demand management mechanisms [5.18]

Here is an example of a daily load profile of a village, which consist of 12 buildings of in the United States with the possibility to control demand for 8 hours. The reduction in consumption was around 70 kW or about 12% of the typical load at the same period (Figure 5.8). This has allowed each homeowner to save about $ 400 a year.

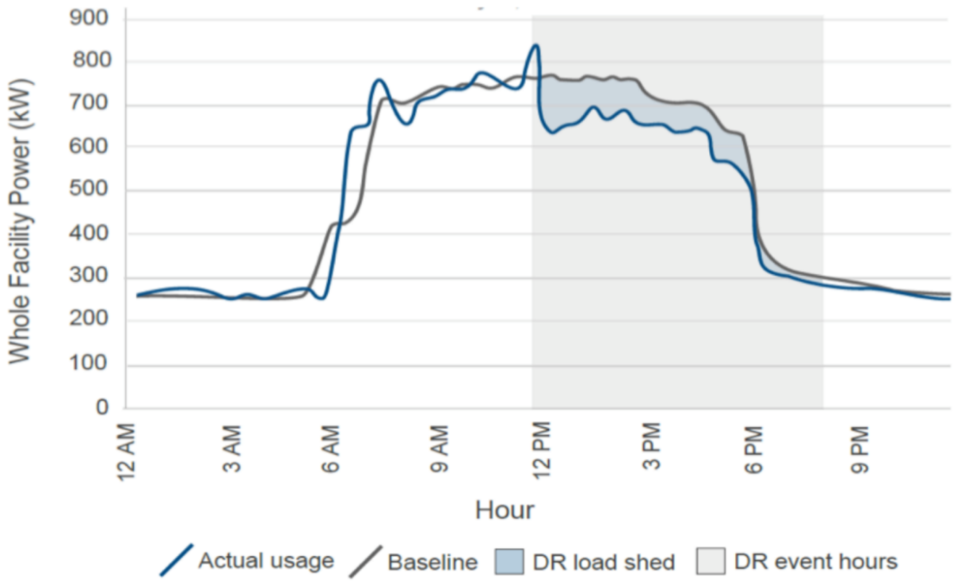


Figure 5.8 - Demand management technology impact on the daily load profile of 12 buildings village with load aggregation

The DMA requires the use of modern management and communication technologies, which include:

- remote control and automatic signaling to reduce the consumer equipment load in accordance with the selected consumer participation program;
- signals transmission from the consumer to the program administrator (confirmation of signal reception from the operator, information about reducing the load);
- two-way communication with the system operator in real-time to manage consumption or provide system services.

Technological platforms that make it possible are available now, and the experience of their operation is being developed. All of them are based on intelligent electricity metering systems, without which effective management of consumer behavior is technically impossible.

5.4 Modern smart metering systems

With unidirectional communication between system agents operational interaction between the participants of the energy market is impossible. It does not allow to fully monitor and control of the electrical energy system. Advanced metering infrastructure (AMI) is the base for bidirectional communication [5.19].

AMI is a complex, customized infrastructure that combines several technologies such as smart meters, communication networks, data acquisition and processing systems, as well as application program interfaces. On the consumer side, the smart meter (SM) collects data that are then sent via the communication network to the central AMI system. After analysis of the data from collection and processing system, the information is presented to other agents in the necessary form.

Two-way communication between a consumer and a service provider, in contrast to previous systems (for example, Automatic system for commercial accounting of power consumption), can be used to send a price signal to a customer's smart meter or a command signal to a load control device [5.20]. The client receives all information about the cost and quantity of electricity consumed through the software, according to daily, monthly or annual load profiles [19], which allows him to take part in demand management programs.

Smart meters

Smart meters collect data and assign timestamps with the correct resolution and send them for analysis. The smart meter structure (Figure 5.9) consists of measurement and communication subsystems.

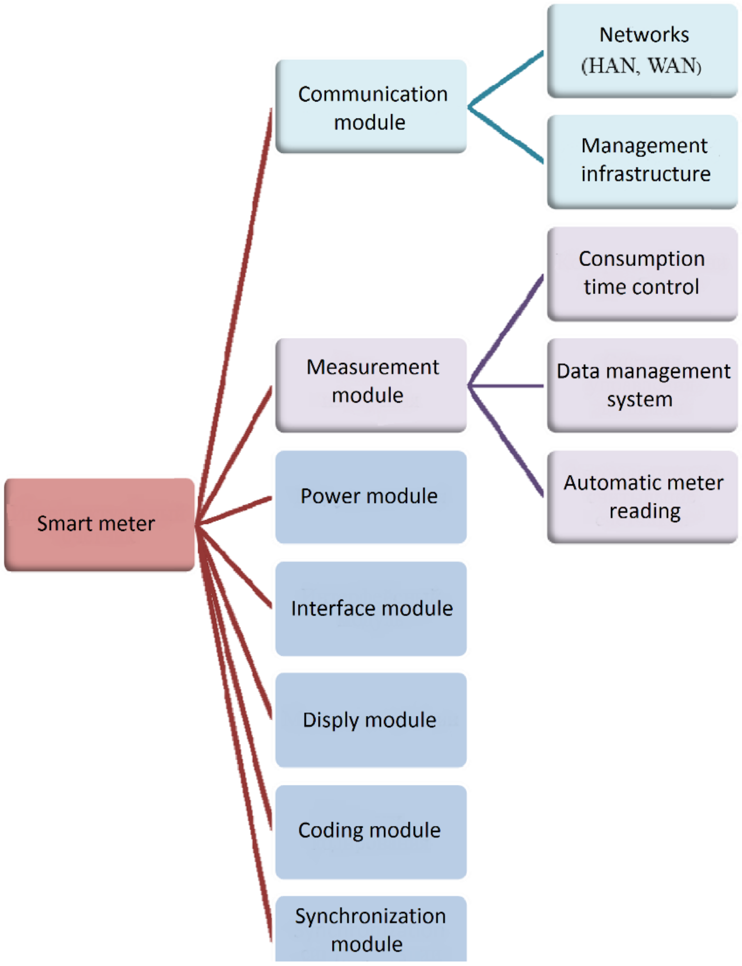


Figure 5.9 – Smart meter structure

The first consists of usage time control, a data management system, and an automatic reading structure. The second is the network connection and management infrastructure, which allows the meter to communicate with remote centers and comply with management commands. In addition to these two main subsystems, smart meters include the following components: power module, interface module, indication module, coding module and synchronization module.

Smart meter requirements: high measurement accuracy; provision of consumption data to agents; electricity cost determination; failure notification in smart meter or energy system;

remote control; load limitation for demand management; power quality control; electricity theft detection; communication with other smart devices.

AMI data center

On the service provider side (demand aggregator, power supply organization) should be the AMI data center. It organizes the payments between participants and allows us to manage demand by limiting the load and respond to changes and emergencies in the energy system in real-time. Its components are: data management system; billing and consumer information system; emergency shutdown control system; system of maintenance planning; geographic information processing system; load forecasting system; electric power quality management system.

The system collects an enormous amount of data (tens of terabytes). Analysis of such amount of data is carried out using the methods of intellectual analysis and allows us to extract useful information for decision-making process. To do this, the following components are required:

- data processing center infrastructure: a building with special auxiliary systems such as backup power, heating, ventilation, etc.;
- servers: hardware necessary for data processing;
- storage system: all equipment necessary for data storage and connection to other equipment in the system;
- data analysis software;
- virtualization systems: for more efficient data storage and computing.

Data consist of a lot of personal and business information, hard drives must be protected from natural disasters and backups must be provided. The cost of building a system with such conditions is enormous. To solve the problem, virtualization and cloud computing on remote servers are used, which significantly aggravates cybersecurity issues.

Communication Network Architecture

In communication networks, a hierarchy is built up, from internal to external networks. External networks are divided into two types: regional and core networks. Figure 5.9 shows the AMI communication network in the energy system, which consists of 6 levels: data center; main data bus; aggregation points; transport communication networks; access points – smart meters; internal networks - HAN.

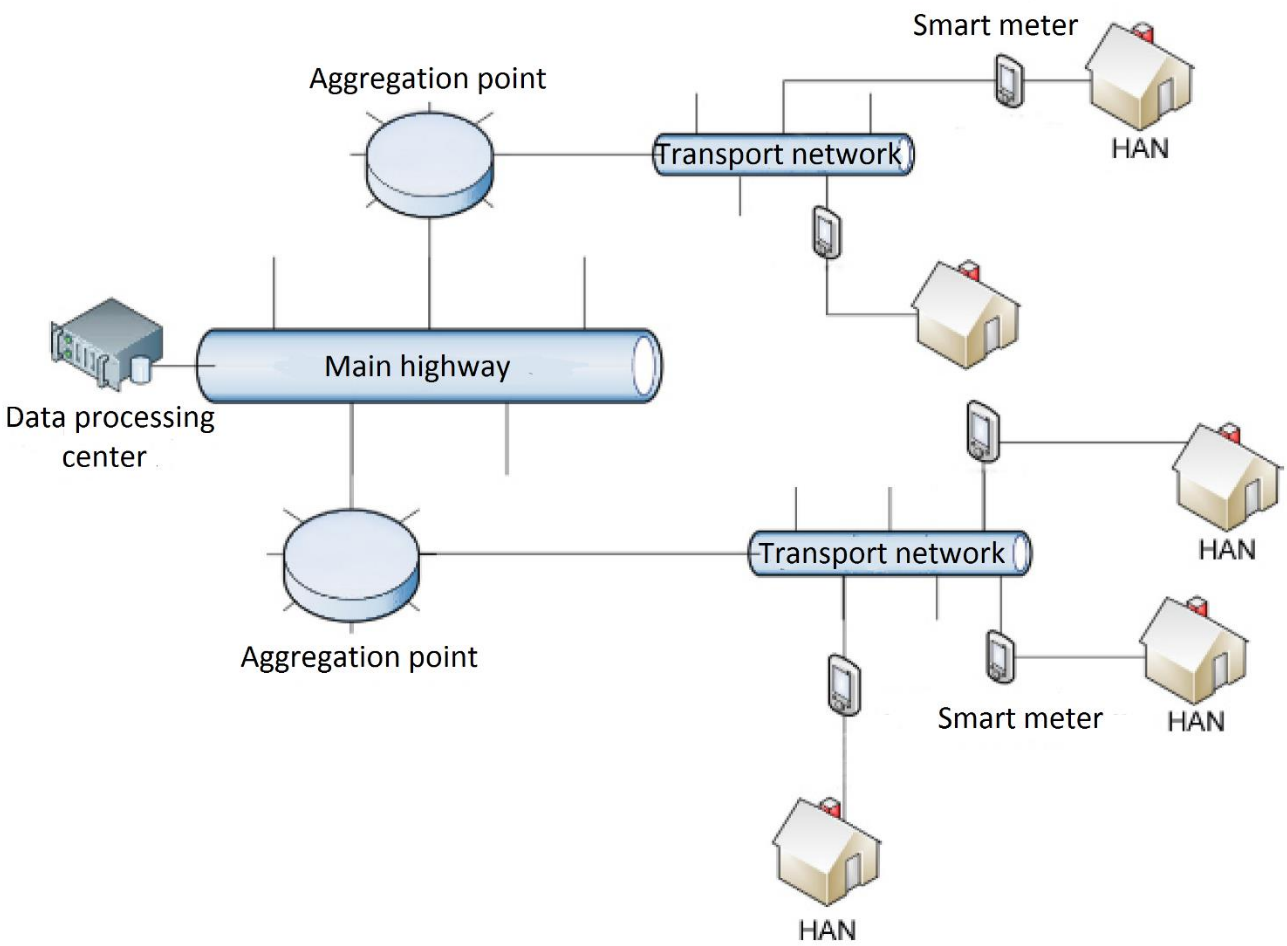


Figure 5.9 - AMI communication network structure in the power system

Devices inside the consumer's units communicate with each other and with other agents' networks in the system via smart meters that act as internal network access points. From them, data are transmitted through transport networks to aggregation points at transformer substations. Through the main data bus, data comes to the central network control center for further processing. Depending on the type of unit served, there are Home Area Network - HAN, Industrial Area Network - IAN and Building Area Network - BAN [5.21].

At the upper level, internal networks communicate with the contract partner, forming external networks. They are already included in the AMI and are fully equipped with all control and monitoring systems. At the distribution level, regional networks (Wide Area Network - WAN) are used, which include regional networks (Neighborhood Area Network - NAN) and industry networks (Field Area Network - FAN). At the top level of external networks, so-called core networks are used, on the levels of electrical energy generation and transmission.

For communication of all AMI devices, standard data exchange protocols are used, among which the most common are ZigBee - a wireless communication protocol between low-consumption devices, with the possibility of building a cellular network topology (common in smart home systems) and Modbus - a standard protocol for organizing communication between electronic devices in the industry.

5.5 Prospects and limitations of demand management technologies

International experience shows that the development of demand management technology in energy markets is based on the principle of "simple to complex":

- first, large consumers with a powerful centrally controlled load are involved in price-dependent programs;

  the demand management further includes smaller loads from industrial and commercial customers. The volume of this total resource is mainly related amount of pumping equipment, ventilation and air conditioning systems, refrigeration units of industrial and especially commercial real estate, this technology is implemented in Russian pilot aggregation projects.

- the largest volume of demand management is expected to be associated with solutions that will allow to aggregate the load capacities from low-power commercial and residential consumers that are not yet available for it [5.9].

The consumers' benefits in relation to energy efficiency in power supply systems are reduction in energy consumption or costs while maintaining the same level of production and / or comfort of the equipment use due to incentive payments to participants in demand management programs.

Power system long-term effects are refusal or delay of construction of new generating and grid capacities, reduction of overloads in existing networks. The added environmental effect is the harmful substance emissions reduction in the atmosphere because of decrease in the amount of electrical power generated by power plants with low fuel efficiency. The effect is especially strong for large volumes, i.e. for the participants of the price-dependent programs that supplant inefficient generation.

There are, of course, demand management technology limitations, which will affect its development.

The smaller and more mass consumers are involved in demand management programs, the higher the specific and total integration and transaction costs. These include capital costs of converting the consumer load into a remotely managed one; capital and operational costs of integrating consumers into the information and management part of demand management and maintenance of relevant information systems; capital and operational costs of integrating consumers into information systems of commercial accounting, calculation and implementation of payments. Taking into account the speed of this kind of digital technologies and platforms equipment cost reduction, it is possible to expect a rapid reduction of these costs.

The second challenge is the preparation of normative regulatory documents and their revision. Currently, there is no unified normative base at the regional level: different indices for the same cost items are set for different of the Russian Federation, which in turn is determined by the competitive advantages of the region. The inertia of the regulatory process is another limiting factor.

Thus, the key factor of competitiveness in the new market will be the development and implementation of fundamentally new digital technologies: transactional platforms, measurement and commercial accounting systems, solutions based on "big data", artificial intelligence, the Internet of things and wireless communication systems with the proper level of cybersecurity. All of them are needed to ensure easy and fast scalability of aggregators' business models and are developing in Russia within the framework of the National Technology Initiative in the "EnergyNET" program [5.2].

Despite the above-mentioned difficulties of demand management technology implementation, the world experience allows us to expect that it may be extremely productive in the near future in terms of increasing consumer power supply system efficient operation at all levels in Russia.

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Test questions

How the effect of consumer participation in demand management is formed when peak hour consumption decreases (as shown in Figure 5.2)

- The demand curve changes in a way that leads to a decrease of the electricity price
- The demand curve changes in a way that leads to an increase of the electricity price
- The demand curve does not change, cheaper generators are connected to the grid and the electricity price drops.
- The demand curve does not change, more expensive generators are connected to the grid and the electricity price is rising.

Who can take part in the large scale price-dependent reduction of electricity and power consumption?

- Large consumers on the wholesale electricity and capacity market
- Large producers on the wholesale electricity and capacity market
- Retail consumers in the electricity grid
- Small generation, including sources that are part of the active consumer
- All listed electricity market participants

The concept of "Active Consumer" corresponds to:

- Ability to change the mode of its power consumption, not taking into account system operator plans
- Choosing the degree of its participation in the provision of controlled active loads to the system operator
- Choosing the degree of its participation in providing controlled reactive loads to the system operator
- All of the above mentioned

The role of demand management aggregators includes, among other things:

- To find consumers with the ability to change their consumption without compromising main production
- Assessing the opportunities for consumers to change their consumption
- Provision in the wholesale market of combined load management resource of a group of consumers' loads as a single element
- Development of optimal algorithms for retail consumer participation in demand management programs
- All of the above mentioned.

What can be used as a resource for changing consumption:

- Electrical energy storage systems owned by the consumer
- Electric vehicle owned by consumers
- Electrothermal load of the consumer
- Consumer pumping and ventilation equipment
- All of the above mentioned

What costs are limiting the development of demand aggregation technology today?

- Maintenance of information systems of demand management systems
- Operating costs for integrating consumers into commercial accounting information systems
- Serving payments between participants in the aggregation program
- All of the above mentioned

6 Financing mechanisms and economic evaluation of energy efficiency measures in power supply systems

6.1. Economic regulation of the state in the field of energy efficiency

Tax support

In accordance with paragraph 5 of Article 67 of the Tax Code of the Russian Federation on investments in the creation of facilities and technologies of high energy efficiency, it is possible to provide an investment tax credit [6.1].

In accordance with paragraph 21 of Art. 381 of the Tax Code of the Russian Federation with respect to newly commissioned facilities having high energy efficiency and for newly commissioned facilities having a high class of energy efficiency for three years from the date of registration of this property, organizations are exempt from paying property tax [6.1]. The list of such facilities is established by Decree of the Government of the Russian Federation of June 17, 2015 No. 600 “On approval of the list of facilities and technologies that relate to facilities and technologies having high energy efficiency” [6.2].

The subjects of the Russian Federation, as measures of tax support for measures in the field of energy efficiency and energy efficiency, are entitled to establish tax incentives for regional taxes.

Budget support

In accordance with part 3 of article 27 of Law No. 261-FZ, federal budget support in the field of energy efficiency can be provided through co-financing of expenditure commitments in the field of energy efficiency of the constituent entities of the Russian Federation and municipalities in the form of subsidies from the federal budget [6.3]. The procedure for providing subsidies is determined by Decree of the Government of the Russian Federation of July 31, 2014 No. 754 [6.4].

In accordance with part 2 of article 27 of Law No. 261-FZ, one of the forms of state support for investment activities in the field of energy efficiency and preservation is the ability to reimburse part of the cost of interest on loans received from Russian credit organizations for investment activities, the implementation of investment projects in the field of energy efficiency [6.3].

Budget support measures for energy efficiency, implemented at the level of the constituent entities of the Russian Federation, municipalities, may include the provision of subsidies from budgets of the appropriate level and the provision of state guarantees of constituent entities of the Russian Federation of municipal guarantees for loans for projects in the field of energy efficiency.

Tariff Support

State support of tariff (price) incentives for energy conservation and energy efficiency can be carried out in accordance with federal laws and other regulatory acts of the Russian Federation and entities of the Russian Federation by:

• differentiation of prices (tariffs) by time of day (set time periods), differentiation by other criteria reflecting the degree of use of energy resources;

• establishment by state authorities in the field of state regulation of tariffs of the social norm of consumption of energy resources by the population;

• implementation of other tariff (price) incentive measures based on a combination of interests of producers, suppliers and consumers of energy resources.

One of the main incentives for increasing the energy efficiency of natural monopolies, organizations of the municipal complex is the use of long-term methods of tariff regulation, including, first of all, the method of return on invested capital, while at the same time fixing the obligations of companies on the quality, reliability and development of the services provided. With such regulation, companies have incentives to reduce costs, including energy resources, to increase the efficiency of resource use, as the resulting savings are saved by the company and can be used at any price.

Investment projects government guarantees to improve energy efficiency in the constituent entities of the Russian Federation

In accordance with the Decree of the Government of the Russian Federation dated December 14, 2010 No. 1016 “On approval of the Rules for the selection of investment projects and principals for the provision of state guarantees of the Russian Federation for loans or bond loans attracted for investment projects” for loans, bond loans for investment projects in the field of energy conservation and energy efficiency it is possible to provide state guarantees of the Russian Federation [6.5]

The general selection criteria for investment projects and principals for the provision of state guarantees of the Russian Federation are the following:

• at least 15% of the total project cost should be financed by the principal from own funds;

• the total volume (share) of state support provided by the Russian Federation and (or) the constituent entities of the Russian Federation to the principal on the project being implemented (financed) in various forms should not exceed 75% of the total project cost carried out (financed) by this principal;

• the planned amount of project financing for the bond loans and (or) loans attracted for its implementation secured by the state guarantee of the Russian Federation does not exceed 50% of the total project cost.

6.2 Mechanisms for financing energy-saving measures.

Energy-saving projects can be financed both on a repayable and non-repayable basis. The predominant form of implementing a project financing scheme on an irrevocable basis is government investment programs. Return-based project financing schemes are more inherent in a market economy. Funds allocated on a repayable basis are repayable in accordance with applicable law [6.6].

Table 6.1 - Schemes for financing projects on a return basis

Name	Description of the financing scheme
Traditional	The traditional financing scheme includes an investor (creditor), a consumer of energy-efficient technology and its supplier. The consumer takes a loan from the lender, enters into a contract with the supplier for the purchase of equipment, pre-paying its cost, and due to subsequent energy savings repays the debt to the lender.
Lease	The consumer rents energy-efficient and expensive equipment with the condition of a gradual payment of value with interest due to savings from the reduction of energy consumption after its implementation. In many cases, it is advisable for the contract to provide, after the full cost of the equipment has been paid, to transfer it to the consumer.
Energy service contract (performance contract)	Energy service company takes over the entire range of activities: from energy audits to identify the reserves for increasing energy efficiency, the introduction of energy-efficient technologies to turnkey. Payment for the services of an energy service company is carried out after the implementation of the project at the expense of part of the funds received as a result of energy savings.

The main source of financing in the field of energy saving is an energy service agreement (contract). The subject of the contract is the implementation by the contractor of actions aimed at energy conservation and improving the energy efficiency of energy use by the customer [6.3].

The energy service agreement must contain:

1) condition on the amount of energy resources savings (including in value terms), which must be provided by the contractor as a result of the execution of the energy service agreement (contract);

2) condition on the duration of the energy service agreement (contract), which must be at least the period necessary to achieve the amount of energy resources saving established by the energy service agreement (contract);

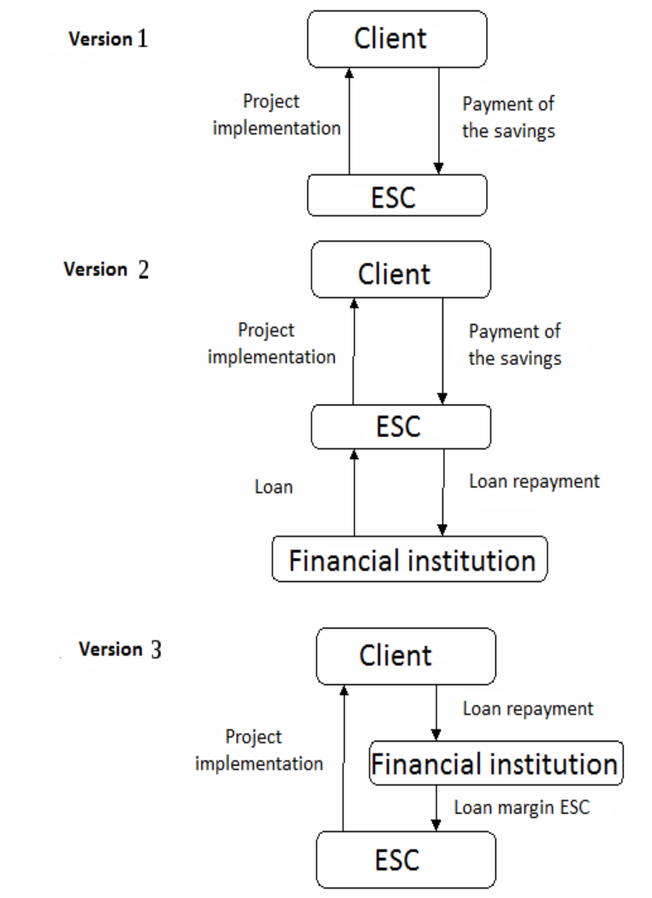
3) other mandatory conditions of energy service contracts (contracts established by the legislation of the Russian Federation.

Energy service is an independent business which functions are to provide specialized services to individual parts of the energy supply process from generation to use of energy, inclusive [6.7].

Distinctive features of the energy service:

- energy consumer does not spend his own money;
- part of the risk is assumed by a specialized company implementing the project;
- all the project costs are then reimbursed from funds saved as a result of the introduction of energy-saving technologies.

Table 6.2 - three schemes for concluding energy service contracts.

<table>
<tr><th>Energy Service Contract Options (ESCOs)</th><th>Description</th></tr>
<tr><td>


</td><td>Version 1. An energy service contract is concluded only between the customer and the ESCO; the credit institution is not involved in this transaction. The application of this scheme is possible if the ESCO has sufficient financial resources.

Version 2. A tripartite loan agreement is concluded between the financial institution, ESCO and the customer, under which the ESCO is the borrower. The purpose of the loan is indicated - the implementation of an energy-efficient project at the customer's site.

Version 3. Under the terms of the energy service contract and the loan agreement, the customer is required to open a current account with a credit institution that finances the implementation of the energy-efficient project, and the customer is entitled to make all payments for energy resources only from this current account.</td></tr>
</table>

6.3 Indicators of economic efficiency of investment projects

The effectiveness of investment projects is determined on the basis of the system of indicators shown in table 6.3.

Table 6.3 - Project performance indicators.

Indicator	Project Performance Indicator Description
Commercial (financial) efficiency	It takes into account the financial consequences of the project for its direct participants. It is determined by the ratio of costs and financial results that provide the required level of profitability. Commercial efficiency can be calculated for the investment project as a whole or for specific project participants, taking into account their contribution.
Budget efficiency	Reflects the impact of project implementation on revenues and expenses of the federal, regional or local budget. The main indicator of the budgetary effectiveness of the project is the budgetary effect, which is used to justify the federal or regional support measures laid down in the project.
Cost effectiveness	It reflects the impact of the investment project implementation process on the external environment for the project and takes into account the ratio of results and costs of the investment project, which are not directly related to the financial interests of the project participants and can be quantified.

Continuation of Table 6.3

Indicator	Project Performance Indicator Description
Social performance	Shows the role of this project for the "target" population. A large energy project should reflect the interests of the population (new jobs, territory development, tariff reduction, etc.) and have the support of the population.
Environmental performance	Shows the environmental impact of the project (greenhouse gas emissions, noise, impact on the soil, alienation of territories). The existing negative consequences should be minimized and compared with the benefits of the project.

The choice of an investment project providing for state support is based on the maximum integrated effect of performance indicators [6.8].

According to methodological recommendations, investment efficiency is also characterized by a system of quantitative indicators that reflect the ratio of costs and results and allow judging the economic advantages of some investments over others [6.9].

The group of static indicators of investment efficiency, when cash flows arising at different times are considered equivalent, include the payback period of investments (Payback Period, PP) and the coefficient of investment efficiency (Accounting Rate of Return, ARR).

The project payback period is understood to mean the period from the moment of its implementation to the moment of operation of the facility in which the operating income becomes equal to the initial investment (capital costs and operating costs). The economic meaning of the indicator is to determine the period for which the investor can return the invested capital.

To calculate the payback period, the elements of the payment series are summed up on an accrual basis, forming the balance of the accumulated flow, until the amount assumes a positive value. The sequence number of the planning interval, in which the accumulated flow balance becomes positive, indicates the payback period expressed in planning intervals.

The general equation for calculating the payback period indicator PP is:

$$PP = min, when \sum P_k \geq I_0 \tag{6.1}$$

where P_k – balance of accumulated flow;
I_0 – initial investment

Upon receipt of a fractional number, it is rounded up to the nearest integer.

Another indicator of a static financial assessment of a project is the Accounting Rate of Return (ARR). This ratio is also called the accounting rate of return or the coefficient of profitability of the project.

There are several algorithms for calculating the effectiveness of ARR investments.

The first calculation option is based on the ratio of the average annual profit (minus deductions to the budget) from the project for the period to the average investment:

$$ARR = P_{\text{r}}/(1/2)I_{\text{cp0}} \tag{6.2}$$

where P_{r} – the average annual amount of profit (minus deductions to the budget) from the project,

I_{cp0} – the average amount of initial investments, if it is assumed that after the expiration of the project, all capital costs will be written off.

Sometimes the project profitability indicator is calculated on the basis of the initial investment:

$$ARR = P_{\text{r}}/I_0 \tag{6.3}$$

Calculated on the basis of the initial volume of investments, it can be used for projects that create a stream of uniform income for an indefinite or sufficiently long period.

The advantage of a static investment performance indicator is its ease of calculation. At the same time, these indicators have significant drawbacks. They do not take into account the value of money over time and do not involve discounting, respectively, do not take into account the distribution of profits by years, which means that they are applicable only for evaluating short-term projects with a uniform income stream.

References

6.1 The tax code of the Russian Federation: part 1 of July 31, 1998 No. 146-FZ (as amended on December 27, 2019); Part 2 of August 5, 2000 No. 117-FZ (as amended on December 27, 2019)

6.2 Decree of the Government of the Russian Federation of June 17, 2015 No. 600 “On approval of the list of facilities and technologies that relate to facilities and technologies having high energy efficiency” (as amended on January 23, 2019).

6.3 Federal Law of November 23, 2009 No. 261-ФЗ (as amended on July 26, 2019 No. 241-ФЗ) “On Energy Saving and on Improving Energy Efficiency and on Amending Certain Legislative Acts of the Russian Federation”

6.4 Decree of the Government of the Russian Federation of July 31, 2014 No. 754 “On the provision of subsidies from the federal budget to the budgets of the constituent entities of the Russian Federation for the implementation of regional programs in the field of energy conservation and energy efficiency and recognition of the acts of the Government of the Russian Federation as invalid” (as amended on January 26, 2019 g.)

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15 norm-load.ru
16 StandartGost.ru
17 http://energyland.info

Test questions

Production (economic) activities in the field of energy conservation are characterized by indicators

- energy consumption and energy intensity of production in the reporting year in comparison with the base year in the new conditions
- quality of design and technological development of products
- specific indicators of energy consumption

Budget support in the field of energy conservation and energy efficiency can be carried out by allocating

- soft loans
- grants
- subsidies

Does Law No. 261-ФЗ provide for one of the forms of state support for investment activities in the field of energy conservation and energy efficiency improvement of the possibility of reimbursing part of the cost of paying interest on loans, loans received from Russian credit organizations

- yes
- no

A distinctive feature of the energy service is

- part of the work is performed by a specialized company
- all risks are borne by the consumer
- all project costs are then reimbursed from the funds saved as a result of the introduction of energy-saving technologies

The energy service contract is called

- performance contract
- fulfillment contrast
- service contract
- work agreement

The energy service agreement (contract) must contain

- legal address of the contractor
- a condition on the amount of energy resources savings that must be provided by the contractor as a result of the execution of the energy service contract
- condition on state guarantees of the Russian Federation
- loan agreement

Energy service contract is concluded

- only between the customer and the ESCO
- as a tripartite loan agreement under which the borrower is an ESCO
- both options are possible

Commercial (financial) effectiveness of the project reflects

- the impact of project implementation on revenues and expenditures of the federal, regional or local budget.
- the impact of the investment project implementation process on the external environment for the project and takes into account the ratio of results and costs of the investment project, which are not directly related to the financial interests of the project participants and can be quantified
- financial implications of the project for its direct participants.