TOMSK POLYTECHNIC UNIVERSITY

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INDUSTRIAL ENERGY EFFICIENCY

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This book considers issues, reviewed by the courses “Industrial Energy Efficiency and Energy Audit”, “Optimization and Energy Saving Practices”, “Energy and Resource Saving Practices for Industrial and Utility Facilities.” The structure of power saving regulatory and legal framework is described herein, as well as organization and implementation of energy inspections for consumers, main energy efficiency increase in electrical energy supply systems of industrial enterprises, revenue metering of electrical energy in different voltage systems, calculation and performance analysis for industrial enterprise energy efficiency assessment.

Developed for students trained in the field 13.04.02 “Electrical and Power Engineering”.

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TERMS AND DEFINITIONS

Actual energy losses (reported losses) – a difference between energy volume, delivered to the grid and sold energy, calculated according to ratio of the amount of bills paid to a certain period of time.

Bilateral contract of electrical energy purchase-sale – the agreement, according to which a provider obliges to supply electrical energy to a buyer, meeting the obligatory requirements, in a certain amount and of certain quality, and a buyer obliges to accept and pay for the electrical energy under the terms of contract, concluded in compliance with wholesale market rules and principal regulations of retail market functioning.

Commercial losses of energy – a difference between supplied and useful consumed energy. They are conditioned by metering system imperfection, diversity and inaccuracy of meter readings, metering instrumentation error, irregular payments for energy consumption, the unaccounted consumers and theft.

Domestic energy-using appliance – products, which functional purpose assumes using energy resources, power requirements of which does not exceed twenty one kW of electrical energy, for heat energy – 100 kW and which can be applied for personal, family, household and similar needs.

EE provider of last resort (hereinafter – provider of last resort) – a commercial organization, which duty, according to the current Federal legislation, or by constructive obligation is to conclude the sales and purchase agreement for electrical energy with any applying consumer of electricity or with a person, acting on behalf and for the benefit of electrical energy consumer and willing to purchase electrical energy.

Efficiency factor (EF) – a factor of energy consumption efficiency. It is found as a ratio of supplied power to total consumed power.

Electrical energy consumers – entities, purchasing electrical energy for their own domestic and/or industrial needs [1].

Electrical energy consumers with controlled load – the category of electrical energy consumers, which due to operation modes (electrical energy consumption) have effect on the electrical energy quality, reliability of operation of the Unified Energy System of Russia and due to this render paid services on contractual basis regarding recovery of the Unified Energy System of Russia in case of emergency situation. The specified consumers can also provide other agreed services on contractual basis.

Electrical energy supply – a range of measures and engineering facilities to provide consumers with electrical energy.

Electrical equipment of labor – a ratio of electrical energy amount, used in a production process, to a number of workers.

Electromagnetic compatibility – an adjustment capability of electrical devices, generating electromagnetic fields, for joint work, at which the arising electromagnetic interference does not exceed the specified level and does not interfere with operation of each device.

Energy (output) parameter – a parameter of energy carrier consumption by a unit, depending on a secondary load amount.

Energy balance – a balance of production, processing, transportation, conversion, distribution and consumption of all types of energy and energy resources.

Energy component of a product cost – a share of produced goods cost, spent on purchase and consumption of fuel and energy resources.

Energy efficiency – characteristics, showing a ratio of useful effect from energy resources use to energy resources input, consumed for the purpose of such effect, in relation to a product, production process, legal entity and individual entrepreneur.

Energy efficiency – implementation of organizational, legal, engineering, processing, economic measures and other measures, aimed at reduction of used energy resources volume and keeping the respective useful effect from their use (including the volume of produced goods, performed activities and rendered services).

Energy efficiency class – a characteristic of the product, reflecting its energy efficiency.

Energy efficiency factor – an absolute or specific value of energy resources consumption, required for manufacture of any product, stipulated by the regulating documents.

Energy inspection – is a collection and processing of information about using of energy resources to obtain reliable information about volume of energy resources used, energy efficiency factors, to reveal the energy-saving potential and energy efficiency increase with the results reflected in the energy certificate.

Energy intensity of product (specific consumption) – an economic and statistical factor, determined according to a ratio of consumed energy resources volume to manufactured products in kind.

Energy performance agreement (contract) – agreement (contract), the subject of which means actions performed by Contractor, aimed at energy saving and energy efficiency increase of used energy resources for the Customer.

Energy producer – is a commercial organization, regardless of its organizational and legal form, producing and supplying electrical and heat energy in the grids for further transformation, transmission, distribution and sale to consumers.

Energy resource – an energy carrier, which energy is used or may be used for conduct of an economic or other activity, as well as the type of energy (atomic, heat, electrical, electromagnetic energy or any other type of energy).

Energy sales organizations organizations, which perform selling of produced or purchased electrical energy to other entities as the main activity.

Energy saving reserve (potential) – amount of consumed fuel or energy potential economy, estimated by experts, from any implemented energy-saving measures.

Energy security a protectability of the State, region, enterprise and a person from the threat of energy and energy resources deficiency in the amount and quality, required for vital activity of current and future generations.

Energy supply reliability – capability to perform the assigned functions and keep the performance criteria within conditions, stipulated by regulating documents.

Entities of electric power engineering sector – entities, which engage in activities in the electric power engineering sector, including generation of electrical, heat energy and power, purchase and sale of electrical energy and power, power supply to consumers, rendering of services on electrical energy transmission, operational dispatch management in the electric power sector, sale of electrical energy (power), organization of purchase and sale of electrical energy and power.

Estimated losses of energy – losses, conditioned by energy consumption for heating, thermodynamic cycle imperfection, which are calculated according to the well-known physical regularities and operation mode parameters.

Fuel and energy consumption standard – a regulated amount of fuel and energy consumption for the given enterprise, process, products, works and services.

Fuel and Energy Resource (FER) – a set of all natural converted types of fuel and energy, which are currently used in economic activities. Energy carrier which is currently used or may be (usable) applied in future.

Gross Domestic Product (GDP) – a generalizing statistical factor, expressing a total cost of domestically manufactured products in market prices.

Gross National Product (GNP) – an economic index, expressing a total cost of final goods and services in market prices. It includes the cost of goods and services consumed by population, public purchases, capital investments and balance of payments.

Market price – price for goods, formed at the goods market without federal influence on the price.

Monitoring – observation, evaluation and forecast of the object under study in view of varying external environmental factors or internal processes, and people's economic activity.

Non-productive consumption of energy resources – energy resources losses, caused by violation of federal standards requirements for equipment, design criteria, process regulations or mismanagement.

Operating generating capacity – a part of the maximum available capacity of facilities for electrical and heat energy generation, excluding the capacity of industrial power facilities, taken out of service for maintenance according to established procedure.

Organizations with the participation of government or municipality – legal entities, where a share (contribution) of the Russian Federation, a constituent entity of the Russian Federation, a municipality in charter capitals makes more than 50 percent and (or) regarding which the Russian Federation, a constituent entity of the Russian Federation, of a municipality are entitled to exercise more than 50 % of the votes directly or indirectly, which fall within voting stocks (shares), constituting charter capitals of such legal entities as the state or municipal unitary enterprises, state or municipal institutions, state-owned companies and corporations, as well as legal entities which property belongs to the state-owned corporations either by over 50 % of stocks or shares in charter capital.

Power consumers – entities, purchasing power, including for their own domestic and/or industrial needs, and/or for further sale, entities, selling electrical energy in retail markets, entities, selling electrical energy in the territories, where electric power systems of foreign states are located.

Prices (tariffs) in electric power engineering sector – the system of price rates, according to which payments for electrical energy (power) are settled, also for services, provided in wholesale and retail markets (hereinafter – prices (tariffs)) [2, 3].

Reference fuel – a conventional physical unit, applied for proportioning of different fuel types, using the factor which equals to the ratio of 1 kg fuel heat content of this kind to heat content of 1 kg reference fuel, which is equal to 29.3076 J/kg (7000 kcal/kg).

Regulated activities – activities, performed by entities of natural monopolies, communal organizations, in regard of which the price (tariff) regulation is exercised according to the Russian Federation legislation.

Regulated price – price for goods (tariff), formed at the goods market with the direct federal influence on the price, including setting of its limit or fixed size.

Regulation period – a time interval (quarter, six months, a year), taken for calculation of indices, included in the tariff-setting offers for electrical and heat power, and payment amounts for services.

Renewable energy sources – solar, wind and water energy (including energy of waste waters), except for cases of such energy use in pumped-storage power stations, tidal energy, wave energy of water bodies, including reservoirs, rivers, seas, oceans, geothermal energy using the natural subsurface heat transfer agents, low-potential geothermal energy, energy of air, water with special heat carriers, biomass, including specifically grown plants for obtaining energy, among them trees, as well as production and consumer wastes, excluding wastes from raw hydrocarbons, biogas, landfill gas from production and consumer wastes, and gas emitted in coal mines.

Retail markets of electrical energy (hereinafter – retail markets) – the area of electrical energy distribution beyond the wholesale market with participation of electrical energy consumers.

Revenue metering of electrical energy (power) – a process of electrical energy metering and defining a volume of power, accumulation, storage, processing, transfer of these readings results and formation, including by means of calculation, data about amount of generated and consumed electrical energy (power) for purposes of mutual settlement payments for provided electrical energy and power, as well as for related services.

Secondary energy resource – an energy resource obtained as production and consumer waste or potential of products, wastes, intermediate and by-products, generated as a result of a production process or operation of equipment which functions are not related to production of the respective energy resource.

Social norm of electrical energy (power) consumption – a specific amount (volume) of electrical energy (power), which is consumed by population and equivalent categories of consumers, within boundaries of which and above which electrical energy (power) delivery is done at varying regulated prices (tariffs) [2, 3].

Specific energy (fuel) consumption – a factor, found by ratio of actually consumed fuel amount (in physical terms or in reference units) to amount of actually manufactured products of this kind.

Standardization – an activity of regulating documents development and approval, which stipulate a complex of norms, rules, provisions and requirements, obligatory for design development, manufacture, construction, reconstruction and operation of equipment, processes and devices.

Unaccounted consumption of fuel and energy resources – consumption of fuel and energy resources (FER) by enterprises, organizations or individuals without metering devices, or using defective and low-quality meters, including such readings that can be falsified easily.

Wholesale market agents – legal entities, which obtained according to current Federal law procedure the right to participate in relations, connected with electrical energy and/or power distribution in wholesale market, in compliance with the wholesale market rules, approved by the Government of the Russian Federation.

Wholesale market of electrical energy and power (hereinafter – wholesale market) – is the area of special products distribution – electrical energy and power within the Unified Energy System of Russia in the boundaries of the common economic zone of the Russian Federation with participation of major producers and major buyers of electrical energy and power, as well as other parties, which have obtained the status of wholesale market entities and acting based on the wholesale market regulations. Criteria of referring to electrical energy producers and buyers to the category of major producers and major buyers are set by the Government of the Russian Federation.

INTRODUCTION

The issues of rational and efficient consumption of fuel and energy resources (FER) acquire more important value.

Calculation methods for electrical energy losses in electric equipment, electrical energy saving by improvement of engineering processes, process equipment productivity increase, etc., given in this book, only cover general industrial units.

Application of electrical energy is versatile and it is practically impossible to provide for all possible saving measures, that is why activities, carried out for most industrial facilities, are recommended in this textbook.

Great attention to rational use of electrical energy, fuel and energy resources, is also given at the government level. Main trends of the Federal Energy Efficiency Policy are given in Federal Law No. 261 ‘On Energy Conservation and Energy Efficiency Increase and about Amendments to Certain Legislative Acts of the Russian Federation’ approved by the State Duma on November 11, 2009 [4].

Main trends of the Federal Energy Efficiency Policy

Goal of the energy efficiency policy of Russia consists in the maximum efficient use of natural energy resources and energy sector potential for a sustainable development of the economy, increase of population life quality and contribution to strengthening of its foreign economic position.

Objectives of the Russian Federation Energy Strategy up to 2030 are determined by major domestic and external challenges of the forthcoming long-term period [5].

A major domestic challenge consists in necessity for an energy sector of the country to implement its most important role of transition to innovative way of economy development within the Concept framework. The guaranteed meeting of domestic demand for energy resources should account for the following requirements:

- ✓ Provision of welfare standards by Russia that correspond to those of the developed economies;
- ✓ Achievement of research and engineering leadership of Russia for a number of major trends, providing its competitive advantages and national, including energy, security;
- ✓ Transformation of the country’s economy structure in favor of less energy-consuming industries;
- ✓ Transition of the country from raw materials export towards resource-innovative development with a quality renovation of power sector (both fuel and non-fuel) and related sectors;

✓ Rational reduction of fuel and energy complex share in total volume of investment in the country economy along with increase of absolute volume of investment in energy sector, required for development and accelerated modernization of the sector and growth of its activity scale;

✓ Necessity to increase energy efficiency and reduce energy intensity of economy to the level of countries with similar natural and climate conditions (Canada, Scandinavian countries);

✓ Gradual limitation of fuel and energy complex load on the environment and climate by reducing the pollutants emission, polluted wastewater discharge, and greenhouse gases emission, reduction of production wastes and energy consumption.

A major external challenge consists in the necessity to address the threats, related to the world energy markets instability and volatility[1] of world prices for energy resources, as well as provision of energy sector contribution to increase of its foreign economic activity and strengthening of Russia's position in the global economic system. It means that the following shall be provided for:

✓ Achievement of sustainable results of foreign economic activity in the area of fuel and energy complex in conditions of the increasing global competition for resources and sales markets;

✓ Minimization of negative effects of a global economic crisis and using it for a complete renovation diversification of economy structure in favor of less energy-consuming industries, stimulation of a Russian energy sector transition to an accelerated innovative development and a new technological pattern;

✓ Increase of a strategic presence of Russia in the markets of high-technology products and intellectual services in the energy sector, including due to deployment of globally oriented specialized enterprises;

✓ Geographic and product diversification of the Russian energy export in conditions of steady and expanding supply of energy resources to largest world consumers;

✓ Rational reduction of a fuel-energy resources share in the Russian export structure, transition from selling the primary raw and energy resources abroad towards selling the products of advanced processing, as well as development of petroleum products, produced by foreign refineries, owned by the Russian oil companies;

✓ Development of major hubs of international energy infrastructure in the territory of Russia, using new energy technologies.

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[1] **Волатильность** (от английского volatility) – статистический показатель, характеризующий тенденцию рыночной цены или дохода изменяться во времени.

The RF Energy Policy is implemented at the federal and regional levels based on the RF Constitution, legislative and regulatory acts and provides for a legal regulation of relations in the sector of fuel and energy supply, cooperation of the federal executive bodies with the RF entities for solving the energy problems.

A New Regional Energy Policy combines a natural intention of regions towards self-government and self-provision with end energy carriers along with keeping the unity of FEC of Russia as the most important factor of economic and political integration of the country. Interests of regions will be satisfied by expanding their share of ownership in energy facilities stock of federal level and the rights for economic administration of the facilities along with keeping the unity of process management. The regional energy policy takes into consideration the significant difference in energy supply and structure of fuel-energy balance of different regional zones – the northern, southern, central regions of the European part of Russia, Ural, Siberia, Far East and Far North regions.

CHAPTER 1. ENERGY EFFICIENCY REGULATORY AND LEGAL FRAMEWORK

An important component of anti-recessionary measures complex in the country's economy is the Federal energy efficiency policy.

Energy efficiency is an initial stage of structural reconstruction of all economy sectors in the country. Regulatory and legal framework of the following hierarchy was developed for establishing conditions and raising an interest for energy efficiency of all parties to production –… – consumption – utilization:

I. General legislation:
   1.1. Constitution of the Russian Federation [6].
   1.2. Civil Code of the Russian Federation [7].
   1.3. Administrative Offences Code of the Russian Federation [8].
   1.4. The Criminal Code of the Russian Federation [9].
II. Federal legislation:
   2.1. Federal laws, adopted by the State Duma of the Russian Federation.
   2.2. Decrees of the RF President.
   2.3. Regulations and resolutions of the RF Government.
III. Regional legislation:
   3.1. Regional laws, regulations and resolutions of regional authorities.
IV. Regulations and resolutions of the municipalities.
V. Orders and instructions of enterprises and organizations CEOs of all property forms.

The RF Constitution (as of 12 December 1993) has divided the powers among federal and other authorities. According to the RF Constitution, the RF entities possess a full state power. Regulation issues in the area of electrical energy sector at the level of JSC-Energy Sector and lower are placed under the jurisdiction of the Federation entities.

The Civil Code of the RF (Para 6 Energy Supply) considers the following:

- ✓ Rules of electricity supply agreement conclusion, including those with population;
- ✓ Rules of such agreement amendment and termination;
- ✓ Methods for supplied energy quality metering;
- ✓ Requirement to maintain the electrical energy quality standard;
- ✓ Buyer's responsibility on maintenance and operation of grids, instruments and equipment;

✓ Liability under Energy supply agreement.

✓ Recognition of economic liability of a power supplier for damage, incurred by a consumer during power outages;

✓ Stipulation of CEO responsibility for electrical and heat energy wasteful consumption by their enterprises, organizations and institutions.

Among recent laws, passed at the federal level, the most urgent is the Federal Law No. 261-FZ *"On Saving Energy and Increasing Energy Efficiency, and On Amendments to Certain Legislative Acts of the Russian Federation"* dated 23 November 2009, purpose of which is establishing a legal, economic and organizational basis for energy saving stimulation and energy efficiency increase.

Legal regulation in the area of energy saving and energy efficiency increase according to FZ No. 261 is based on the following principles:

1. Efficient and rational use of energy resources.
2. Support and encouragement of energy saving and energy efficiency increase.
3. Consistency and integrity of measures on energy saving and energy efficiency increase.
4. Planning of energy saving and energy efficiency increase.
5. Consumption of energy resources with consideration for resource, production and processing, environmental and social conditions.

The law clearly regulates the following:

1. Powers of the state authorities of the Russian Federation (RF), the state authorities of the RF entities, the local government authorities in the area of energy saving and energy efficiency increase.
2. State regulation in the area of energy saving and energy efficiency increase, which is done by setting the following:

✓ Requirements to certain goods distribution, which functionality assumes use of energy resources;

✓ Prohibition and limitation of production and distribution of goods with a low energy efficiency in the RF;

✓ Obligations to meter the consumed energy resources;

✓ Requirements to energy efficiency of buildings and structures;

✓ Obligations to carry out an obligatory energy inspection;

✓ Requirements to Energy Certificate;

✓ Obligations for energy saving and energy efficiency increase measures in respect of common property of premise owners in a block of flats;

✓ Requirements to energy efficiency of goods, works, services, order placement for which is done for federal or municipal needs;

- ✓ Requirements to regional, municipal programs in the area of energy saving and energy efficiency increase;
- ✓ Requirements to programs in the area of energy saving and energy efficiency increase in organizations with state or municipality ownership, performing the regulated activities;
- ✓ Basis of state information system functioning in the area of energy saving and energy efficiency increase;
- ✓ Obligations to distribute information in the area of energy saving and energy efficiency increase;
- ✓ Obligations to implement informing and educational programs in the area of energy saving and energy efficiency increase;
- ✓ Order of obligations performance, stipulated by the FZ No. 261;
- ✓ Other measures of state regulation in the area of energy saving and energy efficiency increase.

In conclusion, it should be mentioned that regulatory legal framework of energy saving is a living adaptive mechanism, which constantly undergoes changes, caused by contemporary requirements, the State policy, etc. However, goal of this basis remains the same – to create conditions for production, generation, transmission, distribution and consumption of fuel-energy resources, meeting the maximum technical and economic efficiency at all levels.

CHAPTER 2. CONTRACTUAL RELATIONS BASIS

The main document, regulating relationships between consumers and power suppliers is Electricity Consumption Agreement (Electricity Supply Agreement). This agreement is not a model document for organizations of different property types and is referred to as public agreements[2].

The norms of current Civil Code, regulating the Electricity supply agreement, are given in Para 6 (“Energy Supply”) pp. 539–548 [7].

The RF Civil Code deals with:

✓ Procedure of Electricity Supply Agreement conclusion, including with population, terms of such agreement amendment and termination;

✓ Metering methods and requirement to comply with electrical energy quality standards;

✓ Buyer's obligations on maintenance and operation of grids, instruments and power equipment;

✓ Liability under the Electricity Supply Agreement.

This is the first time when an actual economic liability of a power-supplying organization for damage, caused to a consumer during power outages, is indirectly reflected in the RF Civil Code.

Electricity Consumption Agreement (hereinafter ECA), besides provisions on distribution of parties’ liability and obligations, has a number of sections, annexed to the Agreement, namely [10, 11]:

✓ Statement of balance attribution of grids and operational responsibility of the parties;

✓ Amount of electrical energy (EE) supply with a monthly breakdown;

✓ Economic values of reactive power consumption [12];

✓ The declared active power value of a facility, participating in the maximum load of energy system (for dual-rate consumers);

✓ Losses rates for feeders and power transformers in cases when revenue metering points do not coincide with the boundary of balance attribution;

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[2] **Public agreement** is an agreement, concluded by a commercial organization and setting its obligations on sale of goods, performance of works, which such organization by the nature of its activity shall perform in respect of anyone, who refers (retail trading, carriage by common use transport, communication services, etc.).
Refusal of commercial organization from public agreement conclusion when there is an availability to provide a consumer with respective goods, services, perform respective works for him is not allowed. Price for goods, works and services, as well as other conditions of public agreement are stipulated the same for all consumers, except for those, which are vested with benefits by law or other legislative acts.
Conditions of public agreement are defined by "preliminary conditions", developed for respective agreements and published or set out in the form of a standard contract.

✓ A list of single rate consumers which are on the main user's books with indication of active powers, consumed during the maximum load hours; reactive energy, consumed by sub-users and leaseholders, paying for EE at a single-rate tariff;

✓ Single-line scheme of external electricity supply with indication of all electrical energy supply points.

2.1. Terms of Agreement Conclusion

As a rule, energy-selling companies start the agreement signing campaign in October. ECA is concluded for the next calendar year till December, 31. It becomes effective from the moment of signing and is considered annually extended unless one of the parties withdraws or claims it to be revised at least one month before the Agreement expires.

In cases when ESA duration expires and none of the parties claims its termination or amendment, or signing a new Agreement, the Electricity Supply Agreement is regarded as extended under the same conditions and for the same period.

Agreement terms can be amended when new normative documents are issued, which regulate relationships of consumers and power suppliers. The concerned party should initiate the Agreement revision. The Agreement conditions are changed by agreement and signing of protocol of disagreements.

Electricity Supply Agreement is concluded with a user provided that he has the power receiving equipment, connected to a power supplier networks and other required equipment, as well as provision of energy consumption metering.

An energy-supplying organization shall supply the user with energy via connected grid in the amount, specified in the Electricity Supply Agreement, and complying with the agreed supply schedule. Amount of the supplied and consumed power is calculated, based on the metering data of its actual consumption [3].

Electricity Supply Agreement can provide for the right of a user to vary the amount of supplied energy, which is specified in the Agreement, under condition of cost reimbursement, incurred by a power supplier due to supplying power over the specified amount.

Quality of supplied energy shall comply with the requirements, established by the state standard (GOST – 13109-97) and other obligatory regulations, or as specified in the Electricity Supply Agreement [3, 7].

In case of power quality requirements violation by a power supplier, a user has the right to refuse to pay for such power. Along with that a power supplier has the right to claim the cost reimbursement that a user has saved groundlessly during this power consumption.

All values and norms, included in the Agreement, shall be economically and legally justified due to specific operating conditions of consumers and power suppliers. Failure to comply with legal requirements can lead to a significant overexpenditure of funds for consumed energy resources.

Further we will consider some ESA provisions, stipulating a rational use of funds for electrical energy.

2.2. Justification of the declared active power maximum

Amount of the declared active power in the energy system peak hours for dual-rate consumers is taken for each quarter (or month) with account for justified needs of the enterprise itself. For different consumers are provided various payment methods for declared power: prior to or during the first days of settlement period or four payments breakdown during settlement period.

Considerable number of modern enterprises include energy for non-production needs (catering, stores, sports facilities, social and cultural facilities, etc.) in their energy consumption structure, as well as for sub-users and leaseholders – these are mainly single-rate consumers, besides energy for the main production. Such consumers shall be equipped with active energy metering devices and be included in the ESA Annex with specification of active power amount, consumed by them during hours of the maximum energy system load.

Total active load of single-rate consumers ($P_{\Sigma\text{SGL}}$), participating in the declared maximum load of the main user, shall be excluded from payment according to basic tariff rate (for power)

$$P_{\max_3} = P_{\max} - P_{\Sigma\text{SGL}}.$$

If single-rate consumers are not listed in the ESA of the main consumer, payment for the declared active power will be higher by value $P_{\Sigma\text{SGL}}$.

2.3. Setting the norms of electrical energy losses

The below method is developed for calculating losses during financial settlements among energy systems and power suppliers, and consumers in cases when point of revenue metering devices does not coincide with the balance attribution boundaries and departmental liability of parties.

An additional payment is calculated by two tariff rates, depending on the point of a metering device installation:

1. The lowered tariff rate is applied when a metering device is installed on the primary voltage side (before the user's transformer), i. e. when an installed EE meter registers the consumed energy, including the EE losses in user's transformer.

2. The increased tariff rate is applied when a metering device is installed on the secondary voltage side (after user's transformer), i. e. when an installed electricity meter does not register electrical energy losses in user's transformer. In this case an increased tariff accounts for the payment of energy losses in the transformer.

Losses, not registered by a meter, should be attributed to the consumer, the owner of user's transformer.

To calculate the amount of unaccounted electrical energy losses in double-wound transformers, the following methods should be used.

2.3.1. Calculation of electrical energy losses in transformers when evaluating a design average power factor

Average power factor of consumer electrical installations is calculated for a settlement period (month) on the basis of total readings of active and reactive energy meters, installed on the primary voltage side of consumer transformers.

When EE is accounted on the primary voltage side of consumer's 35 kV and over transformers, and when a value of average power factor from total amount of consumed active and reactive energy is calculated, the EE losses are excluded for the stated transformer (feeder), and are calculated by the method, given below.

2.3.1.1. Losses in double-wound transformers

The following data is required for calculation of EE losses:

1. Catalogue or nameplate data:
   - ✓ Rated power of transformer S_R, $\mathrm{kV \cdot A}$;
   - ✓ Active power losses in transformer steel $\Delta P_\mathrm{ST} = \Delta P_\mathrm{NL}$, kW;
   - ✓ Active power losses in transformer copper windings for the rated load $\Delta P_\mathrm{c} = \Delta P_\mathrm{SC}$, kW;
   - ✓ No-load current of transformer I_NL, %;
   - ✓ Short circuit voltage U_SC, %.
2. Design data:
   - ✓ Reactive power losses of transformer, kvar:
     - No-load current $\Delta Q_\mathrm{NL} = S_\mathrm{N} \cdot \dfrac{I_\mathrm{NL}}{100}$;
     - Short circuit $\Delta Q_\mathrm{SC} = S_\mathrm{N} \cdot \dfrac{U_\mathrm{SC}}{100}$.

When calculating losses according to the method in the sequence, given below, the following can be found:

1. Active W (kW·h) and reactive V (kvar·h) energy for a month, registered by meters;

2. Average power factor $\cos\varphi_{\text{av}}$ by the formula $\text{tg}\varphi_{\text{av}} = \frac{V}{W}$ and then then by reference to trigonometric tables;

3. Load factor $k_{\text{L}} = \frac{W}{S_{\text{R}} \cdot T_{\text{p}} \cdot \cos\varphi_{\text{av}}}$,

where T_{p} – number of transformer operation hours, taken equal to 744 h for January, March, May, July, August, October, December; for April, June, September, November – 720 h; February – 672 h, and for a leap year – 696 h.

In case of transformer shutoff for holidays or weekends, the stated time should be reduced by the transformer shutoff period.

4. Transformer losses are calculated according to the formulae:

- ✓ Active energy losses

$$\Delta W = \Delta P_{\text{NL}} \cdot T_{\text{p}} + \Delta P_{\text{SC}} \cdot k_{\text{L}}^2 \cdot T_{\text{op}}, \text{ kW·h;}$$

- ✓ Reactive energy losses

$$\Delta V = \Delta Q_{\text{NL}} \cdot T_{\text{p}} + \Delta Q_{\text{SC}} \cdot k_{\text{L}}^2 \cdot T_{\text{op}}, \text{ kvar·h,}$$

where T_{op} – number of transformer operation hours during a month with the rated load, which equals to 200 h for one-shift operation enterprises, two-shift – 450 h, three-shift – 700 h.

The design average power factor $\cos\varphi_{\text{des}}$ for enterprises which have their meters installed on the primary voltage side (before user's transformer of 35 kV and over high voltage), is calculated by the formula

$$\text{tg}\varphi_{\text{des}} = \frac{V - \Delta V}{W - \Delta W},$$

and then by trigonometric tables we find $\cos\varphi_{\text{des}}$.

2.3.1.2. Losses in triple-wound transformers

To calculate losses, the following data is required:

1. Catalogue or nameplate data

- ✓ Rated power of transformer S_{R}, kV·A;
- ✓ Winding voltage of high, medium and low voltages S_{HV}, S_{MV}, S_{LV}, kV·A (they are given as the rated power percentage on the nameplate or in catalogue);
- ✓ Active power losses in transformer steel $\Delta P_{\text{ST}} = \Delta P_{\text{NL}}$, kW;

- ✓ Active power losses in transformer copper windings of high, medium and low voltage for the rated load ΔP_{HV}, ΔP_{MV}, ΔP_{LV}, kW;
- ✓ No-load current of transformer I_{NL}, %;
- ✓ Short-circuit voltage between windings $U_{\mathrm{HV-MV}}$, $U_{\mathrm{HV-LV}}$, $U_{\mathrm{MV-LV}}$, %;

2. Design:

- ✓ Reactive power losses of transformer, kvar:
  - – No-load current $\Delta Q_{\mathrm{NL}} = S_{\mathrm{R}} \cdot \frac{I_{\mathrm{NL}}}{100}$;
  - – Short-circuit voltage for every transformer winding, %

$$U_{\mathrm{HV}} = 0.5 \cdot (U_{\mathrm{HV-MV}} + U_{\mathrm{HV-LV}} - U_{\mathrm{MV-LV}}),$$
$$U_{\mathrm{MV}} = 0.5 \cdot (U_{\mathrm{MV-LV}} + U_{\mathrm{HV-MV}} - U_{\mathrm{HV-LV}}),$$
$$U_{\mathrm{LV}} = 0.5 \cdot (U_{\mathrm{HV-LV}} + U_{\mathrm{MV-LV}} - U_{\mathrm{HV-MV}});$$

– Reactive power, consumed by windings of high, medium and low transformer voltages at their full load, kvar

$$\Delta Q_{\mathrm{HV}} = S_{\mathrm{HV}} \cdot \frac{U_{\mathrm{HV}}}{100},\ \Delta Q_{\mathrm{MV}} = S_{\mathrm{MV}} \cdot \frac{U_{\mathrm{MV}}}{100},\ \Delta Q_{\mathrm{LV}} = S_{\mathrm{LV}} \cdot \frac{U_{\mathrm{LV}}}{100}.$$

When calculating losses according to the method in the sequence, given below, the following can be calculated:

1. Active energy W (kW·h) that passed through windings of high $W_{\mathrm{HV}} = W_{\mathrm{MV}} + W_{\mathrm{LV}}$, medium W_{CH} and low W_{LV} voltages and reactive energy (kvar·h), that passed through the windings of high $V_{\mathrm{HV}} = V_{\mathrm{MV}} + V_{\mathrm{LV}}$, medium V_{MV} and low V_{LV} voltages, which are accounted by billing meters during the month.

2. Average power factor on the side of high, medium and low voltages $\cos\varphi_{\mathrm{av}_{\mathrm{HV}}}$, $\cos\varphi_{\mathrm{av}_{\mathrm{MV}}}$, $\cos\varphi_{\mathrm{av}_{\mathrm{LN}}}$.

3. Load factor of each transformer winding

$$k_{\mathrm{L}_{\mathrm{HV}}} = \frac{W_{\mathrm{HV}}}{S_{\mathrm{HV}} \cdot T_{\mathrm{p}} \cdot \cos\varphi_{\mathrm{av}_{\mathrm{HV}}}},\ k_{\mathrm{L}_{\mathrm{MV}}} = \frac{W_{\mathrm{MV}}}{S_{\mathrm{MV}} \cdot T_{\mathrm{p}} \cdot \cos\varphi_{\mathrm{av}_{\mathrm{MV}}}},$$

$$k_{\mathrm{L}_{\mathrm{LV}}} = \frac{W_{\mathrm{LV}}}{S_{\mathrm{LV}} \cdot T_{\mathrm{p}} \cdot \cos\varphi_{\mathrm{av}_{\mathrm{LV}}}},$$

where W_{HV}, W_{MV}, W_{LV} – active EE that passed through windings of high, medium and low voltages during a month, kW·h; S_{HV}, S_{MV}, S_{LV} – the rated power of high, medium and low voltage windings, kV·A; $\cos\varphi_{\mathrm{av}_{\mathrm{HV}}}$, $\cos\varphi_{\mathrm{av}_{\mathrm{MV}}}$, $\cos\varphi_{\mathrm{av}_{\mathrm{LV}}}$ – average power factor for the side of high, medium and low voltages; T_{p} – total number of transformer operation hours.

4. Energy losses in transformer

- ✓ Active energy losses:

$$\Delta W = \Delta P_{\text{NL}} \cdot T_{\text{p}} + (\Delta P_{\text{HV}} \cdot k^2_{\text{L}_{\text{HV}}} + \Delta P_{\text{MV}} \cdot k^2_{\text{L}_{\text{MV}}} + \Delta P_{\text{LV}} \cdot k^2_{\text{L}_{\text{LV}}}) \cdot T_{\text{op}} \text{ kW·h.}$$

- ✓ Reactive energy losses:

$$\Delta V = \Delta Q_{\text{NL}} \cdot T_{\text{p}} + (\Delta Q_{\text{HV}} \cdot k^2_{\text{L}_{\text{HV}}} + \Delta Q_{\text{MV}} \cdot k^2_{\text{L}_{\text{MV}}} + \Delta Q_{\text{LV}} \cdot k^2_{\text{L}_{\text{LV}}}) \cdot T_{\text{op}} \text{ kvar·h,}$$

where T_{op} – number of transformer operation hours per month with the same rated load as for double-wound transformers.

Design average power factor is found in the same way as for double-wound transformers.

2.3.2. Electrical energy losses in overhead and cable power lines

To calculate energy losses in overhead lines and cables, the following data is required:

1. Catalogue or nameplate data:
   - ✓ Line length L, km;
   - ✓ Resistance of the line r_0, Ohm/km;
   - ✓ Reactance of the line x_0, Ohm/km;
2. Design data:
   - ✓ Resistance of lines, Ohm

$$R = r_0 \cdot L,\ X = x_0 \cdot L \text{ Ohm.}$$

3. Active energy W and reactive energy V are taken according to the billing meters.

4. Average current in the line is calculated by the formula

$$I_{\text{av}} = \frac{\sqrt{W^2 + V^2}}{\sqrt{3} \cdot U_{\text{R}} \cdot T_{\text{p}}} \text{ A,}$$

where T_{p} – number of line operation hours during the settlement period, h; U_{R} – the rated voltage of line, kV.

5. EE losses in all three phases of the line

$$\Delta W = 3 \cdot I^2_{\text{av}} \cdot R \cdot T_{\text{p}} \cdot 10^{-3} \text{ kW} \cdot \text{h,}$$

$$\Delta V = 3 \cdot I^2_{\text{av}} \cdot X \cdot T_{\text{p}} \cdot 10^{-3} \text{ kvar} \cdot \text{h.}$$

Active energy losses in cable lines of insignificant length are taken equal to 0 due to a small active resistance value.

Example 2.1. To estimate the losses value ΔW_{p} in a feeder cable line of KGHL brand, length L = 0.03km, size F = 16 mm^2 and overpaid amount by consumer for overestimated agreed amount of EE losses, if losses under the agreement are $\Delta W_{\mathrm{a}} = 5.89\ \%$, annual EE consumption $W_{\mathrm{year}} = 28\,700\ \mathrm{kW \cdot h}$, reactive power factor $\mathrm{tg}\varphi = 0.35$, specific resistivity $r_0 = 1.1\ \mathrm{Ohm/km}$, rated voltage $U_{\mathrm{R}} = 0.38\ \mathrm{kV}$, tariff $T = 5\ \mathrm{Rub./kW \cdot h}$

Solution.

1. We calculate the agreement-based losses in the named units

$$\Delta W_{\mathrm{a}} = \frac{5.89 \cdot 28\,700}{100} = 1690.4\ \mathrm{kW \cdot h}.$$

2. Then we find the resistance in CL

$$R = 0.03 \cdot 1.1 = 0.033\ \mathrm{Ohm}.$$

3. Next, average current of line

$$I_{\mathrm{av}} = \frac{\sqrt{28\,700^2 + 10\,045^2}}{\sqrt{3} \cdot 0.38 \cdot 8760} = 5.3\ \mathrm{A},$$

where $V_{\mathrm{year}} = W_{\mathrm{year}} \cdot \mathrm{tg}\varphi = 28\,700 \cdot 0.35 = 10\,045\ \mathrm{kvar}.$

4. We calculate design losses in the line

$$\Delta W_{\mathrm{d}} = 3 \cdot I_{\mathrm{av}}^2 \cdot R \cdot T_{\mathrm{p}} \cdot 10^{-3} = 3 \cdot 5.3^2 \cdot 0.033 \cdot 8760 \cdot 10^{-3} = 24.5\ \mathrm{kW \cdot h}.$$

5. We calculate the excess losses

$$\Delta W_{\mathrm{a}} - \Delta W_{\mathrm{p}} = 1690.4 - 24.5 = 1445.4\ \mathrm{kW \cdot h}.$$

6. So, annual overpayment for overestimated agreement-based losses is

$$\Delta P = (\Delta W_{\mathrm{a}} - \Delta W_{\mathrm{d}}) \cdot T = 1445.4 \cdot 5 = 7227\ \mathrm{Rub.}$$

Thus, a consumer annually overpaid for the agreement-based losses in the amount of 7227 Rub.

By filing a claim to the Arbitration court, a consumer (with all payment documents available) can get reimbursement for all unjustified payments for a three-year period.

Example 2.2. To evaluate the estimated losses ΔW_{p} in a feeding transformer of brand TM-2500/10 and consumer's overpayment for the agreement-based amount of EE losses per year, if losses under the agreement are $\Delta W_{\mathrm{a}} = 9\ \%$, EE consumption $W_{\mathrm{year}} = 900\,000\ \mathrm{kW \cdot h}$, reactive power factor $\mathrm{tg}\varphi = 0.4$, $\Delta P_{\mathrm{NL}} = 3.9\ \mathrm{kW}$, $\Delta P_{\mathrm{sc}} = 23.5\ \mathrm{kW}$, $T_{\mathrm{op}} = 4500\ \mathrm{h}$, $T_{\mathrm{p}} = 8760\ \mathrm{h}$, tariff $T = 5\ \mathrm{Rub./kW \cdot h}$

Solution.

1. We calaculate the amount of agreement-based losses in the named units

$$\Delta W_{\text{a}} = \frac{9 \cdot 900\,000}{100} = 81\,000 \text{ kW} \cdot \text{h}.$$

2. We find transformer load factor for active energy

$$k_{\text{l}} = \frac{900\,000}{2500 \cdot 744 \cdot 0.93} = 0.52.$$

3. We find design losses

$$\Delta W_{\text{d}} = 3.9 \cdot 8760 + 23.5 \cdot 0.52^2 \cdot 4500 = 62\,759 \text{ kW} \cdot \text{h}.$$

4. We find excess losses

$$\Delta W_{\text{a}} - \Delta W_{\text{d}} = 81\,000 - 62\,759 = 18\,241 \text{ kW} \cdot \text{h}.$$

5. Annual overpayment for agreed excess losses is

$$\Delta P = (\Delta W_{\text{a}} - \Delta W_{\text{d}}) \cdot T = 18\,241 \cdot 5 = 91\,206 \text{ Rub}.$$

Overpayment per year equals to 91 206 Rub.

2.3.3. Method of average loads

The method is commonly used for calculation of variable EE losses in open-loop networks of 110 kV and lower voltage [14].

Calculation of EE variable losses in electric network elements (overhead lines (OHL), cable lines (CL), transformers, autotransformers, and current limiting reactors) is done by the formula:

$$\Delta W = k_{\text{l}} \cdot k_{\text{c}} \cdot \Delta P_{\text{av}} \cdot T \cdot k_{\text{f}}^2 \text{ thous. kW} \cdot \text{h},$$

where ΔP_{av} – power losses in the network element with average load of buses for a settlement period, kW, are calculated by the formulae, depending on the element (2.1, 2.3, 2.4–2.7); k_{f}^2 – square shape factor of total network load curve for a settlement period, r. u.; k_{c} – a factor, considering the difference in curve configuration for active and reactive load of different network branches (taken equal to 0.99), r. u.; k_{l} – overhead-line hardware losses factor is taken equal to 1.02 for 110 kV and over lines and equal to 1.0 for lower voltage lines, r. u.; T – number of hours in a settling period, h.

1. Variable power losses for average loads during a settlement period in the grid elements 6(10) kV and over (OHL, CL, transformers) are calculated according to the formula:

$$\Delta P_{\text{av}} = 3 \cdot I_{\text{av}}^2 \cdot R = \frac{P_{\text{av}}^2 + Q_{\text{av}}^2}{U_{\text{av}}^2} \cdot R = \frac{P_{\text{av}}^2 \cdot (1 + \text{tg}^2 \varphi)}{U_{\text{av}}^2} \cdot R, \qquad (2.1)$$

where P_{av}, Q_{av} – average values of active and reactive power for a settlement period *T*, kW, kvar, calculated by the formula (2.2); tgφ – reactive power factor, r. u.; U_{av} – average voltage of grid element for a settlement period *T*, kV; I_{av} – average value of current load, A, calculated by the formula (2.2); *R* – element resistance.

Average load is calculated by the formulae:

$$P_{\text{av}} = \frac{W_T}{T},\ Q_{\text{av}} = \frac{V_T}{T},\ I_{\text{av}} = \frac{W_T}{\sqrt{3} \cdot U_{\text{av}} \cdot T \cdot \cos\varphi}, \tag{2.2}$$

where W_T, V_T – electrical energy (active and reactive), consumed (generated) in a bus during a settlement period *T*.

2. Variable power losses at average loads in autotransformers during a settlement period (triple-wound transformers) are calculated by the formula 2.3:

$$\Delta P_{\text{av}} = \frac{P^2_{\text{HV}_{\text{av}}} + Q^2_{\text{HV}_{\text{av}}}}{U^2_{\text{í V}_{\text{av}}}} \cdot R_{\text{ò}_{\text{HV}}} + \frac{P^2_{\text{MV}_{\text{av}}} + Q^2_{\text{MV}_{\text{av}}}}{U^2_{\text{MV}_{\text{av}}}} \cdot R_{\text{ò}_{\text{MV}}} + \frac{P^2_{\text{LV}_{\text{av}}} + Q^2_{\text{LV}_{\text{av}}}}{U^2_{\text{LV}_{\text{av}}}} \cdot R_{\text{ò}_{\text{LV}}} =$$

$$= \frac{P^2_{\text{HV}_{\text{av}}} \cdot (1 + \text{tg}^2\varphi)}{U^2_{\text{HV}_{\text{av}}}} \cdot R_{\text{ò}_{\text{HV}}} + \frac{P^2_{\text{MV}_{\text{av}}} \cdot (1 + \text{tg}^2\varphi)}{U^2_{\text{MV}_{\text{av}}}} \cdot R_{\text{ò}_{\text{MV}}} + \frac{P^2_{\text{LV}_{\text{av}}} \cdot (1 + \text{tg}^2\varphi)}{U^2_{\text{LV}_{\text{av}}}} \cdot R_{\text{ò}_{\text{LV}}} = (2.3)$$

$$= 3 \cdot (I^2_{\text{HV}_{\text{av}}} \cdot R_{\text{ò}_{\text{HV}}} + I^2_{\text{MV}_{\text{av}}} \cdot R_{\text{ò}_{\text{MV}}} + I^2_{\text{LV}_{\text{av}}} \cdot R_{\text{ò}_{\text{LV}}}),$$

where $P_{\text{HV}_{\text{av}}}$, $P_{\text{MV}_{\text{av}}}$, $P_{\text{LV}_{\text{av}}}$, $Q_{\text{HV}_{\text{av}}}$, $Q_{\text{MV}_{\text{av}}}$, $Q_{\text{LV}_{\text{av}}}$, $I_{\text{HV}_{\text{av}}}$, $I_{\text{MV}_{\text{av}}}$, $I_{\text{LV}_{\text{av}}}$ – average values of active and reactive powers, current loads for a settlement period *T* for transformer windings, MW, Mvar, A, accordingly; $U_{\text{HV}_{\text{av}}}$, $U_{\text{MV}_{\text{av}}}$, $U_{\text{LV}_{\text{av}}}$ – average voltage values during a settlement period *T* for high-voltage, medium and low-voltage windings of autotransformer, kV; tgφ – reactive power factor, r. u.; $R_{\text{T}_{\text{HV}}}$, $R_{\text{T}_{\text{MV}}}$, $R_{\text{T}_{\text{LV}}}$ – resistance of autotransformer windings, Ohm.

When measurements on a low side of autotransformers are not available, it is allowed to calculate EE losses using the data for high and medium-voltage windings for a settlement period *T*.

If winding resistances, corrected to higher winding voltage, were used in the formula (2.3), then U_{HV} is applied instead of U_{MV} and U_{LV}.

3. Variable power losses in electric grid elements 0.4 kV (OHL and CL) are calculated, using average grid loads for a calculation interval *T*:

$$\Delta P_{\text{av}} = \sum_{n=1}^{3} I^2_{\text{Fav}_n} \cdot R_{\text{F}} + I^2_{\text{Nav}} \cdot R_{\text{N}}, \tag{2.4}$$

where I_{Fav_n} – average current value for a time period T in the phase n, A; I_{Nav} – average current value for a time period T in a neutral conductor, A; R_{F} – phase wire resistance, Ohm; R_{N} – neutral conductor resistance, Ohm.

Average current values in phase and neutral wires are calculated using metering results.

When measurements are not available, it is allowed to calculate EE losses in the 0.4 kV line, according to its type by formulae (2.5–2.7):

- ✓ For a four-line section (three phases and a neutral):

$$\Delta P_{\mathrm{av}} = \frac{1}{3} \cdot \frac{P_{\mathrm{av}}^2 \cdot (1 + \mathrm{tg}^2 \varphi_{\mathrm{av}})}{U_{\mathrm{av_F}}^2} \cdot R_{\mathrm{F}} \cdot k_{\mathrm{AL_{av}}}, \tag{2.5}$$

where P_{av} – active power flow along the line, kW; $U_{\mathrm{av_F}}$ – average value of phase voltage in the line for a settlement period T, kV; $k_{\mathrm{AL_{av}}}$ – average load irregularity factor for phases during a settlement period, r. u. [14]:

$$k_{\mathrm{AL_{av}}} = 3 \cdot \frac{\sum_{n=1}^{3} I_{\mathrm{F_n}}^2}{\left(\sum_{n=1}^{3} I_{\mathrm{F_n}} \right)^2} \cdot (1 + 1.5 \cdot \frac{R_{\mathrm{N}}}{R_{\mathrm{F}}}) - 1.5 \cdot \frac{R_{\mathrm{N}}}{R_{\mathrm{F}}}.$$

- ✓ For a three-line section (two-phases and a neutral):

$$\Delta P_{\mathrm{av}} = \frac{1}{2} \cdot \frac{P_{\mathrm{av}}^2 \cdot (1 + \mathrm{tg}^2 \varphi_{\mathrm{av}})}{U_{\mathrm{av_F}}^2} \cdot (R_{\mathrm{F}} + 0.5 \cdot R_{\mathrm{N}}) \cdot k_{\mathrm{AL_{av}}}, \tag{2.6}$$

where phase load irregularity factor is as follows:

$$k_{\mathrm{AL_{av}}} = 2 \cdot \frac{\sum_{n=1}^{2} I_{\mathrm{F_n}}^2}{\left(\sum_{n=1}^{2} I_{\mathrm{F_n}} \right)^2} \cdot (1 + 1.5 \cdot \frac{R_{\mathrm{N}}}{R_{\mathrm{F}}}) - 1.5 \cdot \frac{R_{\mathrm{N}}}{R_{\mathrm{F}}}.$$

- ✓ For a two-wire section (a phase and a neutral):

$$\Delta P_{\mathrm{av}} = \frac{P_{\mathrm{av}}^2 \cdot (1 + \mathrm{tg}^2 \varphi_{\mathrm{av}})}{U_{\mathrm{av_F}}^2} \cdot (R_{\mathrm{F}} + R_{\mathrm{N}}). \tag{2.7}$$

When the load power factor is not available, its value is taken equal to 0.93 – for public-utility consumers, 0.75 – for industrial and 0.85 – for mixed load [14].

When the data for calculating additional losses are not available, its value should be taken for the lines with $R_{\text{N}} / R_{\text{F}} = 1 \;\; k_{\text{AL}} = 1.13$; for lines – $R_{\text{N}} / R_{\text{F}} = 2 \;\; k_{\text{AL}} = 1.2$.

Value of a squared curve shape factor is calculated by the formula [14]:

$$k_{\text{F}}^2 = \frac{1 + 2k_{\text{L}}}{3k_{\text{L}}}, \text{ r. u.,}$$

where k_{L} – load factor, calculated using the formula:

$$k_{\text{L}} = \frac{W}{P_{\max} \cdot T} = \frac{T_{\max}}{T} = \frac{P_{\text{av}}}{P_{\max}}, \text{ r. u.,}$$

where W – EE supply in the network during time T, kW·h; $T_{\max}$ – number of peak load hours, h.

When there are no data for calculating the curve shape factor for each settling period, it is allowed to use load readings of the main line section, made in the days of control measurements.

CHAPTER 3. TARIFFS FOR ELECTRICAL ENERGY

Electrical energy market is currently being formed and introducing such notions as management and marketing.

Analysis of tariff systems in the electric power sector is one of the most important marketing researches and is meant to solve such problems, as increasing the market competitiveness, support of a sustainable financial position, a fast adaptation to ambient changes, market minimization with investment solutions justification, pricing for electrical energy and supply services.

The tariff, which is correctly set, does not only stimulate a demand for electrical energy, but helps to smooth over contradictions among suppliers, consumers and regional authorities. Conflicts of interests often arise due to absence of effective cooperation between an energy supplying organization and consumers when developing and regulating the tariffs.

3.1. Electrical Energy Pricing Principles

When developing tariffs, two main technical and economic aspects of energy production process are considered:

1. Congruence of EE generation and consumption period;
2. Irregularity of consumption during the day and over the year.

Three consecutive stages can be specified in developing the electricity tariffs in the region: estimation of total cost of service and average tariff; differentiation of tariff rates by consumer groups and categories, according to electricity supply costs and calculation of basic (pricelist) tariffs; development of special tariffs, aimed at implementation of specific goals and deviating individual expenses of electrical energy supply [15].

3.1.1. Cost of service for regional consumers

Total cost of service is the required gross revenue of a power supplier during a settlement period; it includes total current expenses and profit, and becomes the basis for calculating the average regional tariff. In order to calculate it, cost of service should be divided by the electricity consumption volume during a settlement period. Average tariffs are differentiated by country regions, depending on conditions of energy production and nature of electric loads.

Total expenses usually include costs for electrical energy generation, transmission and distribution in a vertically integrated power company. A variable component of costs, which depends on a produced volume, and a constant component, depending on the installed plants power and value of the company’s fixed assets, is specified.

Constant costs play a special role in the electric power industry due to a high capital intensity of the sector, the requirement to produce peak and reserve capacities and constantly keep them ready for electricity supply.

Composition of constant and variable costs should be determined using standard calculations, approved by the Federal Tariff Service. For optimization of a power supplier costs, a normative approach should be added by a selection of fuel and equipment suppliers, and maintenance service on a competition basis solely.

A particular problem is to set a profit rate in the service charge. In most of the Russian power companies profits are still calculated by means of expense items, which company is going to finance from the profits. It is obvious that such method of profit forming initiates the growth of normal tariffs.

A solution to this problem consists in a transition to a profit rate when developing the tariffs for the invested capital. A profit rate should be sufficient to guarantee a financial stability of a power supplier when additional funds need to be raised.

The above-stated suggestions on improvement of service charge regulation in a vertically integrated company allow optimizing the regional normal electricity tariff at a lower level and stabilizing its dynamics in future.

3.1.2. Types of electrical energy tariffs

1. Dual-rate tariff (basic)

As it was stated above, constant costs of a power supplier provide for development of generating capacities and keeping them ready for the load. Therefore, they are called “power costs” or “load costs”. In particular, they include depreciation charges, equipment operation and maintenance expenses, and some taxes.

The stated costs, as well as standard profits, which serve as a source of the fixed capital increase, should be paid by all consumers irrespective of the electricity consumption mode. Hence, it follows that separate reimbursement of fixed costs (together with profit) and variable costs is necessary, varying in proportion to electricity production volume (fuel costs mainly).

Consequently, every consumer pays a specific part of the fixed costs in proportion to the subscribed (ordered) power and a variable part in proportion to an actual consumed EE to a power supplier during the settlement period. Thus, the tariff is formed and consists of two rates: basic for 1 kW of consumer power (load) and for 1 kW/h of electricity. A dual-rate tariff model is the initial basis for different modifications, including those to obtain a single-rate tariff.

Total payment for electricity, according to such tariff system, will be as follows

$$P = P_{\max_{\mathrm{L}i}} \cdot T^{(\mathrm{M})} + W \cdot T^{(2)}.$$

This tariff stimulates a consumer to increase energy use efficiency by load leveling and reduce the power, declared for peak hours.

2. Single-rate tariff (according to an electricity meter) only provides for payment (P) for electricity in kilowatt-hours, registered by meters:

$$P = W \cdot T^{(1)}.$$

This tariff system is widely used for settlements with population and other non-industrial consumers, which power is usually less than 670 kW [15].

With a single rate tariff, the payment grows in proportion to consumption what leads to tariff separation from service cost. The tariff is simple and comprehensive for consumers, but does not stimulate them to reduce energy consumption.

3. Differentiated tariffs

The basic pricing principle is the tariffs should be based on full costs of electrical energy supply, i. e. cost of service. These costs vary widely, depending on time of energy production, supply conditions and energy processing parameters for different consumers. Electricity tariffs are currently differentiated:

1. By the zones of daily load.
2. By voltage levels (generator voltage (GV), high voltage (HV 110 kV and over), first medium voltage (MVI 35 kV), second medium voltage (MVII 6(10) kV), and low voltage (LV 0.4 kV).
3. By number of hours of load peak operation.
4. By value of installed power.

In Table 3.1 the dynamics of tariffs, differentiated by voltage levels and installed power, is given as an example.

Table 3.1

Fragment of tariff options

Installed power	Voltage level, kV				
	GV	HV	MVI	MVII	LV
Tariffs, Rub./MW·h					
up to 150 kW	1949.73	2036.40	2569.93	2921.41	3711.01
from 150 to 670 kW	1929.53	2016.20	2549.73	2901.21	3690.81
from 670 kW to 10 MW	1810.83	1897.50	2431.03	2782.51	3572.11
over 10 MW	1716.09	1802.76	2336.29	2687.77	3477.37

Time-based differentiation of tariffs is caused by power consumption irregularity and consists in application of rates that vary during the day, days of the week and seasons.

Thus, payment for consumed electrical energy by the tariff, differentiated for daily load zones per one working day, is calculated by the following formula

$$P_{\text{w}} = (W_{\text{pm}} + W_{\text{pe}}) \cdot T_{\text{n}} + W_{\text{i/l}} \cdot T_{\text{i/l}} + W_{\text{n}} \cdot T_{\text{n}},$$

where T_{p}, $T_{\text{i/l}}$, T_{n} – tariff rates for EE, consumed during peak, intermediate and night zones of daily load schedule, accordingly; W_{pm}, W_{pe}, $W_{\text{i/l}}$, W_{n} – EE, consumed during peak load hours in the morning, evening, in intermediate and night hours.

Payment for EE, consumed for operation during holidays or weekends – per one day

$$P_{\text{w(h)}} = (W_{\text{pm}} + W_{\text{pe}}) \cdot T_{\text{i/l}} + W_{\text{i/l}} \cdot T_{\text{n}} + W_{\text{n}} \cdot T_{\text{n}},$$

i. e. EE, consumed during morning and evening maximum load is paid according to tariff for the intermediate load zone $T_{\text{i/l}}$, EE, consumed during the intermediate load and night hours, is paid according to tariff rate T_{n}.

To estimate the payment for a settlement period, it is required to know number of working days D_{w}, number of weekend days and holidays $D_{\text{w(h)}}$ within a settlement period, which is calculated using calendar timesheet. Then

$$P_{\sum} = P_{\text{w}} \cdot D_{\text{w}} + P_{\text{w(h)}} \cdot D_{\text{w(h)}}.$$

During night hours of the minimum system load when there is available energy and generation increase is possible at the minimum cost, lowered rates are set for electricity payment. On the contrary, the maximum tariffs are applied during the peak loads. Separate power rates for basic and peak zones during the daily schedule can also be applied. Depending on the yearly schedule of energy system loads, different rates for winter and summer seasons are set.

All this requires estimation of fixed and variable costs of electrical energy generation by the load schedule zones with account for operating equipment configuration. Calculation of such tariffs is based on the concept of short-term marginal costs – additional costs, required for covering an incremental demand unit within the existing power plant capacity and transfer capacity of power grids. Such approach to electricity tariffs stimulates a consumption increase during off-peak periods, what, as it is known, leads to reduction of total costs and the average price for electricity supply.

Diurnal differentiation of tariff rates requires additional costs, related to organization of separate electricity consumption metering and increment of payroll budget (if night shifts are introduced). Therefore, it is important to determine its purpose clearly. First of all, such tariffs should be offered to consumers which have actual capabilities and are ready to reduce the peak load or increase electricity consumption during the load fall hours (organization of additional shifts in the industry sector). They can also be applied for energy-intensive enterprises with an even load schedule to reduce the average tariff for such consumers. At the same time it is unreasonable to implement daily differentiated tariffs for consumers, which due to processing limitations or specific behavior, cannot, and are not going to change the electricity consumption mode.

Differentiation by hours of the maximum load, by installed power and voltage level is conditioned by industrial difference in power consumption modes, energy and power demand volume and costs of electricity distribution (See Table 3.1). Thus, cost per unit of service for a major industrial consumer with a high load factor, receiving electrical energy directly from high voltage OPL and having its own transformer substation, considerably differs from costs of a domestic consumer with irregular load during the day and need for expensive transformers and low voltage distribution system.

For a more detailed reflection of additional costs in energy supplier's tariffs on supply reliability level increase, markups (discounts) to the electricity rate (for dual-rate tariff) can be set. The markups (discounts) are fixed for different consumer groups, according to their reliability classes, and calculated depending on the amount and types of sources, the electricity supply scheme, and also on power backup use.

Example 3.1. Select the most cost-efficient payment method for EE for an enterprise, which load schedule is given in Fig. 3.1. Single-rate tariff $T^{(1)} = 2.8$ Rub./kW·h, dual-rate tariff: rate for power $T^{(M)} = 805$ Rub./kW·h per month, EE rate $T^{(2)} = 0.95$ Rub./kW·h, differentiated rate: $T_{\mathrm{p}} = 4$ Rub./kW · h, $T_{\mathrm{i/l}} = 2.7$ Rub./kW·h, $T_{\mathrm{n}} = 2.4$ Rub./kW·h, number of working days $D_{\mathrm{w}} = 247$, number of weekend days and holidays $D_{\mathrm{w(h)}} = 118$.

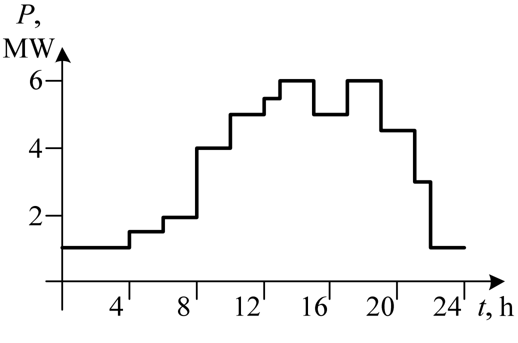


Fig. 3.1. Typical daily load diagram of the enterprise

Using the load diagram we find:

1. Daily consumption of EE $W_{\mathrm{day}} = 82.5$ thous. kW · h.
2. Consumption of EE in the system peak hours $W_{\mathrm{p}} = 29.5$ thous. kW · h.
3. Consumption of EE in night hours $W_{\mathrm{n}} = 8$ thous. kW · h.
4. Consumption of EE in intermediate load hours $W_{\mathrm{i/l}} = 45$ thous. kW · h.

5. Power, declared for the system maximum load $P_{\max_3} = 6$ MW.

6. Annual payment, according to a single-rate tariff, is

$$P = W_{\text{year}} \cdot T^{(1)} = 82.5 \cdot 365 \cdot 2.8 = 84.315 \text{ mln Rub.}$$

7. Annual payment, according to a dual-rate tariff, is

$$P = 12 \cdot P_{\max_3} \cdot T^{(\text{M})} + W_{\text{year}} \cdot T^{(2)} = 12 \cdot 6000 \cdot 805 + 82.5 \cdot 365 \cdot 0.95 =$$

$$= 58 \text{ mln Rub.}$$

8. Annual payment, according to the tariff, differentiated by daily load zones:

8.1. We calculate the payment per 1 working day

$$P_{\text{d}} = 29.5 \cdot 4 + 45 \cdot 2.7 + 8 \cdot 2.4 = 258.7 \text{ thous. Rub.}$$

8.2. We calculate the payment per 1 weekend day and a public holiday

$$P_{\text{d}} = 29.5 \cdot 2.7 + 45 \cdot 2.4 + 8 \cdot 2.4 = 206.9 \text{ thous. Rub.}$$

8.3. Annual payment

$$P_{\text{d}} = 258.7 \cdot 247 + 206.9 \cdot 118 = 88.3 \text{ mln Rub.}$$

Thus, the most cost-efficient tariff for the enterprise is dual-rate.

3.2. Method for consumer electricity tariff calculation

The calculation basis for justification and control of electrical energy (power) tariffs is the EE (power) balance sheet, developed by a power supplier, according to the electrical energy generation and supply balance, approved by FTS and effective within the Unified Energy System framework for the OREM entities.

Based on general financial funds required for electricity supply to consumers (D), the funds demand for electrical energy generation, transmission and distribution is calculated as follows:

$$D_{\text{E}} = D - D_{\text{TE}} - D_{\text{UES}},$$

where D_{E} – a demand for financial funds for EE generation, transmission and distribution; D – total demand for financial funds by a power supplier for the regulated activities; D_{TE} – funds demanded for TE generation, transmission and distribution; D_{UES} – cost of power supplier's services on electrical grid maintenance and services, related to provision of a reliable energy supply to consumers, introduced at the OREM market.

Average electricity tariff (T_{e}^{av}):

$$T_{\text{e}}^{\text{av}} = \frac{D_{\text{e}} - D_{\text{o}}}{W_{\text{s}}}, \text{ Rub./kW·h},$$

where D_{O} – cost of EE and power supplied to the wholesale market, mln Rub.; W_{S} – a useful EE supply to consumers, including EE supply to consumer-resellers, mln kW·h.

Tariff calculation procedure provides for calculation of dual-rate tariffs for all categories and groups of consumers.

Generally, payment for consumed electric power and energy (R_i) of the i-th consumer is calculated by the formula:

$$R_i = \sum T_{ij}^{\mathrm{ep}} \cdot P_{ij}^{\mathrm{av.max}} + \sum T_{ij}^{\mathrm{e}} \cdot W_{ij},$$

where T_{ij}^{ep} – a tariff rate for the i-th consumer power of j-th voltage range, Rub./(kW); T_{ij}^{e} – a tariff rate for energy, Rub./kW·h; W_{ij} – electricity consumption volume, kW·h; j – a voltage range for the given category of consumers (HV, MV, LV).

Average value of the declared (or design) power $P_{ij}^{\mathrm{av.max}}$ is calculated on the basis of monthly maximum declared powers by a consumer according to the formula:

$$P_{ij}^{\mathrm{av.max}} = \frac{\sum_{i}^{n} P_n}{n} \text{ kW},$$

where n – number of months during regulation period; P_n – declared (design) power in a month n, starting from the first month of regulation period.

Tariff rate value for electric power T_i^{ep} for the i-th category of consumers is calculated so that to provide reimbursement of the justified conventionally-fixed costs of a power supplier for maintaining the given power (generating sources, electric networks and substations) in operating condition during the entire regulation period and reach the justified profit size.

Due to cancellation of “Rules for Electrical and Heat Energy Usage”, consumer got the opportunity to decide independently on EE payment method: a single-rate or a dual-rate tariff, or differentiated tariff for daily load schedule zones. The decision made about such transition should be guided by economic benefit.

The transition from one tariff to another is feasible only when EE payment reduces. Here the following condition should be met for every i-th month

$$T^{(\mathrm{P})} \cdot P_{\mathrm{max}_{\mathrm{L}i}} + T^{(2)} \cdot W_i \le T^{(1)} \cdot W_i,$$

where $T^{(\mathrm{p})}$ – a rate for declared power, participating in the system maximum load, Rub./MW per month; $P_{\max_{Li}}$ – declared power per month *i*, participating in the system maximum load, MW; $T^{(2)}$ – rate for EE in a dual-rate tariff, Rub./kW·h; $T^{(1)}$ – rate for EE in a single-rate, Rub./kW·h; W_i – EE consumed during a month *i*, kW·h.

Tariff regulation for heat and electrical energy is one of the most considerable elements of the State influence in this sector. It is aimed at reaching the following goals:

✓ Antimonopoly consumer protection from unreasonable increase and discrimination during allocation of energy supply total costs;

✓ Sustainable provision of power companies with financial resources to cover expenses;

✓ Stimulation to reduce costs for generation and rationalization of energy consumption;

✓ Increase of energy efficiency and energy saving promotion;

✓ Financial support of specific consumers and social security of population.

In such manner the energy saving stimulation is already assumed when forming the tariffs.

However, connection between tariff level and demand for energy, tariff and energy saving intensity is not quite clearly seen.

For a long time there was an established opinion that increase of price for goods definitely leads to demand decrease. If only price is raised, people immediately start saving the energy. Experience proved the lack of such certainty. No matter the tariff growth, demand for electrical energy keeps growing every year. This contradicts the basics of market theory, according to which the price increase for a goods leads to reduction of its volume, which proves the demand elasticity [17].

As Paul Heyne said, when less of a good is available – the supply decreases in comparison to demand – the price rises. Increased price stimulates buyers to buy less. It stimulates suppliers to produce more. The decreased price signals that the good became scarcer. The price stimulates people to substitute it with other goods and suppliers to produce other more valuable goods [17].

In case with electrical energy and other energy carriers the role of price manifests itself differently.

In Tomsk region during period from 1993 till 2010 EE consumption changed as it is shown in Fig. 3.2.

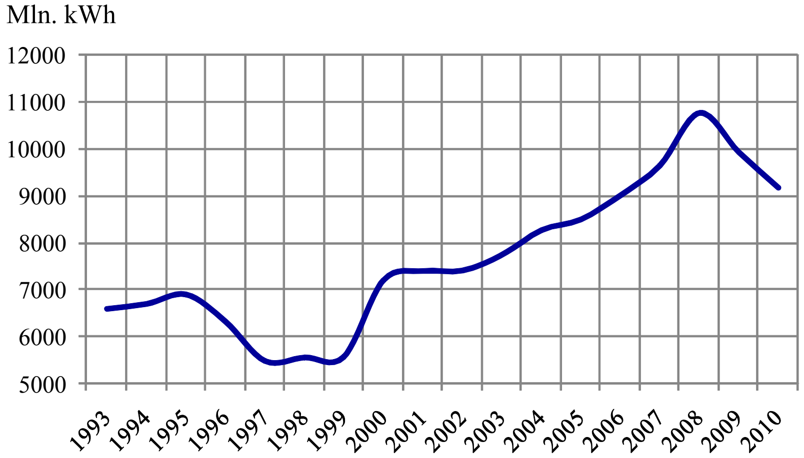


Fig. 3.2. Electricity consumption in Tomsk region in 1993–2010, mln kW·h

A general tendency of demand is formed by imposition of natural growth of consumption, demand reduction due to crises in 1998 and 2008 and reduction, related to energy saving measures implementation according to Regional Program on Energy Efficiency Increase. Here the average annual consumption growth during the period made 190 mln kW·h or 2.52 %.

Change of average tariff is shown in Fig. 3.3 within the same period of time.

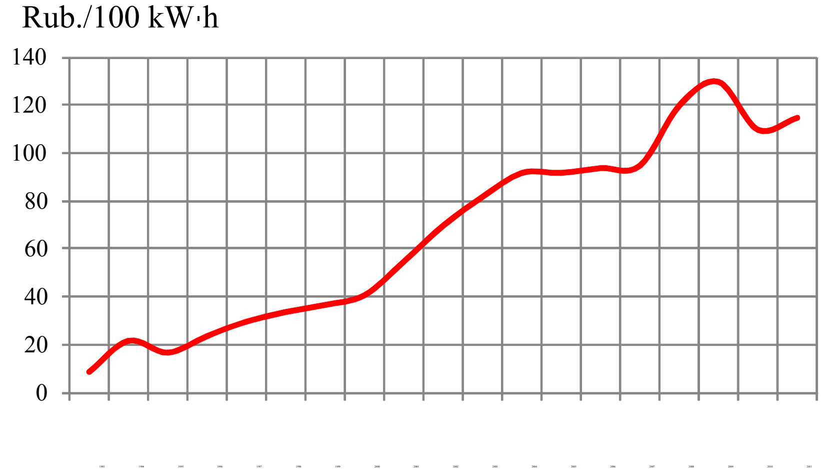


Fig. 3.3. Change of average electricity tariff in Tomsk region in 1993–2011, Rub./100 kW·h

Annual average tariff growth made 6.1 Rub./100 kW·h or 9.1 %. This is four times more than percent increase of demand. Tariff increase is accompanied by electricity demand increase. Elasticity factor, calculated as a ratio of demand percent variation to price percent variation, in this case it’s equal to 0.28. This speaks of demand inelasticity.

Reforming of national energy systems in some countries, based on competitive energy markets, started long time ago. Great Britain and Norway, France and the USA follow different paths to energy sector liberalization and practical implementation of ‘free entrepreneurship’ philosophy.

When determining the ways of market transformation in energy sector, the main guideline should be a global purpose: increase of efficient energy supply in the economy as the basis for economic growth and population living standard increase [24]. Due to this the following aspects become essential:

✓ Dates and levels of achieving the energy carrier tariffs, acceptable for producers and consumers;

✓ Rates of favorable investment opportunities creation for the sector development, reconstruction and re-equipment;

✓ Maintenance of the required reliability of energy and heat supply and energy resources quality;

✓ Minimization of energy sources environmental effect.

CHAPTER 4. ENERGY INSPECTIONS

Energy inspections are performed according to the Federal Law No. 261-FZ *“On Energy Saving and Energy Efficiency Improvement and On Amendments to Specific Legislative acts of the Russian Federation»* to assess the efficiency of fuel-energy resources use by organizations (electrical and heat energy, natural and associated gases, solid fuel, petroleum and its products), to determine possibilities of its increasing and the costs for energy efficient solutions implementation.

Energy inspection (EI) can be done in respect of produce, technological process, as well as in respect of a legal entity or individual entrepreneur [4].

The main objectives are:

- ✓ Obtaining of objective data about the volume of energy resources used;
- ✓ Calculation of energy efficiency factors;
- ✓ Evaluation of energy saving potential and energy efficiency increase;
- ✓ Development of a list of standard, available measures on energy saving and energy efficiency increase, as well as their cost estimation.

According to energy inspection results, an inspector issues an Energy certificate and gives it to the person that ordered the energy inspection. The Certificate issued according to the energy inspection results of apartment building, is subject to passing on by the person issuing it to apartment owners or a person, responsible for maintenance of the apartment building.

Energy Certificate, issued according to energy inspection results, shall contain the following information [16]:

- ✓ General information about facility;
- ✓ Information about standalone divisions;
- ✓ Information about equipment with metering instruments;
- ✓ Information about energy resources consumption;
- ✓ Electrical energy balance;
- ✓ Heat energy balance;
- ✓ Boiler and furnace fuels balance;
- ✓ Motor fuel consumption balance;
- ✓ Information about secondary energy resources use, alternative fuels and renewable energy sources;
- ✓ Energy resources consumption by the main process systems;
- ✓ Brief description of buildings and facilities;
- ✓ Information about energy efficiency indicator;

✓ Energy saving potential;

✓ List of energy efficiency measures;

✓ Information about personnel qualifications, implementing energy saving measures and energy efficiency increase.

Structure and contents of Energy Certificate for fuel-energy resources consumer are unified. First of all, this refers to a state standard GOST 51379-99 “Energy Certificate of and Industrial Consumer of Fuel and Energy Resources. General provisions. Standard forms”.

Energy Certificate issuance is an obligatory element of energy inspection.

4.1. Energy inspection management

Energy inspection activity can only be performed by persons who are members of self-regulatory organization (SRO) in the field of energy audit.

Besides that an energy auditor should meet the following requirements: have the rights of a legal entity or an individual entrepreneur; possess the required instrumental, metering and procedural equipment; have qualified and certified personnel; be experienced in respective activities.

4.2. Types of energy inspections

The following organizations are subject to obligatory energy inspections [4]:

✓ Government authorities, local government authorities, incorporated as legal entities;

✓ Organizations partially owned by the State or municipality;

✓ Organizations, performing regulatory activities;

✓ Organizations, performing production and transportation of water, natural gas, heat and electrical energy, production of natural gas, petroleum, coal, petroleum products, natural gas and petroleum processing, petroleum and its products transportation;

✓ Organizations, which total costs for fuel-energy resources consumption exceed ten million rubles per calendar year;

✓ Organizations, carrying out measures in the area of energy saving and energy efficiency increase, fully or partially funded by the federal budget, budgets of the Russian Federation entities and local regional budgets.

Recurrence of obligatory EI for FER consumers is specified once in five years. In respect of other organizations – energy resources consumers, the inspections are done on a voluntary basis.

There are the following types of energy inspections:

- ✓ Pre-project, pre-starting and pre-commissioning;
- ✓ Primary;
- ✓ Periodic (reinspection);
- ✓ Local;
- ✓ Express-inspection.

The primary inspection is carried out to assess the FER consumption efficiency; energy efficiency indicators are established for equipment operation, FER metering state, records on their use, analysis of fuel and energy supply costs, as well as data, used for calculation of standards for specific consumption of fuel and energy per unit of produce and services, norms for fuel inventory, norms for processing losses of electrical and heat energy [17].

During EI the saved reserves of FER are calculated, which means a relative reduction of FER consumption, in comparison to the basic value, for product manufacture, works and services of the established quality without violation of any environmental and other limitations and measures developed to cut costs on fuel and energy provision.

EI and validation of normative values are done according to industry requirements and regulations.

Periodic inspections (reinspections) are done routinely, to compare the current energy efficiency indicators with those from the previous inspection and record changes in the Energy certificate, etc.

Universal diagram in Fig. 4.1 gives a better overview of energy inspections [17].

EI Procedure is regulated by normative documents. Along with that it would be useful to formulate the main principles it should be based upon:

- ✓ Inspection is done under the rules, implementing the federal energy policy;
- ✓ Professionally trained specialists with a sufficient experience of professional, practical, research or engineering activity can become experts;
- ✓ EI results cannot serve as the ground for sanctions, except for cases, stipulated by current legislation;
- ✓ Information, obtained by experts during inspection, shall not be given to a third party except for cases, stipulated by legislation of the Russian Federation;
- ✓ Personnel of an inspected facility provides the maximum cooperation during the inspection;
- ✓ Inspection program is to be agreed with the parties prior to works commencement.

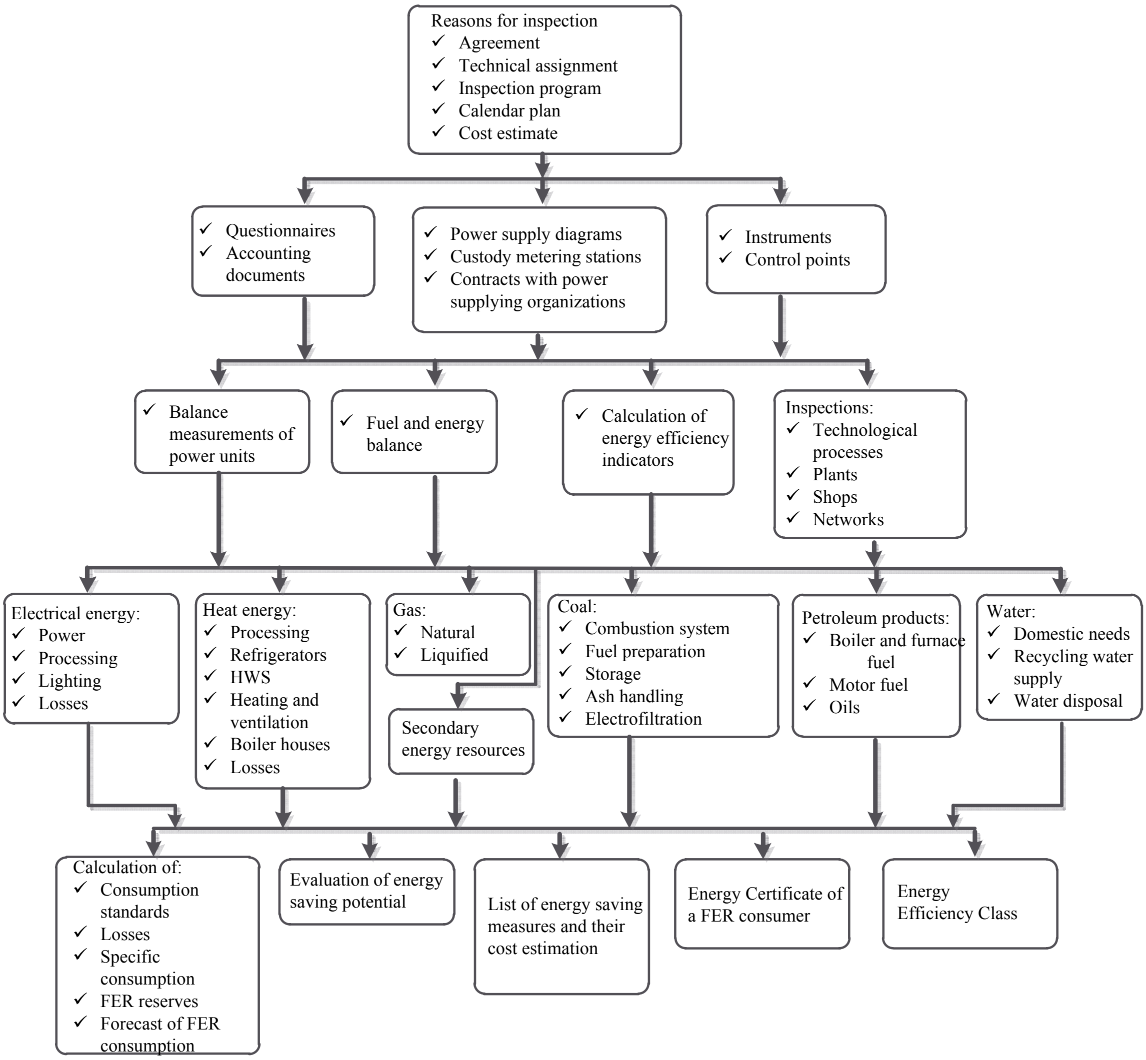


Fig. 4.1. Universal diagram of an energy inspection

4.3. Energy inspection procedure

- ✓ Preparation, completion of questionnaires, collection of metering records on FER consumption;
- ✓ Analysis of agreements with power-supplying organizations;
- ✓ Instrumental inspection in control buses;
- ✓ Measurement results processing and their analysis;
- ✓ Calculation of energy efficiency factors;
- ✓ Calculation of norms and energy consumption forecast;
- ✓ Energy Certificate development;
- ✓ Making a list of energy-saving measures and their cost estimation;
- ✓ Energy-saving potential evaluation;
- ✓ Evaluation of energy-saving measures efficiency;
- ✓ Preparation of materials for determining a class of energy efficiency.

At the preliminary stage the most of available information on energy resources use is gathered and its reliability is evaluated. The sources are such as:

✓ Interviews and questionnaires for management and engineering staff;
✓ Energy supply diagrams;
✓ Energy resources metering schemes;
✓ Reporting records on revenue and technical metering of energy resources;
✓ Energy load diagrams;
✓ Documents on produce shipment;
✓ Technical regulations, records on maintenance, adjustment and testing measures.

Instrumental inspections are done to fill in the gaps and verify information about energy resources consumption, insufficient for energy efficiency assessment and increasing of inspection results reliability.

Fixed (regular) and portable dedicated instruments are used for an instrumental inspection. To obtain a full picture of energy mode, standard instruments are usually not enough, therefore portable instruments and connection devices are used. As a rule, they should have a higher class of accuracy than regular instruments. Amount and composition are given in reference books. Here is only one limitation – instruments should be included in the State Register of Measuring Devices and be timely verified. For multichannel synchronous measurements in points distant from each other, it is reasonable to use a set of miniature loggers – Mini Loggers.

Nowadays digital measuring methods and means are primarily used. Complete multifunctional digital metering instruments with an internal microprocessor control and wide scope of capabilities of processing, storage and display of information provide for all inspection objectives. As for computers, the preference should be given to industrial samples (Industrial Standard PC), as there are often severe operating conditions in the enterprises, such as temperature conditions and electromagnetic field, etc., that requires respective operating specifications of instruments. In order to solve the problems and provide a reliable instrumental inspection, performance specifications are often more important than metrological.

A specific nature of instrumental inspections can be stated as follows:

✓ Big number and variety of parameters to be measured;
✓ Range of measured parameters can vary in several orders;
✓ Static and dynamic characteristics of processes are surveyed;
✓ Relatively narrow bandwidth of inspected signals;
✓ Information flows are relatively small for every specific channel;
✓ Measurement accuracy is limited;

- ✓ Undesirability (often impossibility) of interference in the technological process to install an instrument, circuit breaking or opening;
- ✓ A long duration of experiments;
- ✓ Severe operating conditions, strict occupational, fire and sanitary safety;
- ✓ Distrust and sometimes counteractions of the facility personnel.

Instrumental section of EI provides for measurements in the systems of electric power supply, heat supply (steam and water), heating, ventilation, air conditioning and hot water supply, gas supply, water supply and disposal, air treatment and compression, compressed and liquefied gases (oxygen, nitrogen and other), and cold supply.

Energy inspection assumes survey of plant systems operation that provide for organization, management and control of energy provision of the entire production process.

Questionnaires and interviews with managers of technical units give a view of object under consideration. Main features of the enterprise, such as range of products, composition and volume of consumed energy resources, industrial structure and management diagram, equipment arrangement and current problems of energy supply – all these features are detected at the stage of making and studying the questionnaires and interviews.

When gathering information, a special attention should be given to:

- ✓ Energy supply flowcharts;
- ✓ Energy resources metering flowcharts;
- ✓ Records of revenue and technical metering of energy resources;
- ✓ Daily, weekly and monthly diagrams of energy and heat loads;
- ✓ Records about shipped produce;
- ✓ Technical documents for equipment;
- ✓ Records about maintenance, adjustment, testing and other events;
- ✓ Production program and development program.

Metering and metering system is meant for continuous, reliable registration of supplied and consumed energy resources.

According to [4] “the entire volume of produced, manufactured, processed and transported resources is subject to obligatory instrument metering”. Rules for metering instruments equipment are set by normative acts.

Metering of consumed energy resources is done in the form of technical (to reveal target consumption of energy resources) and revenue (for instrument support of payment for consumed energy resources) metering.

There is no energy efficiency without proper metering. To save energy resources, control, metering and regulation are required in the first place. Absence of such systems in heat supply stations leads to 40–60 % overconsumption of heat energy.

Metering systems should meet the following requirements:

- ✓ High reliability and normalized accuracy for a long period;
- ✓ A wide range of measured consumptions;
- ✓ Resistance to ambient conditions;
- ✓ Capability to get information as a signal, transmitted for large distances;
- ✓ Non-volatile supply;
- ✓ Self-testing with error indication;
- ✓ Compatibility with automatic control systems.

As a result of metering systems inspection, a view of energy resources share, consumed without a metering device, should be clearly stated.

Balance measurements are applied for electrical and heat (or other energy carriers) energy balance development for certain divisions, sections, buildings or blocks of enterprises. To conduct measurements, a precise diagram of energy carrier flows distribution is required, for which balance is consolidated. There should be as many instruments or separate detectors installed, connected in a common measuring network, as required for balance consolidation. It is important to provide synchronous measurements and sufficient duration in order to cover the entire production cycle.

Fuel and energy balance, considered in the next chapter, gives a more complete picture of receiving, transmitting and use of energy resources on site.

Energy efficiency factors are meant for evaluation of energy resources use efficiency, planning and control over energy-saving measures and energy efficiency increase. Difficulty in indicator selection consists in that a clear correlation between an action taken and a result obtained in FER saving can only be seen in the simplest cases of energy-saving measures. In most cases the result of this or that action or their combination shows as a tendency. Thus it is necessary to calculate multiple factors and judge about the results using them.

Inspection of processing units, equipment, buildings, pipelines, etc., performed during EI, has the purpose of obtaining energy use characteristics. The main factor of efficiency here serves the specific consumption of energy carrier per unit of produce, useful product, volume, area and other physical value, describing the device productivity. Comparison of actual specific consumption with the norm (standard) allows making a conclusion about efficiency. The basic norm (basis for comparison) can be calculated using industry values, values of factor in previous periods (last year or month) or specific consumption norms of related foreign or domestic facilities.

Direct FER losses can be revealed during inspection, significant deviations from regulations and rules for equipment operation, outages, idle running, insulation, etc.

Calculation of norms, forecasts, reserves and other characteristics are made using current guidelines and methods. Energy resources consumption forecast is based on a promising production program and efficiency of planned energy-saving measures.

Energy-saving potential evaluation is done on the basis of suggested energy-saving measures.

Energy-saving and energy efficiency increase measures are developed by using a standard list of energy-saving measures to facilities that during inspection showed the least efficient use of energy resources. Certainly, a standard list of measures does not limit the developer initiative to recommend additional and specific energy-saving measures, however, a complete feasibility study, cost estimate and calendar plan are required to be provided.

CHAPTER 5. ENERGY BALANCES FOR INDUSTRIAL AND ENERGY ENTERPRISES

Energy balances are developed for different purposes at the enterprises: research, analytical, energy equipment installation, energy consumption standardizing and production planning. Variety of energy balance forms requires a clear understanding of what balance is being developed and for what purposes.

Energy balance is a system of indicators, describing a process of energy transformation or its supply to consumers; and reflecting equality of the supplied power, on the one hand, and amounts of useful energy and losses on the other [17, 18].

Classification of energy balances (EB) is given in Fig. 5.1.

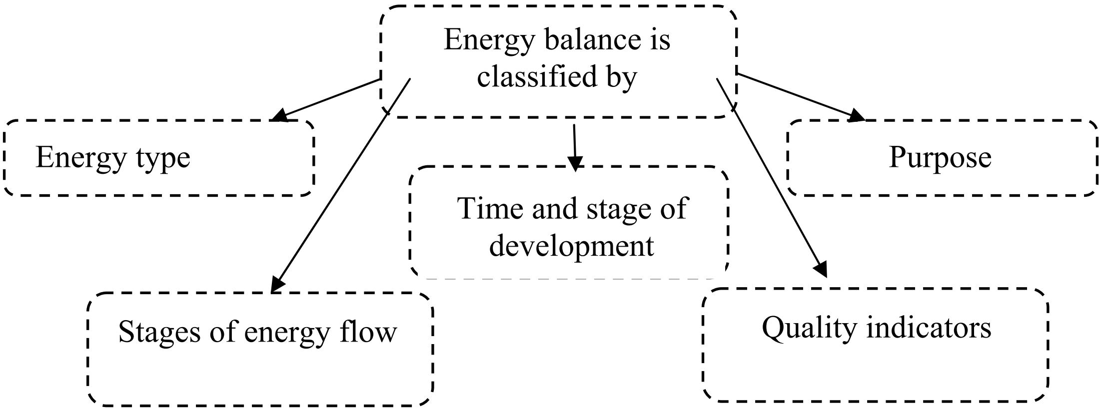


Fig. 5.1. Energy balance classification

1. According to the energy type, particular balances are divided into electrical, heat, fuel, pressurized air and gases, cold, water, etc.

This classification group includes ***consolidated fuel and energy balance,*** where all types of energy are converted to the same energy units and summed up (in Russia such unit is a tonne of reference fuel (trf) with combustion value of 7000 kcal/kg).

Another type of reference fuel – tonne of oil equivalent (toe) with combustion value of 10 000 kcal/kg – is commonly used in the world practice.

Here the ratio is 1 toe = 1.43 trf.

Coefficients, used for converting the different energy and fuel types to the reference fuel, are given in Table 5.1.

Table 5.1

Coefficients used for converting different energy and fuel types to reference fuel

Type of fuel and energy	Coefficient
Petrol	1.5
Kerosene	1.47
Diesel fuel	1.43
Fuel oil	1.4
Anthracite	0.9–1.0
Black coal	0.75–0.9
Brown coal	0.36–0.45
Sod peat, 33 % moisture	0.41–0.43
Milled peat	0.35–0.4
Fuel wood, 40 % of moisture	0.35
Natural gas	1.2
Oil	1.47–1.5
Heat	0.172 trf/Gcal
Electrical energy	0.32 trf/thous. kW·h

2. By time and stage of development: reporting, current, long-term and project energy balances.

3. By purpose: balances are developed for the main production, auxiliary production units and for public-utility needs.

4. By power flow stages the balances are divided into those for natural energy resources production, their processing and treatment, for transportation, converting into other types of energy, consumption and utilization.

5. By qualitative indicators: energy balances can be actual, normalized, rational, optimal and ideal.

✓ Normalized balances are developed for a strict compliance with the technically and economically validated measures.

✓ Rational balances are developed for improvement and rationalization of energy consumption.

✓ Optimal balances provide for a complete technical re-equipment with the most advanced energy-saving equipment.

✓ Ideal is the energy balance, developed only for useful energy, without losses and for research purposes solely.

Any energy balance form consists of input and output parts.

Energy input of the balance contains a quantitative list of energy, incoming by means of different energy carriers (fossil fuel and nuclear fuel, gas, vapor, water, air, and electrical energy).

Energy output of the balance specifies consumption of all energy types in every possible application, losses of energy on conversion from one type to another, transportation losses, as well as energy, accumulated in special devices (for example, in the pumped storage units, thermal boilers, etc.).

If the purpose of energy balance development is specification of fuel amount, required for direct consumption and also for conversion into electrical energy and heat, then such balance sheet is called Fuel and Energy Balance (FEB).

Fuel and energy balance is a generalizing description of production, processing, transportation, conversion and distribution volumes of the primary, processed and converted types of fuel and energy, starting from fuel and energy resources (FER) production stage and ending with the stage of all types of fuel and energy supply to power-consuming units.

FEB development is required for calculating demand for different fuel types at a particular industrial enterprise, for economy sectors, region, city or country, as well as for energy industry planning in certain regions or country in whole.

Heat and electrical energy are the basic types of energy, consumed in industrial, municipal, agricultural and utility sectors. Therefore, it is often necessary to develop ***particular (partial) energy balance*** – heat and electrical.

As soon as electricity is the main energy carrier, consumed in production processes, ***electrical balances (EB)*** are important and common for the industry.

5.1. Types of electrical balances

In conditions of operating industrial facilities, EBs are developed for specific units or their groups, production shops and enterprises in general.

Electrical balance is included in the total heat and energy balance of the shop or enterprise as an independent section and reflects a degree of useful consumption of EE. Based on the EB data, an impartial decision about quality and efficiency of electrical energy consumption at the enterprise, in production divisions or power-consuming units, is made; possibility of reducing the unproductive energy consumption and its losses is found, which results in EE consumption efficiency measures.

One of the most important results of the normalized EB development is opportunity to rate the electricity consumption for basic production processes and the finished goods manufacture.

Main purpose of electrical balance is specifying of an electricity useful consumption degree, search for losses reduction and electricity consumption efficiency increase. Therefore, the main type of electrical balance should be considered the balance of active power and energy.

Balance of reactive power and energy is developed in a similar way with the account for reactive energy generation by compensating devices. Its purpose is to solve issues of reactive power compensation and voltage control.

Due to irregularity of electricity consumption by specific units, production shops and the enterprise in general, actual EB for energy should refer to one working shift duration, one 24-hour period, month or year. Selection of any duration depends on the assigned task and conditions of measurement and observations.

Differentiated and ***structural*** electrical balances for shops and those consolidated for the entire enterprise are developed for convenient subsequent analysis.

Output part of a differentiated balance contains items, reflecting energy costs for the main production process and all types of losses, arising during its performance.

Structural EB is larger and reflects electricity consumption for the main process by equipment type (machines, power equipment, electrical technology, ventilation, lighting, etc.), considering the losses that occur and without dividing them into constant, load losses, etc.

Electrical Balance structure

EB input part contains data about electricity, supplied to electric load terminals or shop input leads. A consolidated balance made for the entire enterprise, EE input includes energy, delivered from the power system and supplied by its own generation sources.

Reactive energy input of a shop or the entire enterprise also contains data on energy generation by all reactive power sources, i. e. capacitor banks, overexcited synchronous motors and synchronous capacitors.

Outputs part contains the following items:

1. Direct energy consumption by units for production process performance with specification of constant and load losses in electric and processing equipment.
2. Energy losses in intrashop (distribution) and intershop (feeding) lines, plant-wide and shop transformers.
3. Other losses (starting, heat losses, etc.).
4. EE consumption by handling and transportation equipment, for ventilation and lighting.
5. EE consumption by auxiliary equipment.
6. EE consumption by plant-wide consumers that are not connected with the production process (so-called sub-users, which include dining-halls, clubs and other cultural and domestic consumers).
7. EE supply to outside consumers.

EB output part might not contain some of the listed items. In particular, it refers to Items 4 and 5, which identification in practice can prove to be the most difficult or even impossible. In these cases, electricity consumption for the stated items is calculated together with Item 1.

Losses in shop and plant systems

This item of EB output part cannot be found by direct measurements, and therefore, it should be calculated. Taking into account a small specific weight of these losses in balances of certain shops and the consolidated balance, amount of losses in radial shop systems and bus ducts should be directly calculated, using actual load values and well-known formulae.

In more complicated cases when shop network has multiple branches, the following simplified method is applied.

For each specific feeder, supplying one or several distribution switchboards (or busbar assemblies), losses per typical 24-hour period (average daily losses) can be calculated using the expression

$$\overline{\Delta W}_{\text{day}} = 3\overline{K}_{\text{f}}^{2}\,\overline{I}_{\text{day}}^{2}\,r_{\text{e}}\,\overline{t}_{\text{day}}10^{-3}\,, \qquad (5.1)$$

where $\overline{t}_{\text{day}}$ – average on-load operation hours during typical hours; r_{e} – equivalent resistance of the given feeder and all its resistances.

In the expression 5.1 a shape factor and average current of feeder line are calculated according to daily schedule of this feeder load (or the entire shop), plotted using active and reactive energy meter readings during 24-hours.

Equivalent resistance of the system segment means resistance of the unbranched line, which current equals to the current of the main feeder segment, and losses are equal to actual losses in the feeder and all its connections. Due to impossibility of these losses direct measurement, equivalent resistance can be calculated using the system circuit of the given connection by means of the following methods:

1. In case when this feeder supplies to the network with a small number of branches, r_{e} is found, using a system conversion method by curtailing it.

2. If distribution network, connected to the feeder, is extensively branched, then the simplest way is to calculate according to the following expression:

$$r_{\text{e}} = r_{\text{main}} + \frac{\sum_{i=1}^{n} \overline{I}_{\text{day}i}^{2} r_i}{\overline{I}_{\text{day.main}}^{2}}\,,$$

where r_{main}, $\overline{I}_{\text{day.main}}$ – resistance and average load for 24 hours of the main segment; $r_i, \overline{I}_{\text{day}i}$ – the same for the *i*-th branch line, connected to this feeder.

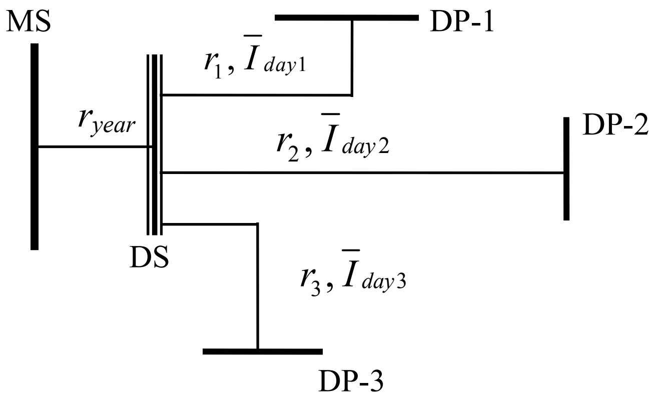


Fig. 5.2. Diagram for calculation of the shop system equivalent resistance

In many cases it is convenient to focus all observations and do all measurements during the maximum loaded shift.

When as-built drawings are unavailable and cannot be drawn during energy inspections, losses in shops up to 1000 V may be taken equal to 0.5–1.5 % from total electrical energy, consumed by the shop.

Losses in power transformers

When load diagrams for specific substations are available for the period concerned, losses are calculated by these diagram stages. However, such diagrams are unavailable in practice, and, therefore, energy losses can be calculated with sufficient accuracy, according to the following expressions:

- ✓ In case of parallel operation of transformers

$$\Delta\overline{W}_t = n \cdot \Delta P_{\text{NL}} \cdot \overline{t} + \frac{1}{n} \cdot \Delta P_{\text{SC}} \cdot \left(\frac{S_{\max}}{S_{\text{rated}}}\right)^2 \cdot \tau_{\max},$$

- ✓ In case of isolated operation transformers

$$\Delta\overline{W}_t = n \cdot \Delta P_{\text{NL}} \cdot \overline{t} + n \cdot \Delta P_{\text{SC}} \cdot \left(\frac{S_{\max}}{S_{\text{r}}}\right)^2 \cdot \tau_{\max},$$

where ΔP_{NL} – losses in steel, kW; ΔP_{SC} – losses in copper for the rated load, kW; $S_{\max}$ – the maximum load at substation, kV·A; S_{r} – rated power of one transformer, kV·A; n – number of similar transformers at substation; $\overline{t}$ – average time of transformers under voltage during concerned period; $\tau_{\max}$ – the maximum losses time during the period $\overline{t}$, h.

When developing a consolidated EB for the entire enterprise, the period under consideration often applies to a year ($t = T_{\text{year}} = 8760\ \text{h}$).

When transformers of uneven power are installed at the substation, calculation should be done for every transformer separately (distributing the load proportionally to their rated capacities).

5.1.1. Electrical balance for a shop

Electrical energy balance is obtained by summing the similar items in the electrical balance outputs for supplying feeder lines.

Unlike EB for specific processing units, it is reasonable to develop shop EB both in a differentiated and structural form. Reactive energy balance also needs to be accounted, as it's the input part of such EB is formed partially by compensating devices, installed in certain shops, and synchronous motors, operating with the leading current.

Input part of a shop electrical balance is developed as shown in Table 5.2. As an example, here are given values, describing a 24-hour energy input for a factory's medium-size machinery shop, supplied by 0.4 kV factory system via three power feeders and one lighting feeder.

Table 5.2

Input part

EB input item	Electrical energy	
	P, kW·h	Q, kvar·h
The factory network supplied by feeder No. 1	1810	1940
Feeder No. 2	1560	1450
Feeder No. 3	1590	1845
Feeder No. 4	270	–
Generated in the shop: capacitor banks	–	1840
synchronous motors	–	–
Total	**5230**	**3395**

EB outputs of the same shop are given in a differentiated from in Table 5.3.

Table 5.3

Output part

EB output item	Electrical energy consumption, kW·h					
	Feeder No. 1	Feeder No. 2	Feeder No. 3	Feeder No. 4	Total for shop	
					kW·h	%
Main production process	940	845	815	–	2600	49.7
Constant losses	556	520	456	–	1532	29.4
Load losses	128	92	90	17	327	6.3
Heat losses	–	12	32	–	44	0.8
Starting losses	15	–	20	–	35	0.7
Losses in the shop network	16	13	14	5	48	0.9
Lighting	–	–	–	248	248	4.7
Auxiliary needs	125	78	131	–	334	6.4
Utility needs	30	–	32	–	62	1.1
Total	**1810**	**1560**	**1590**	**270**	**5230**	**100**

The structural form of EB can be based on data about type of process equipment used and its purpose. Here losses should be broken down by specific equipment types. As for the shop under consideration, structural balance is given in Table 5.4.

Table 5.4

Structural energy balance

Type of equipment and item of expenses	Electrical energy consumption	
	kW·h	%
Power equipment	3409	65.2
Electrical processing equipment	1078	20.7
Handling equipment	209	4.0
Ventilation	125	2.4
Lighting	248	4.7
Domestic needs	62	1.1
Losses in the shopfloor system	48	0.9
Unaccounted equipment	51	1.0
Total	**5230**	**100**

Electrical process equipment includes electric furnaces and heaters of all systems and types, electrolysis plants, electric welding equipment and other.

5.1.2. Plant-wide electrical balance

Electrical balance for the plant is done by summing up the shop EBs, considering all plant energy consumers and electricity supply to outside users. Transformer losses in the main step-down substation (MSDS), as well as in plant distribution system lines are accounted here.

Besides balance of active energy consumption, reactive power EB should be made up for the enterprise in general. Such form of EB gives an opportunity to identify a ratio of consumed reactive energy to locally generated by reactive power sources, and also determine a further strategy of satisfying the plant's demand for reactive energy.

Due to difficulty of covering all plant consumers in the EB outputs, it is balanced with some statistical discrepancy (10 % stat. discrepancy is considered allowable). Moreover, it always has a positive sign (energy input is bigger than consumption, calculated by summing up all particular EBs, the losses of plant systems and plant-wide consumption). Summary EB of the entire plant is often represented as a diagram shown in Fig. 5.3.

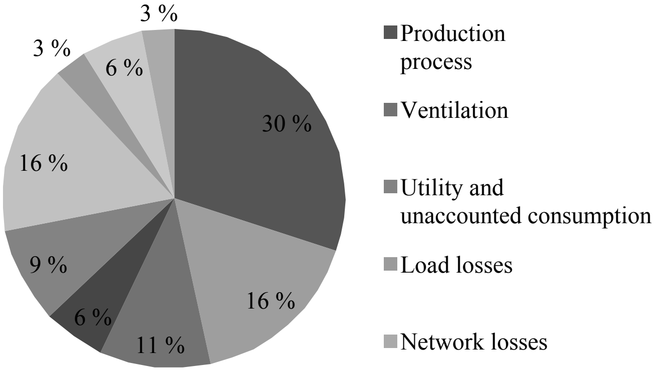


Fig. 5.3. Structure of plant-wide electrical balance

EB normalization is based on review of particular electrical balances of the most energy-intensive units and shops. Scientifically grounded processing and shop specific consumption rates should become the basis for a normal energy consumption.

Equipment losses normalization is done by considering its typical specifications, and for the most energy-intensive units – by special control tests and calculations. Normalization of system losses sometimes requires the reviewing of electricity supply diagrams and operation modes of transformers.

5.1.3. Energy and financial balance

Making the energy balance sheet for an enterprise, stipulated by the national standard GOST 27322–87, is a quite complicated task; however, its analysis provides elaborate consideration of energy saving measures and efficient use of energy resources.

Energy balance is first developed in a material form for every used energy resource, and then in reference fuel. Synthetic balance in reference fuel allows planning of energy efficiency increase measures such as consumption reduction, replacement of one energy resource with the other, etc.

Analysis of balance output parts developed for buildings, areas, departments and units of an enterprise, help to reveal the points of evident losses and plan the loss reduction measures. Considering the relative interchangeability of energy resources, variation of each resource share; balance optimization is done by reducing losses and balance restructuring. In view of this, ***energy and financial balance of enterprise***, expressing flows of funds, related to energy resources receiving and consumption (Table 5.5), presents a significant interest [19].

Table 5.5

Energy and financial balance of enterprise

Energy resources inflow (payments received for energy resources), Rub.		Energy resources outflow (cost of energy resources, converted in produce), Rub.	
1. Payment for fuel: • coal • gas • petroleum products • other	 + + + +	1. Cost of fuel and energy for production needs, included in the cost price	+
2. Payment for outside energy: • electrical energy • heat energy	+ +	2. Cost of fuel and energy for domestic and utility needs, not included in the cost price	+
3. Debts of subusers	+	3. Cost of standard losses, included in the cost price	+
4. Debts for earlier supplied energy	+	4. Payments of subusers *	+
Total: Rub.	+	**Total: Rub.**	+

***Note:** only subusers, paying for energy to the enterprise, are accounted.

Efficiency of FER consumption can be based on the system of energy efficiency factors.

✓ Specific consumption of FER per unit of manufactured produce in (trf/pc.);

✓ Energy intensity of manufactured produce – a ratio of all FER types consumption in tonnes of reference fuel to annual produced volume in monetary terms (trf/Rub.);

✓ Energy component in the produce cost price, expressed as percentage;

✓ Eficiency factor, losses and other technical indicators.

During energy efficiency analysis an important task is accounting of energy expenditure when calculating the product cost price, where usually cost of fuel and energy is not itemized separately. It is related to absence of FER accounting for certain engineering process cycles for most of product types; and to a large nomenclature of enterprise products, as well as to the fact that many products are made of parts, manufactured in different enterprise divisions.

To determine a share of energy resources cost, included in the product cost price for multiproduct manufacture, the following algorithm is suggested.

- ✓ *Calculation of all manufactured products energy intensity*

$$E = \frac{W_{\text{pr}}}{P} \text{ (trf/Rub.)},$$

where W_{pr} – annual consumption of all FER types for production and utility needs, reduced to the uniform fuel equivalent in trf; P – annual cost of manufactured products (thous. Rub.).

- ✓ *Calculation of the reference fuel cost unit at the enterprise*

$$C = \frac{Z}{W_{\text{pr}}} \text{ (Rub./trf)},$$

where Z – financial costs for all FER types consumed for production and utility needs (Rub.).

- ✓ *Calculation of FER specific consumption for output of products, specified in the i-th nomenclature*

$$Y_i = \frac{C_i}{C \cdot V_i} \text{ (trf/pcs.)},$$

where C_i – cost price of the i-th product type (Rub.); V_i – annual output of the i-th products (pcs.).

- ✓ *Calculation of the energy component in product cost price*

$$EC = E \cdot C \cdot 100\ \%.$$

Obtained values of energy efficiency factors can be corrected during consumed FER accounting for different operations and production process cycles.

As an example, we will consider use of financial and energy balance for calculating specific FER consumptions of an enterprise, manufacturing 8 product types. Calculation results according to the suggested algorithm are given in Tables 5.6 and 5.7.

Table 5.6

Calculation results

Item No.	Type of FER	Annual FER consumption (trf)	Financial costs by FER types (thous. Rub.)	Annual output (thous. Rub.)
1	Electrical energy	3630	10 230	–
2	Heat power	2210	1865	–
3	Gas	2170	1270	–
	Total:	8010	13 365	171 600

Table 5.7

Calculation Results

Item No.	Description of products	Cost of product (Rub.)	Annual output (pcs.)	Specific FER consumption (trf/pcs.) $\cdot 10^{-3}$
1	P-1	1000	1600	0.374
2	P-2	2000	3000	0.4
3	P-3	3000	5000	0.36
4	P-4	4000	10 000	0.24
5	P-5	5000	10 000	0.3
6	P-6	6000	2000	1.8
7	P-7	7000	1000	4.19
8	P-8	8000	5000	0.96

Regular preparation of different balances at the enterprises allows for timely identification of fuel-energy resources wasteful consumption areas, their eliminating and optimizing the FEB; thus, reducing the payments for energy resources.

CHAPTER 6. INDUSTRIAL ELECTRICAL ENERGY EFFICIENCY

Industrial facilities refer to the category of consumers, to which requirements of FZ No. 261 apply in part of obligatory energy inspections, development of energy efficiency increase and reduction product of output energy intensity programs.

Further a list of standard solutions is offered, which are aimed at electrical energy losses reduction in systems of facility's external and internal electricity supply to consumers.

6.1. Reduction of electrical energy losses in the networks

Reduction of electrical energy losses during transmission and distribution is an urgent problem for energy-supplying organizations and one of main energy saving areas in distribution networks of industrial facilities.

The principal condition of grid operation with minimum losses is its rational structure. Here a special attention should be given to the right designation of division point in closed-loop systems, efficient distribution of active and reactive powers, implementation of closed, semi-closed system circuits of 0.4 kV [21–26].

Reduction of electrical energy losses in electrical grids can be achieved as a result of both grid optimization when energy losses reduction is one of integrated plans constituent, and measures aimed at losses reduction. In terms of this criterion, all measures on losses reduction can be conventionally divided into three groups:

Group 1 – organizational, which include measures on improvement of grids operational maintenance and optimization of their circuits and modes (low-cost and no-cost).

Group 2 – technical, which include measures on grid reconstruction, modernization and construction (medium-cost).

Group 3 – electricity metering improvement, which can be either no-cost, or requiring additional costs (when organizing new metering points).

Organizational measures include:

✓ Selection of optimal points of 6–10 kV grid;

✓ Reduction of a period when line is in off-position for maintenance and repair of equipment and lines;

✓ Reduction of asymmetry (imbalance) of phase load;

✓ Rational load of power transformers.

The priority technical measures in distribution networks of 10 (6)-0.4 kV include:

- ✓ In projects involving transfer of operational 6 kV grids during reconstruction to a higher voltage of 10 kV, it is recommended to use the specified equipment if it complies with higher voltage specifications;
- ✓ Increase of 35 kV grids share;
- ✓ Reduction of range and construction of 0.4 kV OHL in three-phase arrangement along the entire length;
- ✓ Application of pole-type transformers (10(6)/0,4 kV) of small power to reduce the length of 0.4 kV grids;
- ✓ Transfer of low-voltage grids from 220 to 380 V;
- ✓ Application of self-supporting insulated and protected wires for OHL of 0.4–10 kV;
- ✓ Use of the maximum allowable wire section of electrical grids of 0.4–10 kV to adjust their transmission capacity to load growth during service life;
- ✓ Enhancement of current grid elements by installing new lines or replacing wires and cables with larger section;
- ✓ Works on reactive loads compensation;
- ✓ Keeping the electricity quality factor values in compliance with the requirement [13];
- ✓ Implementation of automatic voltage control devices under load, voltaic transformers, means of in-built voltage control;
- ✓ Implementation of a new economic electrical equipment, particularly, transformers with reduced active and reactive losses of no-load operation, installation of capacitor banks, built in transformer substations;
- ✓ Integrated automation and remote control engineering of grids, application of a new generation switching devices;
- ✓ Application of remote fault location in electrical grids to reduce the search and response time.

Measures on electrical energy metering improvement should include:

- ✓ Metering devices (electricity meters, measuring transformers) of a higher accuracy class;
- ✓ Measures on prevention of unauthorized access to metering device terminals;
- ✓ Implementation of automated systems of accounting, information acquiring and transfer;
- ✓ Arrangement of organizational and technical measures on prevention, finding and elimination of unaccounted electrical energy consumption.

6.1.1. Reduction of power losses by phase load leveling

A peculiar feature of 0.4 kV network operational mode is the phase load unbalance.

Amount of power losses during unbalanced load of phases ΔP_{l} can be expressed as

$$\Delta P_{\mathrm{L}} = k_{\mathrm{AL}} \cdot \Delta P_{\mathrm{S}},$$

where ΔP_{S} – power losses during symmetrical phase load, kW; k_{AL} – factor of additional losses during the unbalanced load.

Load leveling is done by switching the load from more loaded phases to those having a lower load after measuring the phase loads and results analysis.

A negative effect of unbalance, which cannot be eliminated by phase load leveling, can be reduced by:

- ✓ Replacement of double-star connection power transformers with the forked wye or delta-wye transformers, which are less sensitive to load unbalance;
- ✓ Increase of zero wire section in 0.4 kV line up to phase conductor section.

Example of calculating the efficiency of phase load leveling measures in 0.4 kV grids is given in Table 6.1 where it can be seen that losses reduce two times after measures.

Table 6.1

Example of calculating the efficiency of phase load leveling measures in 0.4 kV grid

Breaker No.	**Prior to phase load leveling measures**								
	Phase current, A			Average current I_{av}, A	Voltage losses, ΔU, V	Hours with maximum losses, τ, ч	Unbalance factor K_u^2	Additional losses factor $K_{A.L}$	EE losses in line ΔA_l, kW·h
	I_a	$I_в$	I_c						
1	11	18	20	16.3	2.35	5650	1.042	1.105	322.9
2	65	29	56	50	14	5650	1.078	1.183	6316
3	18	16	20	18	1.79	5650	1.008	1.03	253
4	36	55	46	45.7	5.5	5650	1.022	1.088	2085
5	60	30	60	50	6.8	2650	1.08	1.2	1460
6	15	48	5	22.7	5	4550	1.684	2.71	1889
7	10	13	70	31	20.6	4550	1.684	4.56	17 887
Total									**30 214**
After phase load leveling measures									
1	16	18	15	16.3	2.35	5650	1.002	1.005	218
2	49	45	56	50	14	5650	1.008	1.025	5446
3	18	18	18	18	1.79	5650	1	1	246
4	40	51	46	45.7	5.5	5650	1.002	1.008	1932
5	50	50	50	50	6.8	2650	1	1	1171
6	25	25	18	22.7	5	4550	1.073	1.16	823
7	31	28	34	31	20.6	4550	1.022	1.11	4354
Total									**14 190**

In prices of 2013 costs for consumed EE reduce for about 50 thous. Rub., which can be allocated to implementation of low-cost organizational and technical measures.

6.1.2. Increase of transformer efficiency

1. An important measure on electricity processing consumption reduction is increase of transformers efficiency due to seasonal disconnection of a transformer in two-transformer substation. Here a less loaded transformer is disconnected and its load is transferred to another transformer.

Calculation example of this measure efficiency is given in Annex 1 (Table P 1.1).

2. Reduction of electricity losses is achieved by replacing the transformers when their power is underutilized. When load factor of 10(6)/0.4 kV transformer is less than 0.5, a significant increase of electricity losses takes place due to no-load running.

Reduction of electrical energy losses by replacing transformers is calculated according to the formula

$$\Delta W_{\mathrm{T}} = (\Delta P_{\mathrm{NL1}} - \Delta P_{\mathrm{NL2}}) \cdot T + (\Delta P_{\mathrm{SC1}} \cdot \beta_1^2 - \Delta P_{\mathrm{SC2}} \cdot \beta_2^2) \cdot \tau_{\max},$$

where ΔP_{NL1}, ΔP_{NL2} – power losses due to no-load run of transformers, kW; ΔP_{SC1}, ΔP_{SC2} – power losses due to short circuit, kW; T – number of hours of maximum load operation; $\tau_{\max}$ – number of hours with maximum losses.

In Annex 1 (Table P 1.2) is given an example of efficiency calculation from replacing less loaded transformers with transformers of a lower power.

6.1.3. EE saving by networks reconstruction

1. Electrical energy saving by transferring the system to a higher voltage class is calculated in the following, kW·h

$$\Delta W = 0.003 \cdot \rho \cdot L \cdot t \cdot \left(\frac{I_1^2}{S_1} - \frac{I_2^2}{S_2} \right),$$

where L – length of a grid segment where rated voltage is increased, m; I – average value of currents in every wire at low and high voltage, accordingly, A; ρ – specific resistivity of wire material at 20 °C (for aluminium 0.026–0.029; copper 0.0175–0.018, steel 0.01–0.14 Ohm·mm^2/m); S_1 and S_2 – wire section at low and high voltage, mm^2 (when measures do not include rewiring $F_1 = F_2$); t – estimated time, h.

2. Electricity saving during system reconstruction, kW·h:

- Replacement of wire section;

- Replacement of wire material;
- Reduction of length without changing voltage;

$$\Delta W = 0.003 \cdot I^2 \cdot \left(\frac{\rho_1 \cdot L_1}{S_1} - \frac{\rho_2 \cdot L_2}{S_2} \right) \cdot t,$$

where ρ_1, L_1, S_1 – specific resistivity of wire material, Ohm·mm^2/m, the line length, m, section of wires prior to reconstruction, mm^2; ρ_2, L_2, S_2 – the same line parameters after reconstruction; I – average current of the line, A; t – a design period of time, h.

3. Loading the backup transmission lines.

Electrical energy losses in the system are in proportion to the wire resistance, consequently, when switching the backup lines, losses will reduce two times, if wire length, section and load of the main and back-up OHL are equal and circuits are similar, accordingly [27, 28].

6.2. Efficient mode of transformer operation

Economical mode of transformer operation determines a number of transformers switched on simultaneously, providing the minimum of electricity losses in them.

At substations, equipped with one type transformers of similar power, number of transformers switched on simultaneously, is determined by the following conditions:

1. Switching of (n + 1)-th transformer is economically viable when load grows and load factor of operating transformers reaches the value

$$k_{\text{L}} \geq \sqrt{\frac{n+1}{n}} \cdot \sqrt{\frac{\Delta P_{\text{NL}} + k_{\text{e}} \cdot \Delta Q_{\text{NL}}}{\Delta P_{\text{SC}} + k_{\text{e}} \cdot \Delta Q_{\text{SC}}}}.$$

2. During load reduction it is economically viable to switch off one of the transformers and when a load factor of operating transformers reaches the value

$$k_{\text{L}} \geq \sqrt{\frac{n-1}{n}} \cdot \sqrt{\frac{\Delta P_{\text{NL}} + k_{\text{e}} \cdot \Delta Q_{\text{NL}}}{\Delta P_{\text{SC}} + k_{\text{e}} \cdot \Delta Q_{\text{SC}}}},$$

where n – number of switched-on transformers, ΔP_{NL} – the nameplate no-load losses of a transformer, kW; ΔP_{SC} – the nameplate short circuit losses of a transformer, kW; $\Delta Q_{\text{NL}} = S_{\text{R}} \cdot \frac{I_{\text{NL}}}{100}$ – reactive losses of no-load transformer, kvar; $\Delta Q_{\text{SC}} = S_{\text{R}} \cdot \frac{U_{\text{SC}}}{100}$ – short circuit reactive losses, kvar; S_{R} – a transformer rated power, kV·A; U_{SC} – a short circuit voltage, %; I_{NL} – no-load current, %; k_e – losses factor (or economic equivalent of reactive power), kW/kvar.

Approximate values of k_e, depending on location of transformer installation, are taken according to Table 6.2.

When there are two or more transformers of different power at the substation, it is reasonable to plot curves, depending on losses from transformers load. The summary reduced power losses for these curves can be calculated using the expression

$$\sum \Delta P = n \cdot (\Delta P_{NL} + k_e \cdot \Delta Q_{NL}) + \frac{1}{n} \cdot (\Delta P_{SC} + k_e \cdot \Delta Q_{SC}) \cdot k_L^2 .$$

Depending on the substation load, a mode of transformers operation is calculated according to these curves, i. e. switching or deactivating of an additional transformer.

Table 6.2

Values of losses factor, depending on transformer installation location

Item No.	Description of a transformer and EE supply system	k_e, kW/kvar	
		k_e in hours of EPP maximum load	k_e in hours of EPP minimum load
1	Transformers, supplied directly by the busbars of electric power plant (EPP)	0.02	0.02
2	System transformers, supplied by EPP at generator voltage	0.07	0.04
3	Step-down transformers 110/35/10 kV, supplied by district grids	0.1	0.06
4	Step-down transformers 10–6/0.4 kV, supplied by district grids	0.15	0.1

Example 6.1. Three transformers of 630 kV·A power are installed at the substation. After plotting curves for the corrected power losses variation, depending on the load (Fig. 6.1), the following conclusion can be made that in terms of the maximum transformer losses reduction, it is reasonable to set the following operation mode:

- ✓ One transformer operated for loads from 0 to 380 kV·A;
- ✓ Enabling of the second transformer for loads from 380 to 1180 kV·A;

✓ Parallel operation of all three transformers would be feasible for loads over 1180 kV·A.

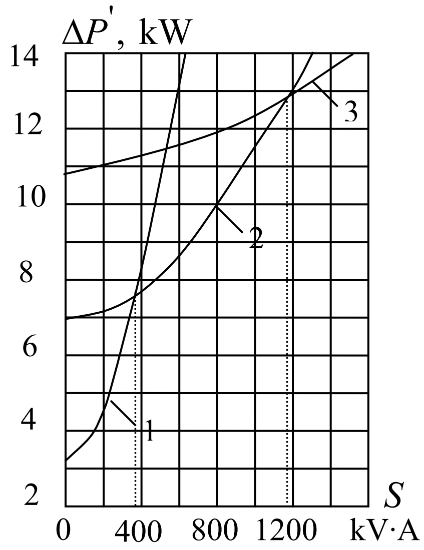


Fig. 6.1. Corrected losses for calculation of a feasible operation mode for 630 kV·A transformers, 10 kV:
1 – isolated operation of transformer;
2 – parallel operation of two transformers;
3 – parallel operation of three transformers

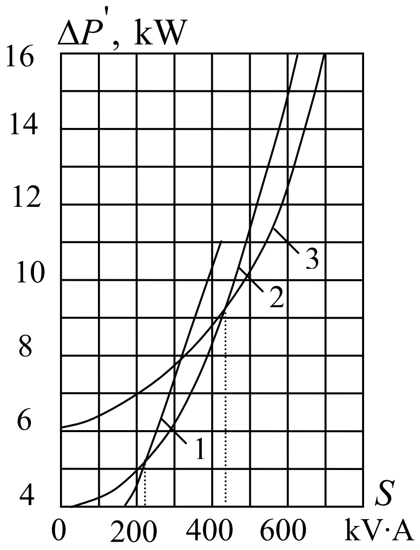


Fig. 6.2. The stated losses for calculation of a feasible operation mode for 400 and 630 kV·A transformers, 10 kV:
1 – isolated operation of a 400 kV·A transformer; 2 – isolated operation of a 630 kV·A transformer; 3 – parallel operation of 400 and 630 kV·A transformers

Example 6.2. Two transformers of 400 and 630 kV·A power are installed at the substation. An optimal operation mode for these transformers can be selected, based on the losses diagrams (Fig. 6.2):

✓ For loads from 0 to 260 kV·A it is feasible to switch on one 400 kV·A transformer;

✓ For loads from 260 to 450 kV·A it is feasible to switch off a 400 kV·A transformer and switch on a 630 kV·A;

✓ For growing loads over 450 kV·A a parallel operation of two transformers is feasible.

6.3. EE saving by increasing the working machines load

Increase of machinery average load reduces the specific electricity costs. As it can be seen in Fig. 6.3, when load reduces, the efficiency factor of electric motor, and especially of a working machine, decreases.

To calculate the electricity savings from increasing the working machines load, a notion of specific power consumption is introduced, which equals to the amount of energy, consumed by motor from the grid W_g, related to every kW·h of useful work for the given processing mode:

$$W_c = P_{max} \cdot T_{max},$$

where W_c – energy consumed by motor, kW·h; P_{max} – power, consumed by a machine's working element, kW; T_{max} – useful operation time of a machine, h.

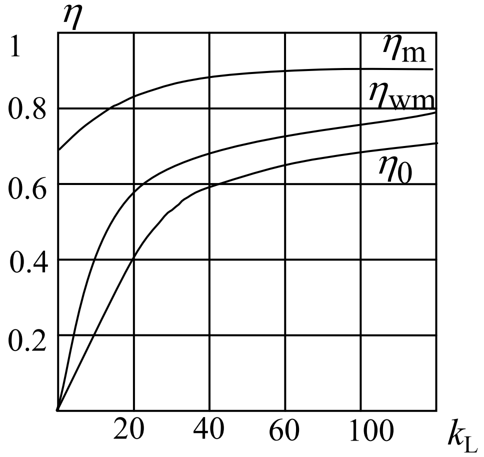


Fig. 6.3. Dependence of working machine efficiency factor η_{wm}, *of the motor* η_m *and the entire drive* η_0 *on the load factor* k_L

Specific power consumption

$$\Delta Y = \frac{1}{\eta_m \cdot k_L} \cdot \left(k_L + \frac{\alpha \cdot (1 - \eta_{wm})}{k_U} \right),$$

where η_{wm} – efficiency factor of a fully loaded working machine; $k_L = P_{max} / P_{wm}$ – load factor; P_{wm} – rated power of working machine, kW; $k_U = T_{max} / (T_{max} + T_{SC})$ – working machine utilization factor; T_{NL} – time of no-load machine operation; α – a factor, depending on working machine type and configuration, equal to 0.7–0.9.

When there is no idle run ($k_U = 1$), a specific power consumption is

$$\Delta Y' = \frac{k_L + \alpha \cdot (1 - \eta_{wm})}{\eta_{wm} \cdot k_L}.$$

During the maximum utilization of a working machine, i. e. when there is no idle run and the machine is loaded to the maximum ($k_R = 1$), a specific power consumption will be minimal

$$\Delta Y_0 = \frac{1 + \alpha \cdot (1 - \eta_{wm})}{\eta_{wm}}.$$

The ratio $\beta = \Delta Y / \Delta Y_0$ gives the factor of specific electric power consumption increase, depending on the load and duration of no-load operation

$$\beta = \frac{k_L \cdot k_U + \alpha \cdot (1 - \eta_{wm})}{\left[1 + \alpha \cdot (1 - \eta_{wm}) \cdot k_L \cdot k_U\right]}.$$

The curves given in Fig. 6.4 $\beta = f(k_R)$, using which efficiency of working machines load increase can be calculated and energy savings, obtained from working machines load increase.

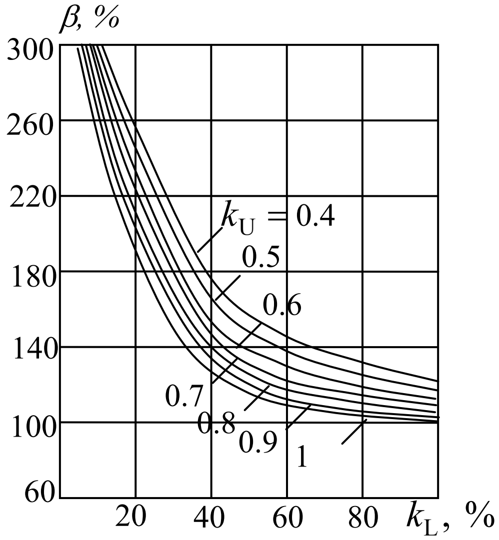


Fig. 6.4. Dependence of specific electric power consumption variation on the load factor of a working machine

Example 6.3. Metal-working machine is continuously operated with the load, equal to 25 % of the rated power ($k_L = 25$ %), and the duration of no-load rotation period, equal to 50 % ($k_U = 0.5$ %).

In this case, specific power consumption in comparison to the minimum possible specific power consumption during full load of the machine, according to diagram in Fig. 6.4, will make 250 %.

When machine load is increased up to $k_R = 80$ % and the period of no-load rotation reduces to $k_U = 0.9$ %, increase of specific power consumption will only be 106 %.

Considering that $\Delta Y_0 = 1.48$ kW·h at $\eta_{wm} = 0.8$ and $\alpha = 0.9$, we get the following hourly saving of electrical energy

$$\Delta W = (\beta_1 - \beta_2) \cdot \Delta Y_0 = (2.5 - 1.06) \cdot 1.48 = 2.14 \text{ kW·h}.$$

With a number of annual operation hours $T = 5000$ h and tariff $T^{(1)} = 3$ Rub./kW · h, annual saving will make

$$\Delta E = \Delta W \cdot T \cdot T^{(1)} = 2.14 \cdot 5000 \cdot 3 = 32\,100 \text{ Rub.}$$

6.4. EE saving by means of electric drive

From 60 to 80 % of load in industry is provided by induction motors. The basic principles of EE saving are in application of electric drive, when speed control is not used, can refer to:

1. **Correct selection of basic equipment**, first of all, electric motor and gear, if applied.

2. **Use of energy saving motors**. Application of induction motors (IM) in the design by 25–30 % more active materials (iron, copper, and aluminium) by 30 % allows reducing EE losses, increasing efficiency factor by 5 % in a low power motors and by 1 % in motors of 70–100 kW power. Price of such motors is by 20–30 % more than for typical motors, payback period due to reduction of operating costs makes 2–3 years [31].

Making decision about replacement of existing IM with energy saving ones, you should consider that estimated EE savings will be achieved only at low-load or close to the rated load. When load changes rapidly (a considerable share of no-load running in the cycle), the savings will be less than estimated.

3. **Losses reduction in feeding networks.** The problem of power losses arises due to low power factor $\cos\varphi$, especially at minor loads. The technical solutions, allowing increase of power factor to normative values [12], include reactive load compensation by controlled capacitor banks, synchronous condensers, and compensating filters.

Most of these methods are oriented to uncontrolled and sometimes considerably underloaded drive with cage induction motors. The effect reached from reactive power compensation can be incomparably less than losses from uncontrolled electric drive operation.

Other ways of energy saving by means of uncontrolled electric drive may include:

- ✓ Reduction of no-load run duration;
- ✓ Winding reconnection using connection $\Delta - \mathrm{Y}$ for the period of no-load or low load;
- ✓ Change of braking type in electric drives with often starts and braking.

6.4.1. EE saving by reducing the no-load run of motors

Limitation of IM no-load run duration of the main drive is done using automatic limitation – special breakers, which turn off the electric motor, if there is no load at the machine main drive for a certain period. It should be noted that limitation of no-load operation (NL) of electric motors, saving some part of active and reactive energy, causes increase of number of drive starts, and growth of losses in it. Besides, motor overheating is possible in some cases due to worse conditions of self-ventilated machines cooling during stops. Also wearing of machine electric instruments increases from often starts and stops [31].

When idle limiters are installed, number of processing cycles per hour should be considered with allowable number of starts, guaranteed by manufacturer of the applied starting equipment. Fast reclosing of motor is not allowed. Besides, frequent inrush currents can bring the savings, obtained by reduction of idle running, to zero [31].

Reason for making a decision about limiter installation is comparison of energy losses during motor idle running with losses that will take place from a motor start. If losses from motor starting are less than losses from idle running, then switching it off will provide energy saving in the electric drive, and vice versa. We get the expression for calculating the boundary time of no-load run, exceeding which the motor shutoff will be viable from point of energy saving.

Equality of energy losses from NL operation and starting can be put down in the following way;

$$K \cdot t_{\text{NL}} = K \cdot t_{\text{st}} + J_{\text{corr}} \cdot \omega_0^2 \cdot (1 + \frac{R_1}{R_2^{'}}) \cdot \frac{k_{\text{R}}}{2},$$

where K – constant power losses in motor; t_{NL} – the boundary time of no-load run; t_{st} – starting time at no-load run; $J_{\text{corr}} = J_{\Sigma}$ – the integral inertia of electric drive corrected to motor shaft; $k_{\text{R}} = \frac{M_{\text{av}}}{(M_{\text{av}} - M_{\text{NL}})}$ – factor, accounting for motor load, when calculating losses of motor starting.

Starting time of no-load motor is calculated according to the formula

$$t_{\text{st}} = \frac{J_{\text{corr}} \cdot \omega_0}{(M_{\text{av}} - M_{\text{NL}})},$$

where M_{av} – average moment of motor during startup; M_{NL} – load torque at no-load run.

Average moment of motor during starting:

$$M_{\text{av}} = \frac{(M_{\text{st}} - M_{\text{cr}})}{2},$$

where M_{st}, M_{cr} – starting and critical torque of motor, accordingly.

Boundary time of motor no-load operation

$$t_{\text{NL}} = \frac{J_{\text{corr}} \cdot \omega_0}{(M_{\text{av}} - M_{\text{NL}})} + J_{\text{corr}} \cdot \omega_0^2 \cdot (1 + \frac{R_1}{R_2^{'}}) \cdot \frac{M_{\text{av}}}{2K \cdot (M_{\text{av}} - M_{\text{NL}})}.$$

When neglecting the load torque M_{xx} due to its smallness in comparison with M_{cp} the formula simplifies and looks as follows:

$$t_{\text{NL}} = \frac{J_{\text{corr}} \cdot \omega_0}{M_{\text{av}}} + J_{\text{corr}} \cdot \omega_0^2 \cdot (1 + \frac{R_1}{R_2'}) \cdot \frac{1}{2K}.$$

Example 6.4. Motor 4A180S4 has the following rating data: power $P_{\text{R}} = 22$ kW, voltage 380/220 V, slip $s_{\text{R}} = 0.02$, stator current $I_{\text{R1}} = 41.2$ A, efficiency factor $\eta_{\text{R}} = 90\,\%$, $\cos\varphi_{\text{R}} = 0.87$, stator winding resistance $R_1 = 0.219$ Ohm, rotor corrected $R_2 = 0.112$ Ohm, rotor moment of inertia $J_{\text{rot}} = 0.19$ kg/m^2, breakdown $\lambda_{\text{c}} = 2.3$ and starting $\lambda_{\text{st}} = 1.4$ torque ratio.

Solution

1. We find the integral inertia of the corrected to motor shaft electric drive

$$J_{\text{corr}} = 1.2 \cdot 0.19 = 0.23 \text{ kg} \cdot \text{m}^2.$$

2. We neglect motor load torque of no-load run M_{NL}.

3. We find total, variable and constant power losses for the rated mode:

$$V_{\text{R}} = M_{\text{R}} \cdot \omega_0 \cdot s_{\text{R}} \cdot (1 + \frac{R_1}{R_2}) = 143 \cdot 157 \cdot 0.02 \cdot (1 + \frac{0.219}{0.112}) = 1327 \text{ W},$$

$$\Delta P_{\text{R}} = P_{\text{R}} \cdot \frac{(1 - \eta_{\text{R}})}{\eta_{\text{R}}} = 22 \cdot \frac{(1 - 0.9)}{0.9} = 2444 \text{ W},$$

$$K = \Delta P_{\text{R}} - V_{\text{R}} = 2444 - 1327 = 1117 \text{ W}.$$

4. We calculate the average starting torque of motor

$$\grave{I}_{\text{av}} = \frac{(1.4 \cdot 143 + 2.3 \cdot 143)}{2} = 264.5 \text{ N} \cdot \text{m}.$$

5. We calculate the boundary time of no-load run

$$t_{\text{NL}} = 0.23 \cdot \frac{157}{264.5} + 0.23 \cdot 157^2 \cdot (1 + \frac{0.219}{0.112}) / (2 \cdot 1117) = 7.6 \text{ s}.$$

Thus, if no-load operation period of electric drive exceeds 7.6 s, than motor shutoff will lead to an electrical energy saving in the electric drive and electricity supply system.

To determine the feasibility of motor NL limitation, the power losses balance is drawn at no-load run and start. Shutoff is usually possible for no-load motor operation for over 10 s.

6.4.2. EE saving by replacing the underloaded electric motors with motors of a lower power

Most of driven motors have an overstated rated power in comparison with that required from an electric drive to run a production process. Motor utilization factor k_L lies within range of 0.3–0.5 [31].

Besides, electric drives of some working machines and production mechanisms part of their cycle are operated with low mechanical loads or no-load (for example, electric drives of processing machines, press-forging plants and mechanical handling equipment).

According to the existing dependence of efficiency factor η and power factor $\cos\varphi$ on k_L (Fig. 6.5), motors with a lower load operate with low efficiency, and induction motors – with a lower power factor.

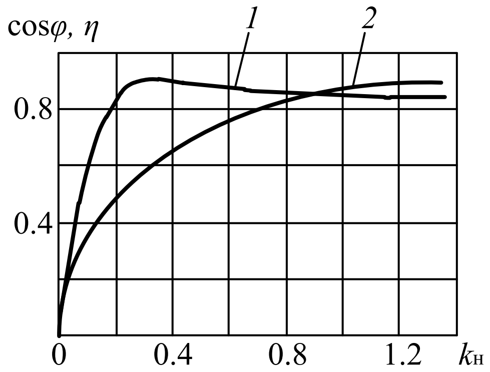


Fig. 6.5. Dependences of efficiency factor (1) and power factor (2) on a motor load factor

Increase of these indicators results in EE reduction in the electric drive and EE supply system and can be achieved, for instance, by replacing the insufficiently loaded electric motors with motors of a lower power.

If average load of an electric motor is less than 40 % of the rated power, then its replacement with motor of a lower power is always feasible and does not require a calculation check. When electric motor (EM) load is over 70 % of the rated power, it can be assumed that its replacement is unfeasible.

For EM load within range of 45–70 % of the rated power, feasibility of their replacement should be confirmed by decrease of total active power losses in the electric system and electric motor. These total losses of active power can be calculated according to the formula

$$\Delta P_\Sigma^{'} = \left[Q_\text{NL} \cdot \left(1 - k_\text{R}^2\right) + k_\text{R}^2 \cdot Q_\text{R} \right] \cdot k_\text{e} + \Delta P_\text{NL} + k_\text{R}^2 \cdot \Delta P_\text{RL},$$

where $Q_\text{NL} = \sqrt{3} \cdot U_\text{R} \cdot I_\text{NL}$ – reactive power, consumed by electric motor from the system during no-load operation, kvar; I_NL – EM no-load current, A;

U_R – EM rated voltage, V; $k_\text{R} = P / P_\text{R}$ – EM load factor; P – EM average load, kW; P_R – EM rated power, kW; $Q_\text{R} = \frac{P_\text{R}}{\eta_\text{m}} \cdot \text{tg}\varphi_\text{R}$ – EM reactive power at rated load, kvar; η_m – efficiency factor of electric motor at full load; $\text{tg}\varphi_\text{R}$ – derivative of the rated power factor of EM; k_e – factor of losses increase (economic equivalent of reactive power), kW/kvar; $\Delta P_\text{NL} = P_\text{R} \cdot \left(\frac{1-\eta_\text{m}}{\eta_\text{m}}\right) \cdot \left(\frac{\gamma}{1+\gamma}\right)$ – active power losses at EM no-load operation, kW; $\Delta P_\text{RL} = P_\text{R} \cdot \left(\frac{1-\eta_\text{m}}{\eta_\text{m}}\right) \cdot \left(\frac{1}{1+\gamma}\right)$ – active power losses growth at 100 % EM load, kW; $\gamma = \Delta P_\text{NL} / \Delta P_\text{RL}$ – rating factor, depending on EM design and calculated using the expression $\gamma = \frac{\Delta P_\text{NL}}{(100 - \eta_\text{R},\%) - \Delta P_\text{NL}}$; $\Delta P_\text{NL},\%$ – no-load losses in percentage of active power, consumed by motor at 100 % load.

Example 6.5. Electric motor A92-2 of power $P_\text{R1} = 125$ kW is operated with the load 70 kW; it is required to check the feasibility of its replacement with electric motor A82-2 of power $P_\text{R2} = 75$ kW. Losses increase factor we take as $k_\text{e} = 0.1$ kW/kvar. Motor A92-2 parameters are: $U_\text{R1} = 380$ V; $\eta_\text{R1} = 0.92$; $\cos\varphi_\text{R1} = 0.92$; $I_\text{NL1} = 71$ A; $\Delta P_\text{NL1} = 4.4$ kW.

Solution

We calculate:

$$Q_\text{NL1} = \sqrt{3} \cdot 380 \cdot 71 \cdot 10^{-3} = 46.6 \text{ kvar};$$

$$Q_\text{R1} = \frac{125}{0.92} \cdot 0.426 = 58 \text{ kvar};$$

$$k_\text{R1} = \frac{P}{P_\text{R1}} = \frac{70}{125} = 0.56;$$

$$\gamma_1 = \frac{3.52}{(100-92)-3.52} = 0.786;$$

$$\Delta P_\text{RL1} = 125 \cdot \frac{1-0.92}{0.92} \cdot \frac{1}{1+0.786} = 6.09 \text{ kW};$$

$$\Delta P'_{\Sigma 1} = \left[46.6 \cdot (1-0.56)^2 + 0.56^2 \cdot 58\right] \cdot 0.1 + 4.4 + 0.56^2 \cdot 6.09 = 9 \text{ kW}.$$

Motor A82-2 parameters are as follows:

$U_\text{R2} = 380$ B; $\eta_\text{R2} = 0.93$; $\cos\varphi_\text{R2} = 0.92$; $I_\text{NL2} = 40.6$ A; $\Delta P_\text{NL2} = 2.2$ kW. We calculate:

$$Q_{\mathrm{NL2}} = \sqrt{3} \cdot 380 \cdot 40.6 \cdot 10^{-3} = 26.7 \text{ kvar};$$

$$Q_{\mathrm{R2}} = \frac{75}{0.93} \cdot 0.426 = 34.3 \text{ kvar};$$

$$k_{\mathrm{R2}} = \frac{P}{P_{\mathrm{R2}}} = \frac{70}{75} = 0.93;$$

$$\gamma_2 = \frac{2{,}93}{(100-93)-2.93} = 0.72;$$

$$\Delta P_{\mathrm{RL2}} = 75 \cdot \frac{1-0.93}{0.93} \cdot \frac{1}{1+0.72} = 3.28 \text{ kW};$$

$$\Delta P'_{\Sigma 2} = \left[26.7 \cdot (1-0.93)^2 + 0.93^2 \cdot 34.3 \right] \cdot 0.1 + 2.2 + 0.93^2 \cdot 3.28 = 8 \text{ kW}.$$

As a result of not loaded motor substitute with motor of a lower power in case its operation during period $T = 5000$ h and the EE tariff $T^{(1)} = 3$ Rub./kW $\cdot$ h we get the following saving

$$\Delta E = (\Delta P'_{\mathrm{total1}} - \Delta P'_{\mathrm{total2}}) \cdot T \cdot T^{(1)} = (9-8) \cdot 5000 \cdot 3 = 15\,000 \text{ Rub.}$$

Replacement of unloaded EMs, even if it is substantiated by calculations, can be done only after a thorough check of possibility to load them fully by correct utilization of working machinery, driven by them. This activity is feasible in cases when a motor is selected incorrectly and has a higher power in comparison to the working machine. Installation of a motor of a lower power kind legitimates the insufficient utilization of a working machine, and in future it can become an obstacle for its full utilization with respective process technology upgrading.

6.5. Power factor and its technical and economic significance

According to [12], the requirements to calculation of active and reactive power consumption ratio at contract signing for electrical energy transmission (electricity supply agreements) in respect of EE consumers, whose connected capacity of power receivers is 150 kW (except for residential consumers and those equivalent to them according to normative and legislative acts in area of state regulation of tariffs for group (categories) consumers (buyers), including apartment buildings, horticultural, garden and other non-commercial associations of citizens).

Values of a ratio of active and reactive powers consumption ($\mathrm{tg}\varphi$) are calculated as limit values of reactive power factor, consumed in peak load during 24-hour period, compliance to which is provided by EE (power) buyers – consumers of EE transmission services by following the electricity (power) consumption regimes or utilization of reactive power compensation devices. Here the factor value of reactive power, generated in hours of low daily load in the electrical system, is set equal to zero.

In case of consumer participation under the agreement with grid organization in reactive power regulation in hours of maximum and/or minimum loads of electric grid in electricity supply agreement are calculated as well as range of values of reactive power factors, specified separately for grid maximum and minimum load hours and applied during consumer participation in reactive power regulation.

6.5.1. General requirements to reactive power factor calculation

Amount of hours, included in periods of maximum and minimum loads and specified by respective agreements, should be equal to 24 hours. Except as otherwise provided in the agreement, the maximum load hours are considered from 7 h 00 min till 23 h 00 min, and minimum load hours – from 23 h 00 min till 7 h 00 min [12].

Reactive power factor values are calculated separately for every connection point in the grid in respect of all consumers, except for consumers, receiving electricity in several lines of voltage 6–20 kV from one substation or power station, for which these values are calculated as cumulative values.

For consumers, connected to 220 kV grids and higher, as well as to 110 kV (154 kV) grids, in cases when they provide a significant effect on power modes of system operation (energy districts and nodes), limit values of reactive power factor, consumed in hours of maximum daily loads, and also range of reactive power factor values, applied in the period of consumer participation in reactive power regulation, are calculated on the basis of grid operational modes in the specified periods, and done for both routine and maintenance diagrams.

Limit values of reactive power, consumed in hours of the maximum daily loads in the electric power system, for consumers, connected to the 220 kV grids, are calculated according to Table 6.3.

Table 6.3

Limit values of reactive power factor

Location of consumer connection point in the grid	$\mathrm{tg}\varphi$
Voltage of 110 kV (154 kV)	0.5
Voltage of 35 kV (60 kV)	0.4
Voltage of 6–20 kV	0.4
Voltage of 0.4 kV	0.35

Power factor $\cos\varphi$ is called a ratio of consumer's active power to total power

$$\cos\varphi = \frac{P}{S}.$$

Every consumer of electricity is characterized by the rated current and voltage and total rated power, equal to the product of rated voltage and rated current. For a three-phase system of alternating current

$$S_{\mathrm{R}} = \sqrt{3} \cdot U_{\mathrm{R}} \cdot I_{\mathrm{R}}.$$

The best utilization of generator capacity will be during its operation with the rated values of current and voltage, and at $\cos\varphi \approx 1$. In this case generator's active power will be equal to total power

$$P_{\mathrm{R}} = \sqrt{3} \cdot U_{\mathrm{R}} \cdot I_{\mathrm{R}} \cdot \cos\varphi = \sqrt{3} \cdot U_{\mathrm{R}} \cdot I_{\mathrm{R}} = S_{\mathrm{R}}.$$

For the rated values of current, voltage and varying $\cos\varphi$, the generator capacity will be directly proportional to the latter, and $\cos\varphi$ decrease will result in the partial utilization of power.

On the other side, if an electricity user operates with constant active power and fixed voltage, however, when $\cos\varphi$ are different, then its current varies in inverse proportion to $\cos\varphi$. Thus, when $\cos\varphi$ decreases, current of an electricity user and the supply system increase, resulting in additional electrical energy losses in electric transmission lines

$$I = \frac{P}{\sqrt{3} \cdot U_{\mathrm{R}} \cdot \cos\varphi}.$$

The following standard values of power factor are currently adopted:

0.85 – when power is supplied to consumers by the electric power plant generators at generator voltage;

0.93 – when power is supplied to consumers by regional grids of 110, 220 kV voltage and by 35 kV system, supplied by electric power stations in two power transformation stages;

0.95 – when power is supplied to consumers by 35 kV voltage system, supplied by regional grids in three transformation stages.

6.5.2. Causes and effects of a low power factor

The main consumers of electricity at industrial facilities are induction motors (IM), which consume reactive power along with the active (useful), used for generation of rotating magnetic fields.

Operational modes of IM and values of consumed power often provide a significant effect on general reactive power of the plant and power system.

Values of $\cos\varphi$ and η characterize the IM technical level, load characteristics and operational modes of driven IM in a number of domestic industries are such that proportion of consumed reactive power often exceeds the active power proportion on their shaft.

Reasons for higher consumption of reactive power by induction motors, resulting in decrease of $\cos\varphi$, are given in Fig. 6.6. Some reasons are objective factors, depending on the IM design. Other reasons depend completely on maintenance and service personnel of facilities, and their elimination is conditioned by compliance with effective Rules for consumer electrical installations operation.

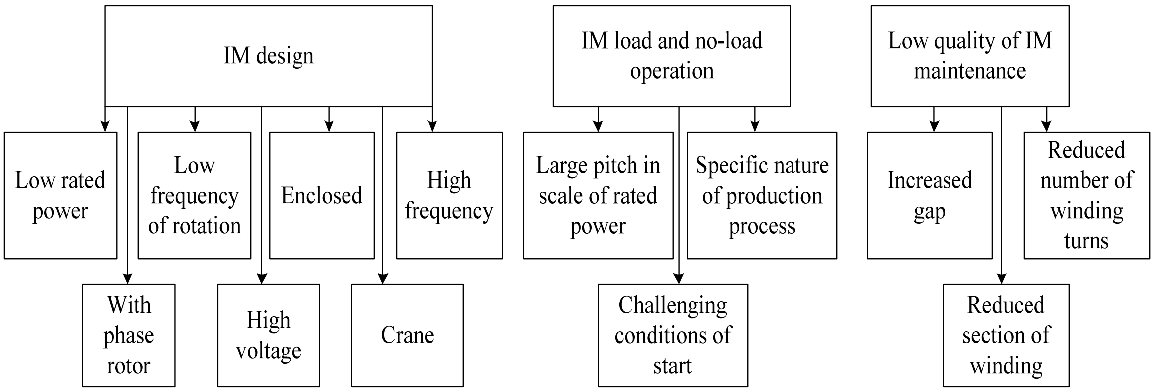


Fig. 6.6. Reasons for increased consumption of reactive power by induction motors

Consumed reactive power of induction motors can be divided into magnetizing, independent of load and used for generation of magnetic flux, and reactive power, proportional to square load and modified by magnetic dispersion field. Total reactive power, consumed by induction motor, can be calculated, according to the formula

$$Q_{\mathrm{m}} = Q_{\mathrm{SC}} + k_{\mathrm{L}}^2 \cdot \Delta Q_{\mathrm{R}} \text{ kvar},$$

$$Q_{\mathrm{NL}} = \sqrt{3} \cdot I_{\mathrm{NL}} \cdot U_{\mathrm{R}} \cdot 10^{-3} \text{ kvar},$$

where Q_{NL} – magnetizing power of no-load run; I_{NL} – no-load current, A; U_{R} – rated voltage, V; k_{L} – load factor; $\Delta Q_{\mathrm{R}} = Q_{\mathrm{R}} - Q_{\mathrm{NL}}$ – incremental reactive power at rated load, kvar; $Q_{\mathrm{R}} = P_{\mathrm{R}} \cdot \mathrm{tg}\varphi / \eta$ – reactive power of motor at rated load, kvar.

Total reactive power, consumed by transformer, is calculated according to the formula

$$Q_{\mathrm{T}} = Q_{\mathrm{NL}} + k_{\mathrm{L}}^2 \cdot \Delta Q_{\mathrm{R}},$$

where Q_{NL} – magnetizing power of transformer,

$$Q_{\mathrm{NL}} = \sqrt{3} \cdot U_{\mathrm{R}} \cdot I_{\mathrm{R}} (I_{\mathrm{NL}}, \%) \cdot 10^{-5} \text{ kvar},$$

where I_{NL}, % – no-load current of transformer in percentage from the rated; ΔQ_{R} – incremental reactive power of transformer,

$$\Delta Q_{\text{R}} = U_{\text{R}}(U_{\text{SC}},\ \%) \cdot 10^{-2}.$$

The main part of reactive power in IM and transformers is power Q_{SC}, generating the main magnetic flux, equal to no-load power. Principal reasons for a relatively high consumption of reactive power, and thus a decrease of power factor are the following:

1. IM and transformers operation at incomplete load. Here the active power of electric machine decreases while reactive power remains almost the same that results in $\cos\varphi$ decrease.
2. Imperfection of IM design and low-quality maintenance (a large gap between stator and rotor). Magnetic resistance of air gap is about 80 % from total resistance.
3. Voltage increase. With increase of voltage of IM and transformers magnetic flux increases consequently, as well as consumed reactive power, however, the power factor decreases.
4. Reduction of electric machinery speed. Low-speed induction motors have a more complex magnetic circuit and consume more reactive power, and, consequently, have a lower $\cos\varphi$ than high-speed ones. A low $\cos\varphi$ of industrial facility results in increase of generators and transformers power and size.

Example 6.6. Induction motors of 12 000 kW total power are installed at an industrial facility. Calculate the required transformers power for cases of operation at $\cos\varphi_1 = 0.9$ and $\cos\varphi_2 = 0.75$.

Solution

We calculate the total transformer power for both cases

$$S_1 = \frac{P}{\cos\varphi_1} = \frac{12\,000}{0.9} = 13\,333 \text{ kV} \cdot \text{A};$$

$$S_2 = \frac{P}{\cos\varphi_2} = \frac{12\,000}{0.75} = 16\,000 \text{ kV} \cdot \text{A}.$$

The difference of 2667 kVA should be covered at the expense of more powerful transformers installation, while useful power remains constant (12 000 kW).

Power losses for wire heating are proportional to the squared current

$$\Delta P = \sqrt{3} \cdot I^2 \cdot R,$$

where I – total current, flowing in wire, A; R – line resistance, Ohm.

Current value I is inversely proportional to $\cos\varphi$.

Example 6.7. Calculate the electricity losses in the line with resistance R = 4 Ohm, according to the data from Example 6.5 for 35 kV voltage and losses during operation with a lower $\cos\varphi$.

Solution

We calculate the total current for both cases:

$$I_1 = \frac{P}{\sqrt{3} \cdot U \cdot \cos\varphi_1} = \frac{12\,000}{\sqrt{3} \cdot 35 \cdot 0{,}9} = 221 \text{ A};$$

$$I_2 = \frac{P}{\sqrt{3} \cdot U \cdot \cos\varphi_2} = \frac{12\,000}{\sqrt{3} \cdot 35 \cdot 0{,}75} = 266 \text{ A}.$$

We calculate power losses for the first and the second cases:

$$\Delta P_1 = \sqrt{3} \cdot I_1^2 \cdot R = \sqrt{3} \cdot 221^2 \cdot 4 = 338 \text{ kW};$$

$$\Delta P_2 = \sqrt{3} \cdot I_2^2 \cdot R = \sqrt{3} \cdot 266^2 \cdot 4 = 490 \text{ kW}.$$

Difference of power losses will be

$$\Delta P = \Delta P_2 - \Delta P_1 = 490 - 338 = 152 \text{ kW}$$

Accordingly the annual difference of power losses will be

$$\Delta W = (\Delta P_2 - \Delta P_1) \cdot T = (490 - 338) \cdot 8760 = 1\ 331\ 520 \text{ kW·h},$$

where T – hours of annual line operation, h.

Annual damage due to low $\cos\varphi$ operation (with electricity cost T = 3 Rub./kW·h, according to 2013 tariff list).

$$\Delta D = \Delta W \cdot T = 1\ 331\ 520 \cdot 3 = 4 \text{ mln Rub.}$$

Example 6.8. Calculate a transformer active power of S = 360 kV·A at $\cos\varphi_1 = 0.8$ and $\cos\varphi_2 = 0.6$.

Solution

We calculate active power for each case:

$$P_1 = S \cdot \cos\varphi_1 = 360 \cdot 0.8 = 288 \text{ kW};$$

$$P_2 = S \cdot \cos\varphi_2 = 360 \cdot 0.6 = 216 \text{ kW}.$$

Consequently, the lower $\cos\varphi$, the worse the equipment capacity is utilized. Thus, every enterprise should be interested in increasing the power factor of both specific consumers and the entire industrial facility.

6.5.3. Ways of power factor increase

Conventionally, measures on reactive power factor increasing can be divided into natural and artificial.

6.5.3.1. Natural ways of power factor increase

Increase of $\cos\varphi$ in *a natural* way provides for a high-quality operation of electrical equipment, which can be achieved by the following activities:

1. Increase of electric motors load due to rational changes to the process technology. Motors, operating with a constant underload, should be replaced with those of lower power (if motor load is less than 40 %, then their replacement is valid, if load varies within range of 40–70 %, necessity of their replacement should be validated by technical and economic reasons).

If active power losses growth in IM will exceed their reduction in the grid, then such replacement of underloaded IM is unfeasible, and vice versa.

To define the feasibility of such replacement, the following two expressions can be used [32]:

$$\Delta P_{\mathrm{N}} = \Delta U \cdot \left(\frac{1}{\cos\varphi_1} - \frac{\cos\varphi_1}{\cos\varphi_2}\right) + 2 \cdot \Delta U' \cdot \sin\varphi_{\mathrm{T}} \cdot (\mathrm{tg}\varphi_1 - \mathrm{tg}\varphi_2), \%,$$

$$\Delta P_{\mathrm{m}} = (\eta_1 - \eta_2) \cdot 100, \%,$$

where ΔP_{N} – active power losses saved in the network by replacing the current IM with a lower power motor; ΔP_{m} – increase (decrease) of active power losses in IM; ΔU and $\Delta U'$ – voltage losses in IM circuit in the feeding mains, %; $\cos\varphi_1$, $\cos\varphi_2$ ($\mathrm{tg}\varphi_1$ and $\mathrm{tg}\varphi_2$) – power factors (reactive power factors) prior to and after IM replacement, accordingly; $\sin\varphi_{\mathrm{T}}$ – angle sine of φ of supply transformer.

For a positive decision on replacement of underloaded IM it is necessary to compare values ΔP_{n} and ΔP_{m}. Besides, with voltage losses increase from such replacement, power losses cuts increase in the grid. Therefore, it is feasible to detect segments with considerable voltage losses in the grids of facilities, i. e. the longest segments, and perform the replacement of underloaded IM with electric motors of lower power.

2. Limitation of motors no-load operation time.

3. Increase of motors maintenance quality.

4. Improvement of transformers operation by transferring their loads to other transformers or switching them off during load decrease. If a transformer continuously operates underloaded, and an average load is less than 30 %, it should be replaced with a transformer of lower power.

5. Replacement of induction wound-rotor motors, when process technology allows, with squirrel-cage induction motors, having a higher $\cos\varphi$.

6. Where it is possible, replacement of IM with synchronous motors, operating with overexcitation. When operating in overexcitation conditions, a synchronous motor (SM) has a negative phase shift (current outruns the voltage) and becomes an active energy generator. Replacement of induction motors with synchronous motors significantly improves a power factor of the facility.

Example 6.9. Average daily power factor for the facility $\cos\varphi_1 = 0.74$. Total power of consumers is 4500 kW. Induction motor of 520 kW, $\cos\varphi_\text{m} = 0.85$ is replaced with a synchronous motor of the same power, working with a leading $\cos\varphi_\text{c} = 0.8$. Find a new average daily power factor for $\cos\varphi_2$ of the facility.

Solution

We calculate the consumed reactive power prior to replacement of induction motor with a synchronous motor

$$Q_1 = P \cdot \text{tg}\varphi_1 = 4500 \cdot 0.9 = 4050 \text{ kvar.}$$

We calculate reactive power of the induction motor

$$Q_\text{m} = P_\text{m} \cdot \text{tg}\varphi_\text{m} = 520 \cdot 0.62 = 323 \text{ kvar.}$$

We calculate reactive power of the synchronous motor

$$Q_\text{N} = P_\text{m} \cdot \text{tg}\varphi_\text{N} = 520 \cdot 0.75 = -390 \text{ kvar,}$$

the minus sign indicates that phase shift is negative.

We calculate reactive power after equipment replacement

$$Q_2 = Q_1 - Q_\text{m} + Q_\text{N} = 4050 - 323 - 390 = 3337 \text{ kvar.}$$

Reactive power factor after replacement of IM with SM

$$\text{tg}\varphi_2 = \frac{Q_2}{P} = \frac{3337}{4500} = 0.74 \to \cos\varphi_2 = 0.805.$$

6.5.3.2. Artificial ways of power factor increase

Artificial methods of $\cos\varphi$ increase are done by installing special electrical equipment in the enterprises that compensate the reactive power.

Regulated compensation of reactive power is provided by means of shunt devices, connected to the substation busbars or the load in parallel. These devices can be divided in two conceptually different groups. The first group of reactive power sources (RPS) includes rotating synchronous machines: synchronous generators of electric power plants, synchronous compensators, and synchronous motors. These devices allow a smooth control of the reactive power both during generation and consumption modes. The second group includes static RPS or static VAR compensators. They include capacitor banks; reactors, not limiting the current; converter-based devices (rectifiers, inverters) with a forced commutation of thyristors or their combinations.

Capacitor banks

Capacitor banks (CB) are simple and reliable static devices. CBs are made of separate capacitors, which are manufactured for different capacities and rated voltages.

A wide application of capacitor banks for reactive power compensation (RPC) can be explained by their considerable advantages in comparison with other existing industrial ways of RPC, namely:

- ✓ A higher efficiency factor, i. e. small specific losses of active power, not exceeding 0.005 kW per 1 kvar of compensator power. In synchronous capacitors this value reaches 10 % of the capacitor rated power, and in synchronous motors – 7 %;
- ✓ Absence of rotating parts;
- ✓ Simple assembly and operation;
- ✓ Relatively low capital investments;
- ✓ A wide capability to select any required capacitor bank power;
- ✓ Capability to be installed in any point of grid;
- ✓ Noise absence during operation, etc.

Rational RPC in industrial networks includes a vast complex of measures: calculation and selection of compensating devices, optimal distribution of CD in enterprise networks, automatic control of CD operational modes.

For a more effective use of compensating devices in operation, some of them should be equipped with control devices for generated power in compliance with objectives of network voltage regulation and its reactive load variation. Total power of unregulated capacitor banks should not usually exceed the value of the lowest reactive load. Thus, total power of CD Q_{CD} should include powers of unregulated $Q_{\mathrm{CD_U}}$ and regulated $Q_{\mathrm{CD_R}}$ parts. Unregulated power of capacitor banks is calculated under condition of rational compensation of RP in minimum load hours in distribution networks of enterprise and the system.

Consumers of RP at the enterprise need additional power from the network

$$Q_{\mathrm{N}} = Q - Q_{\mathrm{CD}} = Q - (Q_{\mathrm{CD_{des}}} + Q_{\mathrm{CD_R}}),$$

where $Q_{\mathrm{N}} = Q_2 = P \cdot \mathrm{tg}\varphi_2$ – RP required to the enterprise, conforming with the compensated $\mathrm{tg}\varphi_2$, kvar; $Q = P \cdot \mathrm{tg}\varphi_1$ – reactive load of receivers at the existing $\mathrm{tg}\varphi_1$; $Q_{\mathrm{CD_R}} = P_{\min} \cdot \mathrm{tg}\varphi_2$ – RP required to the enterprise in minimum load hours, conforming with value $\mathrm{tg}\varphi_2$.

Regulated power of CP will be equal, kvar:

$$Q_{\mathrm{CD_{des}}} = P \cdot [\mathrm{tg}\varphi_1 - \mathrm{tg}\varphi_2 \cdot (1+\alpha)],$$

$$Q_{\mathrm{CD_{des}}} = \frac{W}{T} \cdot [\mathrm{tg}\varphi_1 - \mathrm{tg}\varphi_2 \cdot (1+\alpha)],$$

where α – a factor, considering active load value of enterprise in minimum load hours ($0 < \alpha < 1$); W – active electrical energy consumption during a settlement period *T*.

In such way, an enterprise is required to have constantly switched on unregulated RP compensating device in minimum load hours, which power should conform with the energy system assignment, as well as the expression:

$$Q_{\mathrm{CD_R}} = \frac{\alpha \cdot W}{T} \cdot \mathrm{tg}\varphi_2 .$$

Power of CB regulated part is calculated according to RP schedule at the enterprise, based on the system assignment, providing for impermissibility of overcompensation and considerable undercompensation of reactive loads. For this purpose the above formulae introduce the factor β, characterizing a degree of RP compensation by compensating device, kvar:

$$Q_{\mathrm{CD_{des}}} = \beta \cdot \frac{W}{T} \cdot [\mathrm{tg}\varphi_1 - \mathrm{tg}\varphi_2 \cdot (1+\alpha)] .$$

Value of β factor is limited by boundaries $0 < \beta \le 1$. Value $\beta = 1$ corresponds to complete RP compensation.

Capacitor is a device, which consists of two conductors, separated by a dielectric. A capacitor, if voltage is applied to it, can accumulate an electric charge (to charge) and give it away (to discharge). In the gap between conductors, which can have any shape, an electric field is excited during capacitor charging. Capacitor charge is bigger, the bigger its capacitance and voltage applied to its conductors. Capacitance, in its turn, is bigger, the bigger the internal surface of capacitor conductors, and the less distance between these conductors.

Gap between conductors is filled with the dielectric, a material, possessing high insulating properties or, we can say, a very low electrical conductance. Such materials include, for example, air, a capacitor paper, ceramics, and synthetic film. Dielectric, applied in capacitors, should have a high electric strength, i. e. to maintain its insulating properties at high voltage and small thickness (10–15 μm). Quality of capacitors dielectric is higher, the higher its dielectric permittivity, i. e. ability to accumulate an electric charge. For example, a relative dielectric permittivity of capacitor paper, impregnated with oil, is 3.54, and of a polystyrene film – 2.5–2.7.

A quantity and capacitance of capacitors is calculated, depending on value of the reactive power, required for compensation. Power of a single-phase capacitor is calculated according to the formula

$$Q_{\mathrm{C}} = \omega \cdot U^2 \cdot C \cdot 10^{-3} \text{ kvar},$$

where $\omega = 2\pi f$ – an angular frequency, Hz; f – a current frequency, Hz; U – a phase-to-phase voltage, kV; C – capacitance, uF.

Reactive power of capacitor bank:

1. For Y-connection (wye)

$$Q_c = \omega \cdot U^2 \cdot C_f \cdot 10^{-3} \text{ kvar},$$

where C_f – one phase capacitance, uF;

2. For D-connection (delta)

$$Q_c = 3 \cdot \omega \cdot U^2 \cdot C_f \cdot 10^{-3} \text{ kvar}.$$

Capacitance of one phase of a capacitor bank:

1. For Y-connection (wye)

$$C_f = \frac{Q_c \cdot 10^3}{\omega \cdot U^2} \text{ uF}.$$

2. For D-connection (delta)

$$C_f = \frac{Q_c \cdot 10^3}{3 \cdot \omega \cdot U^2} \text{ uF}.$$

It can be seen from the expressions that capacitance is inversely proportional to the voltage value. Therefore, application of capacitors on a high-voltage side reduces their quantity considerably.

When a bank is D-connected, it requires 3 times less capacitors than for Y-connection.

After finding a total bank power, a type of capacitor is selected and their connection in the bank is specified. It should be considered that only one type of capacitors is applied in the bank. A number of capacitors is decided on the basis of the following expressions:

1) for series connection $C_{eq} = C/n$;
2) for parallel connection $C_{eq} = C \cdot n$,

where C_{eq} – total capacitance of capacitor banks; C – capacitance of one bank; n – number of capacitor banks.

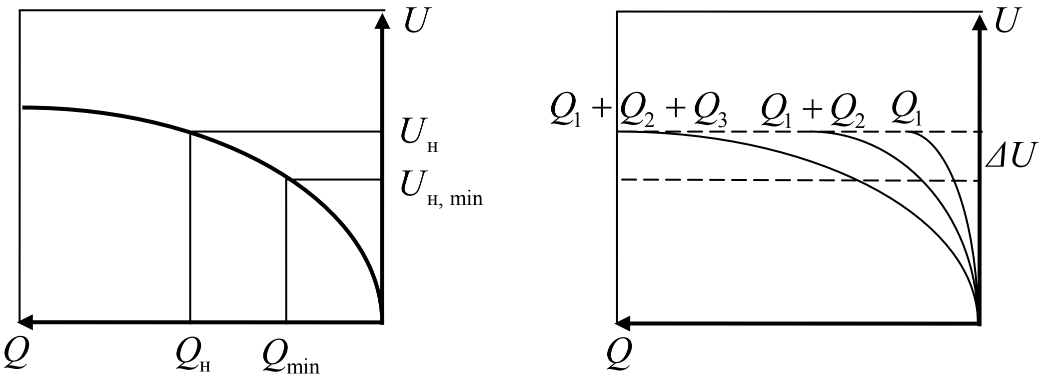
Capacitor, as any other element of energy system, is described by active power losses, which result in its heating. These losses grow more, the higher applied voltage, its frequency and capacitance. Capacitor losses depend on dielectric properties, found using the dielectric losses tangent (tgδ) and describing specific losses (W/kvar) in the capacitor. Depending on the capacitor type and purpose, losses can vary from 0.5 to 4 W/kvar.

So-called cosine capacitors, designed for operation at 50 Hz voltage frequency, are applied for reactive power compensation in the electric power industry. Their power varies from 10 to 100 kvar.

By its design, a capacitor is a metal (steel or aluminum) enclosure, in which sections (packages), coiled by several layers of aluminum foil, interleaved with capacitor paper or synthetic film of 10–15 μm thickness (0.01–0.015 mm), are placed. Connected sections have leads, located outside the enclosure in its upper part. Three-phase capacitors have three porcelain leads, single-phase capacitors have one.

A scale of capacitor rated voltages varies from 230 V to 10.5 kV that allows making installations for 380 V voltage grids and over. Capacitors have a good current overload capacity (up to 30 % from the rated) and for voltage (up to 10 % from the rated). A group of capacitors, connected in parallel or in series, or in parallel-series connection, is called a capacitor bank.

A capacitor bank, equipped with switchgear, protection and control equipment, forms a capacitor plant (CP).



a *b*

Fig. 6.7. Static parameters of CP:
a – consisting of one section; b – consisting of three sections

Therefore, unregulated CBs have a negative regulating effect that in comparison to synchronous capacitors is their disadvantage. It means that CB power reduces along with the decrease of applied voltage, when it should be increased, according to mode conditions.

Regulating effect of CP for reactive power is shown on Fig. 6.7, *a*, and CP, consisting of several sections on Fig. 6.7, *b*. As can be seen on Fig. 6.7, *a*, when voltage decreases from U_{rated} to $U_{\min}$, reactive power decreases in proportion to the squared voltage from Q_{rated} to $Q_{\min}$.

Solution for this shortcoming is found in making CB of several sections, each of them, controlled by voltage and/or power regulator, is connected to the system through its own switch, thus, increasing a general capacitance of a bank. It allows increasing a total CB power during voltage decrease. Thus, when voltage decreases, CP power increases gradually in steps Q_1, $Q_1 + Q_2$, $Q_1 + Q_2 + Q_3$, as shown on Fig. 6.7, *b* for CP, consisting of three CB sections.

Step regulation requires a dead band ΔU in the CP voltage regulator. Connection of another section cannot be allowed within this band when voltage decreases. Failure to comply with this condition would result in an unstable CP operation. Width of dead band should be bigger than voltage growth, caused by another CP section connection. Otherwise, CP voltage will reach the voltage set-point for switching this section off immediately after its switch-on. Probability of such effect grows more, the more is the power of a connected section and the less the dead band of CP regulator.

As a rule, a capacitor plant consists of several sections, having a common control system. Low-voltage 380 V CPs are made of three-phase capacitors, connected in parallel. Fuses are applied for such CP protection against short circuits and overload (Fig. 6.8, *b*). High-voltage capacitor plants are made of single-phase capacitors, connected in series-parallel (Fig. 6.8, *a*).

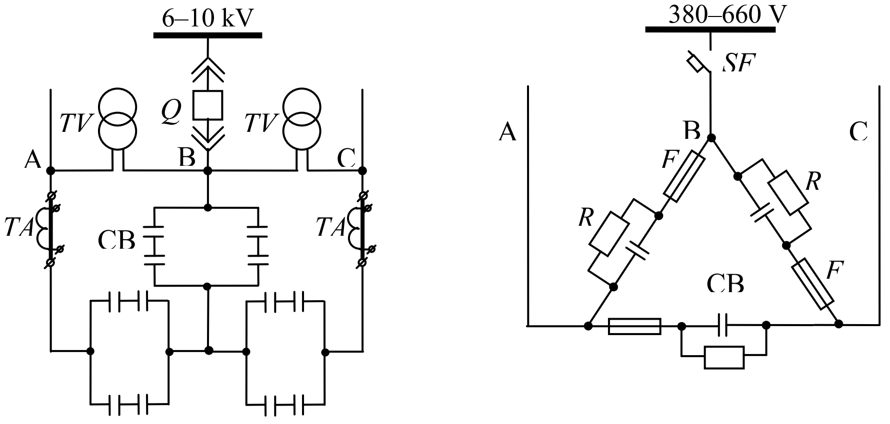
CP startup is accompanied by a current in-rush, and its switching off – by overvoltage that is negative for capacitors and switchgear service life. Therefore, it is not recommended for a CP to be switched on and off more than 2–4 times during 24 hours. To limit the current in-rush, prior to switching capacitors should be discharged by means of discharge resistances *R* or voltage transformers *TV* (Fig. 6.8).

These devices, usually connected to capacitors and resistors, can be placed inside the capacitor.

A value of discharge resistance is calculated according to the expression

$$R \le 15 \cdot 10^6 \cdot \frac{U_\text{f}}{Q_\text{c}},$$

where U_f – phase-to-phase voltage, kV; Q_c – capacitor bank power, kvar.



a *b*

Fig. 6.8. Circuit diagram of a CP three-phase section:
a – for 6–10 kV system; b – for 380–660 V system

Special discharge resistances are not required for direct connection of a bank to a transformer or a motor.

Example 6.10. Total power of industrial substation busbars is 5000 kV·A. Select a compensating device for power factor increase based on from $\cos\varphi_1 = 0.75$ to $\cos\varphi_2 = 0.92$ at 6 kV.

We calculate active load of substation busbars

$$P = S \cdot \cos\varphi_1 = 5000 \cdot 0.75 = 3750 \text{ kW}.$$

The required reactive power of static capacitors

$$Q_c = P \cdot (\mathrm{tg}\varphi_1 - \mathrm{tg}\varphi_2) = 3750(0.882 - 0.424) = 1718 \text{ kvar}.$$

We calculate the phase capacitance when capacitors are D-connected

$$C_f = \frac{Q_c \cdot 10^3}{3 \cdot \omega \cdot U^2} = \frac{1718 \cdot 10^3}{3 \cdot 6^2 \cdot 2 \cdot 3.14 \cdot 50} = 50.4 \text{ uF}.$$

We choose KM-6.3-26 capacitors. A number of capacitors for a phase for parallel connection

$$n = \frac{C_f}{C_c} = \frac{50.4}{2.08} \approx 24,$$

where C_c= 2.08 uF – a capacitor bank capacitance. Total number of capacitors in the bank $m = 24 \cdot 3 = 72$.

Reactive power of capacitor $Q_K = m \cdot Q_c = 72 \cdot 26 = 1872$ kvar, where $Q_c = 26$ kvar – reactive power of the bank.

A value of discharge resistance

$$R = 15 \cdot 10^6 \cdot \frac{U_f}{Q_c} = 15 \cdot 10^6 \cdot \frac{6}{1872} = 45.5 \cdot 10^3 \text{ Ohm} = 45.5 \text{ kOhm},$$

where $U_f = U_l = 6$ kV.

Capacitors due to their properties are very sensitive to the voltage THD factor, i. e. to higher harmonics current. The higher the harmonic frequency $n\omega$ in nonsinusoidality curve of the applied voltage, the less capacitor resistance is. As a result of higher harmonics, penetrating the capacitor, power losses ΔP abruptly increase in capacitors, what results in additional heating:

$$\Delta P = \sum_{n=1}^{n} U_{(n)}^2 \cdot n \cdot \omega \cdot C \cdot \mathrm{tg}\delta,$$

where $U_{(n)}$ – harmonic voltage; n – order of harmonics; C – a capacitor capacitance; $\mathrm{tg}\delta$ – a parameter of capacitor dielectric.

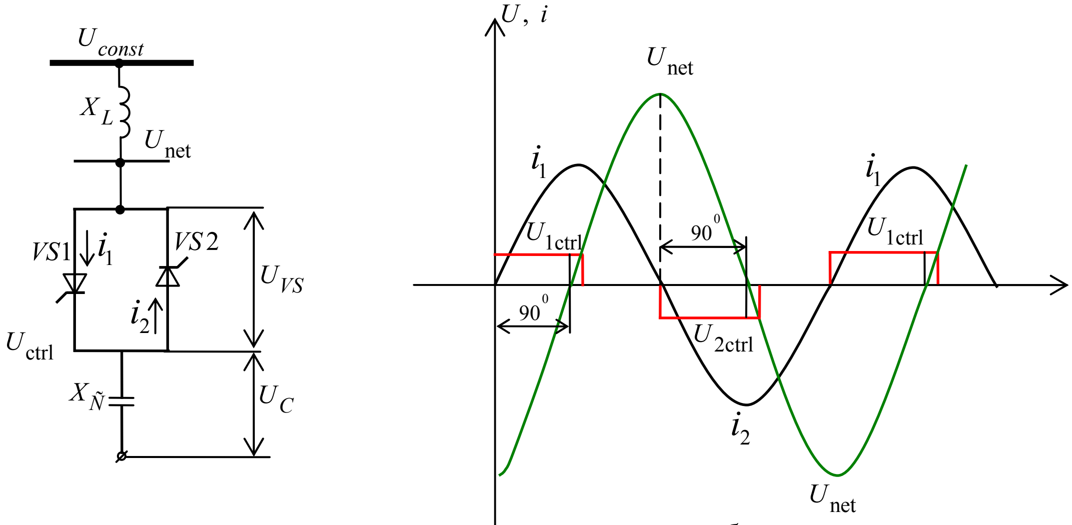
Sensitivity for higher harmonics should always be considered when capacitors are applied in the electric power system. Application of CB involves possibility of resonance phenomena, owing to generation of series and parallel circuits by induction and capacitive elements of the system. Resonance phenomena are accompanied by voltage (voltage resonance) or current (current resonance) amplification at frequencies higher than the rated (50 Hz), conditioned by the existing sources of current higher harmonics in the system. Inductance $X_{L(n)}$ and capacitive $X_{C(n)}$ resistance are equal at the resonance frequency, i. e. $n\omega L = 1/(n\omega C)$, where $X_{L(n)} = n\omega L$ – an input resistance in point of CB connection, which resistance is $X_{C(n)} = 1/(n\omega C)$. Therefore, when selecting a CB power and, consequently, its resistance and also point of CB connection, it is always important to make sure that resonance phenomena are excluded. This requirement also refers to CB, included in FCU.

Static CB-based thyristor compensators

CB application for tasks where a fast control of reactive power is required, frequent switching of CB sections is practically impossible due to regular in-rush and overvoltage, arising during CB switching by common breakers. In order to limit these phenomena, and practically eliminate them, the methods which allow reducing of in-rush current during CB switch-on and overvoltage during switch-off, were suggested in the Moscow Energy Institute in the 1960s. It allowed removing the limitations on CB switching frequency, and providing devices with such properties which make it possible to apply for reactive power compensation and improve the static and dynamic transmission stability of power transmission; voltage oscillations compensation, caused by abruptly varying load.

The stated effect was achieved due to application of thyristor switches instead of common switches, providing CB switching at a certain moment of time.

Thyristor switch consists of thyristors in inverse parallel connection, as shown on Fig. 6.9, *a*. They are applied for capacitor banks and reactors controlling. Due to specific capacitors and reactors switching, their power control by thyristors is conceptually different.



a *б*

Fig. 6.9. Thyristor breaker for CB switching:
a – a single-phase circuit diagram; b – CB current and voltage in a steady-state mode

Thus, to limit the in-rush thyristor should be open at the moment when instantaneous voltage value in the system and in CB are equal (an ideal case) or closed. And a thyristor should be closed for overvoltage limitation during switching off when current passes the zero value.

Following this principle, we can practically exclude the in-rush current and overvoltage by removing a limitation on CB frequency switching. A single-phase CB diagram, switched by thyristors, is given on Fig. 6.9, *a*. As can be seen from Fig. 6.9, *b*, the device operation in a steady-state mode which occurs after thyristor opening in 0.01–0.02 s, is not accompanied neither by current in-rush, nor overvoltage.

A static thyristor-switched capacitor (TSC) in a single-phase configuration, consisting of three CB sections, with each them switched by its own thyristor switch is shown on Fig. 6.10.

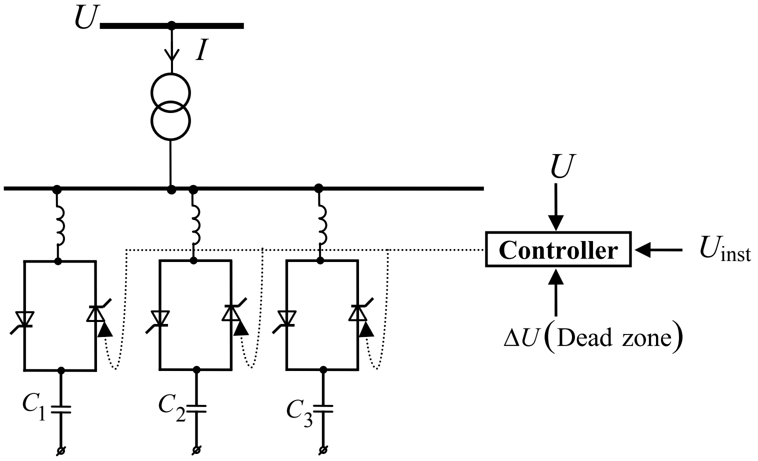


Fig. 6.10. Circuit diagram of TSC, consisting of three CB sections, switched by thyristors

Static specifications of such devices are similar to those given on Fig. 6.7. Requirements to a dead zone controller remain. However, a number of CB section switches is not limited, and they can be done in turns in every 0.02 s, i. e. next but one period of industrial frequency.

6.6. EE saving during pumping units operation

Power of pump electric motor, kW

$$P=\frac{k\cdot Q\cdot H\cdot\gamma}{3600\cdot 102\cdot\eta_{\text{p}}\cdot\eta_{\text{t}}},$$

where Q – pump rate, m^3/h; k – EM power reserve factor (for $Q\le 100$ m^3/h $k=1.2\div 1.3$, for $Q\ge 100$ m^3/h $k=1.1\div 1.5$); H – total head, considering the height of suction head, mWC; η_p – pump efficiency factor, %; η_t – transmission efficiency factor, %; γ – liquid density, kg/m^3.

Specific power consumption for any operating conditions of a pump, kW·h/m^3:

$$\Delta Y = \frac{H \cdot 1000}{102 \cdot 3600 \cdot \eta_p \cdot \eta_m} = 0.00272 \cdot \frac{H}{\eta_p \cdot \eta_m},$$

where H – the effective head, reached by the pump in the given operating conditions, mWC; $\eta_p \cdot \eta_m$ – the pump and electric motor efficiency factor in the given operating conditions.

Centrifugal Pumps

Power losses in the pump are divided into hydraulic, volumetric and mechanical.

Hydraulic losses consist of:

- ✓ Head losses due to liquid friction to walls in the channels of impeller, return channel and volute casing;
- ✓ Losses due to kinetic energy conversion (velocity head) into potential in the return channel and in the volute, and also losses in curves and turns, in transition from one stage to the other, etc.

Power of hydraulic losses is proportional to the pumping cube, kW:

$$P_{\text{loss}} = \frac{\sum Q^3 \cdot \gamma}{102}.$$

Volumetric losses (leakage losses) are found by return leakage through clearance between impeller and sealing rings.

Mechanical losses consist of impeller friction losses, losses of impeller seal friction, thrust and plain bearings.

Total efficiency factor of the pump is based on these losses and depends both on the pump condition and operation mode. Usually an efficiency factor of centrifugal pumps is the following:

- ✓ about 0.4–0.7 for low head pumps;
- ✓ about 0.5–0.5 for medium head pumps;
- ✓ about 0.6–0.8 for high head pumps;
- ✓ pumps of the latest configuration with an efficiency factor of 0.9.

Piston Pumps

Value of the piston pump efficiency factor varies from 0.6 to 0.9, depending on the size, type, pump condition and the type of transmission.

Electricity consumption reduction for pumping units is achieved by the following activities:

- ✓ increase of pumps efficiency factor;
- ✓ improvement of pumps load and upgrading of their operation control;
- ✓ reduction of pipeline resistance;
- ✓ reduction of consumption and water losses.

Increase of pump efficiency factor

1. Replacement of outdated low efficient pumps with highly efficient pumps. Calculation of electricity savings in this case is done according to the following formula

$$\Delta W = 0.00272 \cdot \frac{H}{\eta_{\text{m}}} \cdot \frac{1}{\eta_{\text{n}}'' - \eta_{\text{n}}'} \cdot Q \cdot T, \tag{6.1}$$

where H – the head, mWC; Q – an actual pump head, m^3/h; T – hours of pump operation per year, h; η_{m} – efficiency factor of electric motor; η_{n}'', η_{n}' – efficiency factors of new and replaced pumps.

2. Increase of pump efficiency factor up to the nameplate values. High-quality maintenance of pumps, a thorough balancing of impellers, fresh seals keep the pump efficiency factor on the nameplate level and provide the minimum specific power consumption for water supply.

3. Improvement of pumps load. The least specific power consumption for water delivery is observed at the maximum pump rate. The maximum pump rate depends on water supply system. Comparison of the pump's nameplate data with the resistance of water supply pipelines is required for the maximum rate provision. In case of sharp divergences, a pump replacement is required. Economic effect of such replacement can be found, using the formula 6.1.

4. Pump operation control. In practice there is no invariable (constant) pressure water supply. Pumps operate in a varying duty mode, depending on water consumption. Correct changes to pump operation mode, i. e. rational control, provide considerable electricity savings.

Pump operation control is done by the following:

- ✓ delivery or intake gate valve;
- ✓ changing a number of operating pumps;
- ✓ changing an EM rotation speed.

Analysis of these control methods shows the following:

✓ When controlling by the gate valve and water consumption reduction, the pump efficiency factor decreases, and head values grow. Consequently, when water consumption reduces, a specific electricity consumption rapidly grows;

- ✓ When controlling by changing the operated pumps quantity, the efficiency factor of motor and pump remain unchanged. The pressure head decreases because of consumption and losses reduction; specific electricity consumption also decreases;
- ✓ When controlling by changing a pump rotation speed, pump and EM efficiency factor decrease during consumption reduction, pressure head also decreases. Specific EP consumption reduces insignificantly.

The most efficient method of control is changing the number of operated pumps, then – control over pump rotation speed. The most inefficient control is by the gate valve.

It is rational to control pump operation by changing the rotation speed of electric motor in the systems with abruptly variable flow conversion.

It would be more rational to control the systems with steady flow by changing the operated pumps number.

Use of control valves is only allowed for small pumps, and also in cases when control is performed during a short period of time in a year.

Calculation of electricity economy from the rational methods of control is done, using the formula 6.1.

5. Reduction of pipeline resistance. Reasons for high specific power consumptions to supply water are wrong configuration of the pipeline when the flow goes through abrupt turns; malfunction of gate valves; poor condition and clogged suction devices, etc. Elimination of these reasons results in reduction of pipeline resistance decrease and power consumption reduction.

Loss of pressure head in the straight pipe segment of the pipeline

$$\Delta H = \frac{0.083 \cdot \lambda \cdot L \cdot Q^2}{d^5},$$

for local resistances

$$\Delta H = \frac{0.083 \cdot f \cdot Q^2}{d^4},$$

where λ – the pipeline wall friction factor for water is recommended to be taken 0.02–0.03; L – length of the pipeline segment, m; Q – actual water consumption, m^3/s; d – pipeline diameter, m; f – local resistance factor, equal to 0.5 for valves, for a 90 degree sweep elbow – 0.3, for a back-pressure valve – 5.0.

A head loss is calculated using these formulae, and new specific EP consumption – by the formula 6.1. Consequently, as a result of redundant fittings and unnecessary bends elimination in the pipeline or their resistance decrease by smoothing the acute angles, etc., reduction of specific power consumption for water supply is successful.

6. Elimination of leakage and wasteful water consumption. Direct power losses are caused by leakage through pipeline and fitting flange joints. Amount of these losses is calculated in the following ways:

✓ When there are flow meters available in the beginning and end of the distribution system, losses are found as difference of measured water consumption during the report period in the beginning and end of the segment. For a multibranch network, losses in certain segments are summed up.

✓ For a multibranch network with a large internal volume, water losses can be found by the accurate flow meter readings, having disconnected all consumers from the system.

Metered water losses are required to multiply by actual specific electric power consumption for water supply of the given pumping station, the obtained amount equals to power losses caused by poor condition of water supply network.

7. Implementation of water recirculation supply. A large amount of industrial water is used for cooling of different processing stations. Water for this purpose can be used many times in a closed-loop circulation cycle. Implementation of water recirculation system can reduce primary water consumption in 2 times and provide the energy economy of 15–20 %.

Calculation of energy efficiency can be done, using the formula 6.1, with account for additional power consumption, required for water feed from intermediate intake chambers for process equipment.

8. Reduction of water consumption due to cooling system improvement. To reduce water consumption, the following measures are recommended:

✓ Arrangement of evaporative cooling system for metallurgical and thermal processing furnaces;

✓ Circulation cooling systems for welding sets and high-frequency units;

✓ Compliance with the specified optimal temperatures for water, cooling different process units. Temperature difference of direct and recirculated water should not be less than 10–150 °C;

✓ Aftercooling system for certain process plants and their parts;

✓ Application of automatic control system for cooling water supply.

All these measures can reduce water supply by pumping units in 2–3 times with the respective decrease of electricity consumption. The economy effect from the stated measures implementation can be found, using the formula 6.1, and the data about yearly water consumption reduction, thous. kW·h/year:

$$W = \Delta Y \cdot (Q_1 - Q_2) \cdot T \cdot 10^{-3},$$

where ΔY – specific electricity consumption for water supply, calculated according to 6.1, kW·h/m^3; Q_1, Q_2 – water consumptions prior to implementation of measures and after their implementation, m^3/h; T – hours of annual pump operation, h.

9. Maintenance of the scheduled temperature water difference between direct and recirculated system water. Strict adherence to the schedule with an even heat consumption for heating by means of a heating system regulation and correct selection of pump and electric motor specifications reduces power consumption for heating water circulation systems in proportion to the cube of temperature differences ratio in delivery and return pipelines after and prior to the system adjustment. For example, when temperature conditions are 95–70 °C instead of 95–80 °C, power consumption reduces in

$$\frac{95-70}{95-80}=\frac{25}{15}=1.65 \text{ times.}$$

6.7. EE saving during ventilation units operation

Power consumption by ventilation units reaches large volumes in some productions. Consumption reduction is possible by means of the following activities implementation:

- ✓ Replacement of old fans with the latest, more efficient;
- ✓ Implementation of efficient methods of fan productivity control;
- ✓ Blocking of fan air curtains using gate opening and closing devices;
- ✓ Ventilation units shutoff during lunch breaks, interval between shifts, etc.;
- ✓ Elimination of operational defects and design deviations;
- ✓ Implementation of ventilation unit automatic control.

Power consumption for fans drive gear is calculated according to the specified motor power, kW·h per year:

$$W=\sum_{1}^{n} k_{\text{u}}\cdot P_{\text{inst}}\cdot\tau,$$

where n – number of ventilation units at the enterprise; P_{inst} – installed power of electric motor (according to the nameplate data), W; τ – fan operation period during the year, h; k_{u} – fans utilization factor. k_{u} for different fan types is given in Table 6.3.

Table 6.3

Fans utilization factor

Item No.	Electric users	k_{u}
1	Fans	0.6–0.8
2	High-pressure fans	0.75
3	Fans and crushers	0.4–0.5
4	Gas blowers	0.5–0.6

1. Replacement of outdated fans with state-of-the-art fans. Replacement of old low-efficiency fans with a new type of fans provides the following electricity savings, kW·h:

$$\Delta W = \frac{h \cdot Q \cdot t \cdot (\eta_2 - \eta_1)}{102 \cdot \eta_1 \cdot \eta_2 \cdot \eta_{\text{em}} \cdot \eta_{\text{N}}},$$

where η_1, η_2 – efficiency factor of the replaced and installed fans; η_{em}, η_{N} – efficiency factor of electric motor and the network, accordingly; t – time of fan operation with the increased efficiency factor.

2. Implementation of efficient fan productivity control methods. Significant reduction of fans power consumption is provided by the following activities:

- ✓ Application of multiple-speed EMs instead of gate valve control in the pressure line of a ventilation unit. EE saving here makes 20–30 %;
- ✓ Air blower control by the gate valves during intake instead control during the pumping provides the EE saving up to 15 %;
- ✓ Exhaust ventilation control by the gate valves in work places instead of control during discharge provides the EE saving up to 10 %;
- ✓ Control of smoke exhaust delivery, using cylindrical channels instead of throttle provides the EE saving up to 25 %.

3. Blocking the air curtain fans with gate opening and closing devices. To reduce power consumption for air curtain fans drive, it is recommended to block the air curtain mechanism with gate opening and closing devices in most cases. When gates open, air curtain switches on automatically, and when gates close it switches off.

In case when work places are near the gates, two-speed EMs should be installed on the air curtains, which automatically switch to a higher speed during gate opening and switch to a lower speed during gate closing. Here the EM power at lower speed operation is 2 times lower than during operation at a higher speed.

Usually air curtain is operated at a lower speed of the fan (60–70 % of total operation hours). If we take a heating season duration as 4000 h/year and EM power as 10 kW, then an electric motor should be operated with a half power of 5 kW during 2400 h. Electric power savings here will be

$$\Delta W = 5 \cdot 1600 = 8000 \text{ kW·h per year.}$$

Switching the ventilation units off during lunch breaks and intervals between shifts often provide power saving up to 20 %.

4. Improvement of fan operation. EE losses in the ventilation unit can be reduced by changing the shaft rpm, angle of blade installation on the impeller, turn of channel blades, etc. Here power savings will be, kW·h:

$$\Delta W = \frac{(Q_1 \cdot h_1 \cdot \eta_2 - Q_2 \cdot h_2 \cdot \eta_1) \cdot t}{102 \cdot \eta_1 \cdot \eta_2 \cdot \eta_{\text{em}} \cdot \eta_{\text{N}} \cdot \eta_{\text{tr}}},$$

where Q_1 and Q_2 – fan performance prior to and after changing its operation mode, which is calculated using the combined characteristics of the fan and ventilation system, m^3/sec; h_1 and h_2 – fan pressure prior to and after operation mode changing; $\eta_{\text{em}} \cdot \eta_{\text{N}} \cdot \eta_{\text{tr}}$ – the efficiency factor of electric motor, electric network and transmission (the stated factors of fan for practical calculations can be neglected during transition into a new operation mode); η_1 и η_2 – the fan efficiency factor prior to and after operation mode changing.

5. Elimination of defects during ventilation units operation. Design deviations are often admitted during installation, assembly and maintenance of ventilation units. These defects result in irrational consumption of power. They include:

✓ Operation of axial fan with inverted impeller, efficiency factor of the fan decreases by 20–40 % and consequently, electricity consumption increases;

✓ Gap increase between impeller and suction tube of centrifugal fans (normal clearance value – not more than 1 % of the impeller diameter). Failure to comply with these conditions sharply decreases the efficiency factor and increases power consumption. For example, when clearance of axial fans increases up to 3 % of the blade length, the efficiency factor decreases by 5–10 %;

✓ Removal of a fairing before entry in the impeller decreases efficiency factor by 10 %;

✓ Short diffuser or its absence of axial fans decreases the efficiency factor by 6 %;

✓ Low-quality manufacture and assembly of taps, T-junctions, elbows, dents, poor plaster of channels, etc., considerably increase the system resistance and, consequently, power consumption;

✓ Leakage in flange joints, in air-ducts, connected to the fans, and other leak-in sources increase the power consumption.

6. Implementation of ventilation unit automatic control.

✓ Blocking device for specific exhaust systems decreases EE consumption by 25–30 %;

✓ Blocking device for air curtain fans with the mechanism of gate opening can provide EE efficiency up to 70 %;

✓ A device for ventilation unit automatic regulation and control, depending on external air temperature, provides energy efficiency of 10–15 %.

6.8. EE saving during electric furnaces operation

6.8.1. Electric resistance furnaces

Total power consumption of resistance furnaces consists of useful consumption for metal (or any other heated material) heating and for covering losses through furnace walls, hearth bottom, furnace cover, etc.:

$$W = a_0 \cdot \tau + a_1 \cdot g + a_2,$$

where a_0 – average hourly electricity consumption for covering total heat losses, kW; τ – duration of heat treatment, h; a_1 – useful consumption of electricity for 1 t of charge, kW·h; g – charge weight, t; a_2 – electricity consumption for tare heating, kW·h.

Useful electric power consumption for articles heating, kW·h:

$$W_1 = c \cdot g \cdot (t_2 - t_1) \cdot \frac{1}{860},$$

where c – metal heat capacity (varies, depending on the temperature, therefore average heat capacity values shall be applied for calculations), kcal/(kg·°C); g – metal weight, kg; t_2 – final temperature of metal heating, °C; t_1 – air temperature in the premise where electric furnace is installed, °C (initial temperature of metal). Heating duration, h:

$$\tau = \frac{c \cdot g \cdot (t_2 - t_1)}{\alpha \cdot F \cdot (t_0 - t_2)},$$

where α – heat emission factor, cal/(m·h·°C); t_0 – in-furnace temperature, °C; t_2 – product temperature (final), °C; t_1 – product temperature (initial), °C; F – active surface of treated articles or tare, m^2.

Analysis of the given formulae shows that following methods can be applied for reduction of specific power consumption during heat treatment in resistance furnaces:

- ✓ Reduction of heat losses and improvement of furnace heat insulation;
- ✓ Increase of furnace productivity;
- ✓ Reduction of losses for heat accumulation and application of articles preheating;
- ✓ Rationalization of furnace electrical and process operation modes.

Heat losses reduction. One of the options of heat losses reduction is furnace heat insulation improvement. Furnace heat losses through walls and roof are found in the following way, kW·h:

$$W_2 = \frac{k \cdot (\Theta_2 - \Theta_1) \cdot F}{860},$$

where F – outside surface of walls and roof, m^2; Θ_2, Θ_1 – temperature of furnace inside and outside walls, accordingly, °C; k – factor, depending on heat transfer and lining heat conductivity factors.

Use of the ultralightweight in combination with asbovermiculite slabs for furnace heat insulation reduces EP consumption by 25–26 %; decreases time of furnace heating by 32 %, and increases its productivity by 19 %.

Temperature of furnace shell can serve as an indicator of furnace heat insulation condition. Heat insulation can be considered satisfactory if the furnace operating temperature of 700–800 °C and furnace shell temperature is not more than 30–40 °C, and not more than 40–50 °C at the operating temperature of 800–1200 °C.

6.8.2. Arc steel furnaces

Specific power consumption for 1 t of steel melting in the electric arc steel furnace, kW·h:

$$\Delta Y = \frac{P\cdot\cos\varphi\cdot T_2}{g} + \frac{\Delta P_3\cdot T_3}{g\cdot\eta_{\text{el}}} + \frac{\Delta P_1\cdot T_1}{g\cdot\eta_{\text{el}}} =$$

$$= \frac{P\cdot\cos\varphi\cdot W_{\text{T}}}{P\cdot\cos\varphi\cdot\eta_{\text{el}} - \Delta P_2} + \frac{\Delta P_3\cdot T_3}{g\cdot\eta_{\text{el}}} + \frac{\Delta P_1\cdot T_1}{g\cdot\eta_{\text{el}}},$$

where P – power, supplied to the transformer (on the HV side), kW; T_1 – downtime period (metal discharge, furnace cleaning, back weld of hearth bottom and walls, metal charge), h; T_2 – period of metal melting, h; T_3 – rimming and refining period, h; g – charge weight, t; ΔP_1 – power of heat losses during downtime period, kW; ΔP_2 – power of furnace heat losses during metal melting, kW; ΔP_3 – power of heat losses during rimming and refining, kW; $\eta_{\text{el}} = \frac{P_1}{p}\cdot 100\,\% = \frac{P-p}{p}\cdot 100\,\%$; P_a – arc power, kW; p – electric power losses in the choke, transformer, wiring, and electrodes, kW; W_{T} – theoretically required power consumption for melting of 1 t of metal, kW·h.

The following conclusions can be made on the basis of given expression analysis:

✓ First summand – EP consumption for melting of 1 t steel, which depends on furnace efficiency factor and furnace heat losses;

✓ Power consumption for rimming and refining is inversely proportional to the charge weight;

- ✓ Power consumption, conditioned by the furnace downtime, is also inversely proportional to the charge weight and directly proportional to the downtime period, i. e. it depends on the furnace charging method to a considerable degree.

Increase of charge weight. Specific electricity consumptions depend on the charge weight. Therefore, it is expedient to overload the furnace power, increasing the charge size versus the rated. A possible overload of furnace power depends on the furnace transformer power, furnace tank size and lining life. Depending on these factors, an optimal overload value should be chosen for each furnace.

An optimal charge size for different furnace capacities approximately corresponds to the data, stated in Table 6.4.

Table 6.4

Optimal charge size for steel furnaces

Rated furnace power, t	Optimal charge size, t	
	For commercial quality steel melting	For refining steel melting
0.5	0.8–0.9	0.7–0.8
1.5	2.3–2.5	2.0–2.2
3.0	4.4–5.0	3.8–4.2
5.0	7.5–8.0	6.0–7.0
8.0	11.0–13.0	9.6–11.0
10.0	14–16	12–13
15.0	20–23	18–20
20.0	28–31	24–28
30.0	40–42	35–38
40.0	50–55	46–50

Dependence of specific power consumptions variation on the heat size can be used for calculating the furnace overload efficiency (see Fig. 6.11).

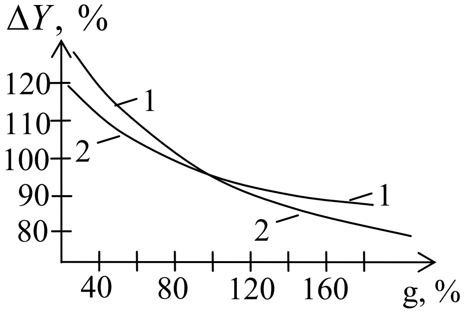


Fig. 6.11. Dependence of specific power consumptions variation on the heat size: 1 – basic-lined furnace; 2 – acid-lined furnace

Example 6.11. Electric furnace of 5 t rated power with the average load of 4.5 t has a specific EE consumption of 750 kW·h/t. The developed activities allow bringing the charge size up to 7 t, i. e. up to 140 % of the rated power.

Solution

According to Fig. 6.11 (curve 2), we find the specific EE consumption prior to and after load increase activities, which in this case will be 102 and 89 % of specific power consumption, accordingly, for 100 % utilization of furnace power.

We calculate specific consumption

$$\Delta Y_1 = 1.02 \cdot \Delta Y_R = 1.02 \cdot 750 = 765 \text{ kW} \cdot \text{h/t};$$

$$\Delta Y_2 = 0.89 \cdot \Delta Y_R = 0.89 \cdot 750 = 667.5 \text{ kW} \cdot \text{h/t}.$$

The achieved economy, referred to 1 t of smelt steel, will be:

$$\Delta Y = \Delta Y_1 - \Delta Y_2 = 765 - 667.5 = 97.5 \text{ kW} \cdot \text{h/t}.$$

Preliminary charge makeup. Prior to loading the charge should be treated so as to exclude "additional charges" during melting. It is provided by selection of the optimal volume charge weight, which shall be 3–4.5 t/m^3 for 1–5 t capacity of furnaces. To obtain an optimal value of the charge volume weight, scraps and waste are selected in certain composition. Thus, the following ratios are recommended for furnaces of 10–40 t capacity: 20 % of fines, 40 % of capital scrap and 40 % of the medium-size scrap.

Capital to fine charge ratio is approximately 60–70:40–30 can be considered optimal. Besides, a qualitative composition of the selected charge is very important.

Correct position of charge in the furnace laboratory should be provided along with the charge selection: half of fine scrap is laid on the furnace hearth, large-scale pieces of scrap metal are compactly placed in the furnace center under electrodes, and then all of this is covered by the medium-size scrap metal first, then by the fine scrap. Coke is loaded under every electrode to facilitate ignition and steady burning of electric arcs.

Electric power savings due to the charge selection, providing the melting without additional "charges", is 5–10 % of total power consumption for melting. If oxidizing period is reduced, then power efficiency will be 10–16 % of total power consumption for melting.

When developing the organizational and technical energy efficiency measures plan, it is possible to estimate an economical effect of activities implementation on the charge selection within range of 5–15 % of actual specific consumption for metal melting, made in the previous year.

Preliminary heating of charge. Heating and melting of solid charge are the most power-consuming activities in electric furnaces operation. Smelting period takes about half of total melting time, and 60–70 % of total electric power is consumed for melting during this period. Specific power consumption is 380–420 kW·h/t. Charge preheating up to 600–700 °C provides reduction of specific power consumption by 20 %; improves operating conditions of furnace transport due to a considerable reduction of in-rush current; improves qualitative conditions of the charge by removing moist and carbon drop from contaminating lubricant; and allows to perform the entire melting process with the switched on choke coil.

Charge preheating is especially effective, using waste-heat with temperature about 1000 °C from different thermal units if they are available in the production shop. Heat of cooling pits and other sources of secondary energy resources can also be used.

Application of special preheating units with oil burners or torches should be validated by feasibility calculations, supporting the additional capital investments and fuel consumption.

In cases when a charge preheating temperature differs from 600–700 °C, the following approximate dependence can be used

$$\Delta Y = 0.243 \cdot t_1^0,$$

where ΔY – electric power savings per 1 t of melted metal, kW·h/t; t_1^0 – temperature of preheated charge, °C.

Electric losses reduction

1. Due to optimal current density in the secondary busduct elements. Based on the arc steel furnaces operation practice, economic current densities of secondary busduct elements can be recommended:

- ✓ copper busbars with the pack section area for a phase up to 5000 mm^2 – 1.5–2 A/mm^2; over 5000 mm^2 – 1–1.5 A/mm^2;
- ✓ copper flexible cables with the pack section area for a phase up to 4000 mm^2 – 1.8–5.2 A/mm^2; over 4000 mm^2 – 1.2–1.8 A/mm^2;
- ✓ copper water-cooled pipes – 4–6 A/mm^2.

For economic current density, given in Table 6.5, EE losses, expressed as percentage of melting power consumption, are given in Table 6.6.

When current density increases in the secondary busduct elements, power losses and specific power consumption for melting will increase. Conditional factors (Table 6.6) of power losses increase in the secondary busduct elements, referred to 1 t of melted metal with the current density increasing over economic values, can be used approximately for preliminary calculations.

Table 6.5

Economic current density in the electrodes

Electrode diameter, mm	Carbon electrodes		Graphitized electrodes	
	Current density, A/cm^2	Current load, kA	Current density, A/cm^2	Current load, kA
100	–	–	0.30	1.7–2.9
150	0.12	2.1	0.25	3.2–5.3
200	0.11	3.4	0.22	5.3–9.1
250	0.10	4.9	0.20	7.8–12.2
300	0.10	7.0	0.18	11.3–16.9
350	0.10	9.6	0.17	15.4–20.2
400	0.09	11.3	0.16	18.8–23.8
450	–	–	0.15	23.8–28.6
500	0.09	17.7	0.14	27.5–33.3
550	–	–	0.14	28.4–38.0
600	0.07	25.0	–	–

Table 6.6

EE losses of economic current density in the electrodes

Secondary busduct elements	Electrical energy losses, in % for furnace capacity	
	0.5–5 t	8–20 t
Busbars, cables and pipes on the LV side	3.5–4.5	3–4
Carbon electrodes	6–8	3–4
Graphitized electrodes	4–5	3–4

Table 6.7

Increase factors of power losses k in the secondary busduct elements for 1 t of melted metal with the current density increase

Secondary busduct elements	Basic process		Acid process	
	Shaped casting	Ingot casting	Shaped casting	Ingot casting
Furnaces of 0.5–5 t capacity				
Busbars, cables and pipes on the LV side	25	28	23	26
Carbon electrodes	43.8	49	40.5	45.5
Graphitized electrodes	28.1	31.5	25.8	29.3
Furnaces of 8–20 t capacity				
Busbars, cables and pipes on LV side	21.9	24.5	20.1	22.8
Electrodes	21.9	24.5	20.1	22.8

Losses are calculated according to the expression

$$\Delta W = k \cdot (\frac{i_\text{a}}{i_\text{e}} - 1),$$

where k – losses increase factor (Table 6.8); i_a – actual current density, A/mm^2; i_e – economic current density, A/mm^2.

2. By reducing resistance of electrical contacts. Electrical transient contact resistance depends on type of materials and the nature of contact (detachable or non-detachable). As a rule, non-detachable connections are welded.

Transient resistance in detachable contacts depends on the contact surfaces and contact pressure, Ohm,

$$R_\text{к} = \frac{C}{p^m},$$

where C – design factor, depending on the contact material (Table 6.8); m – exponent (is taken equal to 0.5–1); p – contact pressure for copper busbars is taken equal to 60 MPa (600 kg/cm^2).

The following current densities are recommended for normal operation of the contact connection, A/mm^2:

Copper – copper	0.3
Aluminium – aluminium	0.16
Copper – aluminium	0.13
Copper – steel	0.1
Aluminium – steel	0.08.

Table 6.8

Design factors, C

Contact materials	$C \cdot 10^4$
Copper – copper	0.8–1.4
Copper – copper (tinned)	0.9–1.1
Copper – steel	30
Copper – aluminium	10
Steel – steel	75–80

Increase of contact resistance results in additional power losses, which are calculated according to the formula, kW

$$\Delta P_\text{c} = 3 \cdot I^2 \cdot (R_\text{c} - R_\text{a.c}) \cdot 10^{-3},$$

where I – current, passing through contact (average for a melting), A; R_c – contact resistance, corresponding to resistance of the entire busbar section of the same length, Ohm; $R_\text{a.c}$ – actual contact resistance, Ohm.

3. By reducing the furnace downtime period. Furnace downtime period in regular conditions is calculated using the time, required for metal tapping, furnace cleaning, back weld of hearth bottom and walls, and charge loading. Furnace downtime depends on the degree of metal tapping and charge mechanization and operation sophistication. Electric power is not supplied to the furnace during charge loading; however, the heat accumulated in furnace lining is dissipated by furnace shell and roof, and when furnace is connected to the system, part of energy heats the lining. Amount of losses for lining heating after a regular break in the furnace operation reaches 15–20 % of total supplied power for the next melting.

Influence of downtimes and delays on the specific power consumption can be set, depending on the downtime duration with furnace shutoff, considering furnace no-load losses, kW·h/t:

$$\Delta Y_{\text{sp.c}} = \frac{\left[P_0 \cdot t + P_{\text{R}} \cdot (24 - t)\right] \cdot Y_{\text{R}}}{P_{\text{R}} \cdot (24 - t)},$$

where P_{R} – the rated furnace power, kW; P_0 – no-load power (no-load losses), kW; t – hours of furnace downtime during 24-hour period, h; Y_{R} – the rated power consumption, kW·h/t.

6.9. EE saving in the lighting systems

It is suggested that specific installed power (SIC) of total artificial lighting for premises, which is the reference basis for EE consumption control in the lighting installations (LI) during energy inspection of facilities and at the project review stage, be used as one of energy factors, determining the rational EE consumption for lighting purposes.

Introduction of LI SIC in the design practice technically excludes utilization of incandescent lamps (IL) for public buildings lighting.

Calculation of EE savings for lighting and recommendations on energy efficiency in the lighting systems are developed by the following LI criteria, its organization and technical components:

- ✓ efficiency of light sources;
- ✓ efficiency of starting and control equipment;
- ✓ standard structural and lighting engineering diagrams and operational groups of lighting fixtures (LF);
- ✓ lighting systems, general-to-local lighting ratio;
- ✓ automatic lighting control systems, depending on the level of natural light and area of industrial premises;
- ✓ compliance with the LI operating regulations.

Calculation of energy consumption in lighting systems

Engineering evaluation is usually done by the method of light installation utilization factor, or point method.

Method of LI utilization factor can be applied for calculation of general uniform illumination. When calculating the LI at the first stage, a number of lighting fixture rows is planned

$$n_{\mathrm{lf}} = E_{\mathrm{R}} \cdot K_{\mathrm{r}} \cdot S \cdot z / (u_{\mathrm{l.i}} \cdot \mathrm{F}),$$

where n_{lf} – number of lighting fixtures, required for illumination of premises; E_{R} – rated illuminance; K_{r} – reserve factor; S – area of premises; z – factor of nonuniformity (1.1 – for fluorescent light (FL), 1.15 – for mercury arc lamps (MAL)); $u_{\mathrm{l.i}}$ – factor of LI utilization; F – luminous flux of all lamps in the lighting fixture.

Calculation of specific LI power starts with determining lighting installation power

$$P_{\mathrm{LI}} = n_{\mathrm{lf}} \cdot P_{\mathrm{lf}} \cdot K_{\mathrm{CG}} \text{ W},$$

where P_{lf} – lighting fixture power, W; K_{CG} – losses factor of the control gear (CG) of lighting fixtures (Table 6.9); n_{lf} – number of the same type lamps of LI in the *i*-th premise.

Table 6.9

Values of K_{CG} for different types of control gear equipment

Item No.	Type of lamp	Type of CG	*K*
1	FLB	General electromagnetic	1.22
		Electromagnetic with lower losses	1.14
		Electronic	1.1
2	CFL	General electromagnetic	1.27
		Electromagnetic with lower losses	1.15
		Electronic	1.1
3	MVAL, MIL	General electromagnetic	1.05
		Electromagnetic with lower losses	1.1
		Electronic	1.1
4	HPSV	General electromagnetic	1.1
		Electromagnetic with lower losses	1.1
		Electronic	1.06

LI specific power, W/m^2

$$p_{\mathrm{sp}} = P_{\mathrm{LI}} / S,$$

The specific power value obtained in calculation is required to be compared with the maximum allowable specific power for this type of premises (Tables 6.10, 6.11).

If calculation result for specific power is higher in comparison with the maximum specific power value from Table 6.10, 6.11, then designed LI is economically inefficient. To increase LI efficiency, it is necessary to select more efficient light sources, the lowest (if possible) height of light installation, and another system of illumination [48].

Table 6.10

Maximum allowable specific powers of artificial illumination of public premises

Illumination on working surface, lx	Index of premises	Maximum allowable specific power, W/m^2, not more than
500	0.6	42
	0.8	39
	1.25	35
	2	31
	3 and more	28
400	0.6	30
	0.8	28
	1.25	25
	2	22
	3 and more	20
300	0.6	25
	0.8	23
	1.25	20
	2	18
	3 and more	16
200	0.6–1.25	18
	1.25–3	14
	over 3	12
150	0.6–1.25	15
	1.25–3	12
	over 3	10
100	0.6–1.25	12
	1.25–3	10
	over 3	8

Note. Values of specific power are given with account for power plants of illumination switching and control.

Table 6.11

Maximum allowable specific power of artificial illumination of industrial premises

Illumination on working surface, lx	Index of premises	Maximum allowable specific power, W/m^2, not more
750	0.6	37
	0.8	30
	1.25	28
	2	25
	3 and more	23
500	0.6	35
	0.8	22
	1.25	18
	2	16
	3 and more	14
400	0.6	15
	0.8	14
	1.25	13
	2	11
	3 and more	10
300	0.6	13
	0.8	12
	1.25	10
	2	9
	3 and more	8
200	0.6–1.25	11
	1.25–3	7
	over 3	6
150	0.6–1.25	8
	1.25–3	6
	over 3	5
100	0.6–1.25	7
	1.25–3	5
	over 3	4

Note. Values of specific power for artificial illumination in other size premises and illumination conditions are calculated interpolation.

Electric loads of lighting installations are required for selection of electric equipment, total installed power of facility and calculation of lighting networks.

Estimated lighting load of production and public buildings, as well as street lighting is calculated on the basis of total power of lamps, obtained by means of lighting design. Installed power is found by summing up of rated power of all lamps over 42 V. In lighting installations with discharge lamps the estimated load is calculated with account for power losses in CG.

Estimated design load at the building entrance or in the beginning of supply line is calculated according to the formula

$$P_{\mathrm{des}} = K_{\mathrm{d}} \cdot \sum_{i=1}^{n} K_{\mathrm{CG}i} \cdot P_{\mathrm{R}i},$$

where K_{d} – light load demand factor; $K_{\mathrm{CG}i}$ – factor, accounting losses in CG of i-th lamp; $P_{\mathrm{R}i}$ – rated power i-th lamp; n – number of lamps, supplied by this line (installed in the building or premises).

When LI inspection data are unavailable, demand factor for calculation of supply network of work light for production premises should be taken equal to: 1.0 – for small buildings and lines, supplying specific group panels; 0.95 – for premises, consisting of separate major stairs; 0.85 – for buildings, consisting of numerous separate premises; 0.8 – for medical, office-utility and laboratory buildings; 0.6 – warehouses, consisting of separate premises, as well as electric substations.

Estimated electric load of lines, supplying sockets, is calculated according to the formula

$$P_{\mathrm{des.s}} = n \cdot K_{\mathrm{n.s}} \cdot P_{\mathrm{i.s}},$$

Where $K_{\mathrm{n.s}}$ – demand factor of socket network, is selected using the Table 6.12; $P_{\mathrm{i.s}}$ – installed power of socket, taken as 0.06 kW (including those for office equipment connection); n – number of sockets.

For mixed supply of total illumination and socket network, total design load $P_{\mathrm{d.t}}$ is calculated according to the formula

$$P_{\mathrm{des.t}} = P'_{\mathrm{d.t}} + P_{\mathrm{des.s}},$$

where $P_{\mathrm{des.t}}$ – design load of general lighting line, kW.

Demand factor for lines load evaluation, that supply stage lighting in halls, clubs and culture facilities, should be equal to 0.35 for regulated lighting and 0.2 – for non-regulated.

Table 6.12

Demand factor of lighting socket network

Organizations, enterprises and offices	Group networks	Network schedule	Inlets of buildings
Management organizations and offices, design developing organizations, research institutes, financing, credit and public insurance institutions, general education schools, special vocational institutions, educational and vocational schools, hospitals and clinics	1	0.2	0.1
Hotels, dining rooms of restaurants, cafes and cafeteria, enterprises of public services, libraries and archives	1	0.4	0.2

Design load of specific premises and buildings, for which a complete lighting calculation is not performed, can be estimated using the expression

$$P_{\text{d}} = K_{\text{s}} \cdot p_{\text{sp}} \cdot F \cdot 10^{-3},$$

where p_{sp} – specific power of general uniform illumination, W/m^2; F – area of premises, m^2.

Specific power of illumination is selected depending on type and rated power of applied light sources, calculation of height, area, intensity of illumination and other factors of illumination.

Value of specific power in every taken case is determined by proportional recalculation, using the formula

$$p_{\text{sp}} = \frac{P_{\text{sp}\tau} \cdot K_{\text{L}} \cdot E_{\text{R}}}{K_{\text{rf}\tau} \cdot \eta \cdot 100},$$

where $P_{\text{sp}\tau}$ – tabular value of specific power illumination; K_{rf} and $K_{\text{rf}\tau}$ – actual and tabular values of reserve factor; E_{R} – rated illumination; η – efficiency factor of selected lighting fixture ($\eta = 0.5 \div 0.8$).

Design load of outdoor illumination can be found in a similar way, or using the following expressions

$$P_{\text{d}} = p_{\text{sp}i} \cdot L \cdot 10^{-3},$$

$$P_{\text{d}} = p_{\text{sp}} \cdot F \cdot 10^{-3},$$

where $p_{\text{sp}i}$ and p_{sp} – specific powers of LI, W/m and W/m^2, accordingly; L – total length of outdoor illumination lines, m; F – illuminated area of outside territory, m^2.

When required the design reactive power of light load is calculated using the formula

$$Q_\mathrm{d} = P_\mathrm{d} \cdot \mathrm{tg}\varphi,$$

where $\mathrm{tg}\varphi$ – average value of LI reactive power factor.

Selection of conductor section of lighting system by heating. Heating of conductors is conditioned by the flowing current, which is calculated according to the following formulae:

- ✓ for three-phase system (four- or five-wire)

$$I_\mathrm{d} = \frac{P_\mathrm{d}}{\sqrt{3} \cdot U_\mathrm{R} \cdot \cos\varphi} = \frac{P_\mathrm{d}}{3 \cdot U_\mathrm{R.f} \cdot \cos\varphi},$$

- ✓ for two-phase system with working and protective zero wires (three- and four-wire)

$$I_\mathrm{d} = \frac{P_\mathrm{d}}{2 \cdot U_\mathrm{R.f} \cdot \cos\varphi},$$

- ✓ for one-phase system (double and three-wire)

$$I_\mathrm{d} = \frac{P_\mathrm{d}}{U_\mathrm{R.f} \cdot \cos\varphi},$$

where $U_\mathrm{R.f}$ and U_R – rated phase and interphase voltage of the network, accordingly; $\cos\varphi$ – power factor.

At non-uniform phase load, the estimated active load of line is taken equal to triple value of the most loaded phase load.

Conductor section of lighting system is selected by means of heating factor, according to tables of admissible continuous current I_adm, depending on I_d value under the following condition

$$I_\mathrm{adm} \geq I_\mathrm{p} / K_\mathrm{cor},$$

where K_cor – corrective factor for actual conditions of wire and cable laying.

If wire and cable laying conditions do not differ from those specified in PUE, then $K_\mathrm{cor} = 1$.

For lighting networks of 1 kV a corrective factor is usually $K_\mathrm{cor} = K_1 \cdot K_2$ (where K_1 and K_2 – factors, which help to account for actual ambient temperature and number of jointly laid conductors (taken according to PUE).

Selection of conductor section for lighting system by allowable voltage losses. Allowable voltage loss value (in percentage) for lighting system is calculated according to formula

$$\Delta U_\mathrm{add} = U_\mathrm{nl} - U_1 - \Delta U_\mathrm{T},$$

where $U_{\text{XX}} = 105\ \%$ – no-load voltage of LV busbars of transformer; $U_{\text{l}} = 95\ \%$ – minimum allowable voltage of the most remote lamp; ΔU_{T} – voltage loss in transformer, to which LI is connected, %.

With account for U_{NL} and U_{l} we can assume that $\Delta U_{\text{add}} = 10 - \Delta U_{\text{T}}$.

Voltage losses in transformers with sufficient practical accuracy can be calculated using the formula

$$\Delta U_{\text{T}} = \beta_{\text{T}} \cdot (U_{\text{c.a}} \cdot \cos\varphi + U_{\text{c.r}} \cdot \sin\varphi),$$

where β_{T} – load factor of transformer; $U_{\text{c.a}}$ and $U_{\text{c.r}}$ – active and reactive components of short circuit voltage, %; $\cos\varphi$ – power factor of transformer load.

Active and reactive components of short circuit voltage are calculated according to formulae

$$U_{\text{c.a}} = \frac{\Delta P_{\text{SC}} \cdot 100}{S_{\text{R}}} \text{ and } U_{\text{c.r}} = \sqrt{U_{\text{SC}}^2 - U_{\text{c.a}}^2},$$

where ΔP_{SC} – short circuit losses (nameplate value), kW; S_{R} – rated power of transformer, $\text{kV} \cdot \text{A}$; U_{SC} – short circuit voltage, %.

Wire section of lighting system with allowable voltage loss is calculated by the formula

$$F = \frac{M}{C \cdot \Delta U_{\text{add}}},$$

where $M = P_{\text{d}} \cdot L$ – load moment of considered network segment, $\text{kW} \cdot \text{m}$; C – calculation factor, which value is taken from the Table 6.13.

Table 6.13

Values of C factor for network calculation by voltage loss

Rated voltage of network, V	Network system and type of current	Factor for wires	
		copper	aluminium
400/230	Three-phase with neutral conductor	79	48
230	Three-phase without neutral conductor	26	16
400/230	Two-phase with neutral conductor	35	21,5
230	One-phase of alternating or two-phase of direct current	13	8

Obtained value of section is rounded to the nearest major standard value.

If a group of lighting fixture of the same power is connected to a group line with even intervals *l*, then distributed load of line is replaced with total concentrated, applied to the middle of segment. Then value L is calculated, using the formula

$$L = l_1 + l \cdot \frac{N_\text{p} - 1}{2},$$

where l_1 – length of line segment from lighting board to the first lighting fixture; N_p – number of fixtures in a row.

Reduction factor is calculated for actual illumination deviation recording from the standardized values according to the formula

$$\theta = \frac{E_\text{a}}{E_\text{st}},$$

where E_a – actual illumination in the i-th premise, according to instrumental energy inspection data; E_st – the standardized value of illumination in the i-th premise (SNiP 23-05-95).

Actual average illumination value with account for the system voltage deviation from the rated is calculated according to the formula

$$E_\text{a} = \frac{E'_\text{a} \cdot U_\text{R}}{U_\text{R} - \xi \cdot (U_\text{R} - U_\text{av})} \text{ lx},$$

where E'_a – actual metered average illumination, lx; ξ – factor, accounting for variation of the light flux with voltage deviation of the supply system (for incandescent lamps – 4; for discharge lamps – 2); U_R – the rated voltage in the system, V; $U_\text{av} = (U_1 + U_2)/2$ – actual average voltage value; U_1, U_2 – voltage values in the electric lighting system at the beginning and end of metering.

Calculation of EE saving potential from transition to the other light source type with a higher output, lm/W

$$\Delta W = W \cdot (1 - \delta \cdot K_\text{rf}),$$

where $\delta = \eta_1 / \eta_2$ – efficiency factor of light source replacement; η_1, η_2 – output of the replaced and suggested light source, accordingly, lm/W; K_rf – reserve factor, considering reduction of the light flux during service life (when replaced by those with close values to K_rf, but of different efficiency, K_rf is excluded or corrected, besides cases when inspection is carried out after group replacement of light sources).

Electricity saving potential from installation of energy efficient ballast control gear

$$\Delta W = W \cdot (1 - \frac{K_\text{CG2}}{K_\text{CG1}}),$$

where K_{CG1} – losses factor in ballast control gear of existing lighting fixture of lighting system of i-th premise; K_{CG2} – losses factor in ballast control gear, installed in the fixtures (see Table 6.9).

Electricity saving potential from efficiency factor increase of available light devices by cleaning them

$$\Delta W = Q \cdot \lambda \text{ kW·h/year,}$$

where $\lambda = 1 - (\gamma_{\text{c}} + \beta_{\text{c}} \cdot e^{-\frac{t}{t_{\text{c}}}})$ – efficiency factor after lighting fixtures cleaning; γ_{c}, β_{c}, t_{c} – constants for the specified conditions of lighting fixture operation (See Table 6.14), t – duration of lighting fixture operation between two subsequent cleanings.

Table 6.14

Constants for the specified conditions of lighting fixtures operation

Dust release characteristic	Work premises	General conditions	β_{c}	γ_{c}	t_{c}, h
Moderate	Offices and working premises of public buildings, laboratories	Favorable	0.05	0.95	10 000
		Unfavorable	0.15	0.85	9000
Average	Production shops, flour and bread storage rooms	Favorable	0.25	0.75	8000
		Unfavorable	0.35	0.65	7000

Electricity saving potential from installation of automatic control gear

$$\Delta W = W \cdot (\rho - 1),$$

where ρ – efficiency factor of the lighting control automation, which depends on the complexity level of control system (Table 6.15).

Table 6.15

Values of the lighting control automation efficiency factor for enterprises and organizations of regular operation (1 shift)

Item No.	Complexity level of automatic lighting control system	ρ
1	Control of illumination level and automatic switching of the lighting system at the critical value E	1.1–1.15
2	Zone lighting control (discrete switching on and off, depending on the natural illumination distribution zone)	1.2–1.25
3	Smooth control of power and the light flux of fixtures, depending on the natural illumination distribution	1.3–1.4

A significant specific weight of EE consumption for illumination in Russia at its low quality is conditioned by utilization of technically outdated lighting fixtures. Inefficient incandescent lamps are used in 70 % of the LF; fluorescent-mercury arc lamps with the low output and, consequently, a higher power are used for outdoor lighting. Lighting fixtures with a small light efficiency factor, increased power losses in the control gear (CG) are used in indoor and outdoor light units. Automatic lighting control units are not applied for the LI. Solution to the energy saving problem in lighting engineering assumes a transition to use of energy-efficient lighting equipment and technologies.

EE saving in LI in Russia plays a great role, as about 1 4 % of all generated power is consumed for illumination purposes in Russia. Proportion of consumed LI electricity in different budgetary organizations varies from 10 to 70 % [48]. Electricity saving can be obtained as a result of optimization of LI part and lighting networks, illumination control and regulation systems, rational organization of illumination operation.

Lighting design and lighting networks optimization includes the following measures: correct selection of illumination and LS types; acceptance of efficient lights arrangement; correct selection of lighting fixtures by light distribution and design.

Lighting effectiveness is evaluated by electricity consumption for 1 m^2 lighting. As an effectiveness evaluation criterion of energy saving in lighting generally acts a ratio of LI modernization expenses and specific premises to cost of saved electrical energy. One of major criteria of energy efficiency is power, consumed for $1m^2$ lighting of surface, per 100 lx at lighting fixture efficiency factor of 100 % and reserve factor 1.5. Maximum allowable values are given in MGSN 2.01–99.

About 14 % of generated electricity is consumed in our country for artificial lighting that in 2010 made over 100 bln kW·h. Thoughtful consumption with the most economic effect of such considerable amount of energy is a major and important economic objective. Electricity saving from lighting should not be completed by switching off a number of LI or rejection from lighting use in conditions of insufficient natural light level, as lighting decrease exacerbate physchophysiological condition of people, increase of injury rate, decrease of labor productivity and produce quality. Losses from lighting conditions worsening exceed the value of saved electricity considerably.

Main recommendations and measures for efficient and rational use of electricity in LI:

1. Application of lighting ACS with sensors of intensity and presence. Only this measure can save electricity up to 50 %.

2. Application of modern LS with a high luminosity (FL in bulbs of 16 mm diameter, CFL, LED, HPSL, MHL with ceramic burners). Electricity

consumption decreases from replacement of IL to FL up to 80 %, to MHL up to 75 % and HPSL up to 90 %.

3. Replace electromagnetic ballasts on ECG, especially for FL. Such replacement allows for saving 10–20 % of electricity.

4. Use of ML of higher power in compliance of regulatory requirements to lighting quality (blinding, reflected glare and illumination ripple).

5. Application of HPSL in production premises, where no strict requirements are stipulated for color rendering.

6. Use of the most rational lighting system for specific working conditions. In the premises where visual performances of I category are done, a system of combined lighting should be applied, for categories II–IV a general lighting system is permitted with available feasibility analysis.

Combined lighting is reasonable to apply: for visual works of II category, when area per worker is in average 3 m^2 and more; III category, when area per worker is 5 m^2 and more, for IV category – 10 m^2 and more.

Application of LI localized arrangement of general lighting in premises with asymmetric arrangement of processing equipment and small density of arrangement, as well as different precision visual works in the premise.

7. Selection of fixtures with the most feasible light distribution and their arrangement in a most efficient ratio of distance between them and installation height.

8. Selection of specific design fixtures for premises with severe conditions, which allow decreasing the reserve factor by 0.2.

9. Application of integrated lighting devices with slotted light guides for lighting of premises with severe conditions (explosive, dust, etc.), referred to category III–VI by visual works precision, as well as for hindered access to LI. It can save electricity of 10–15 % in comparison to fixtures for severe conditions.

10. In production buildings with side and combined (overhead and side) natural light and in the premises of public buildings should be provided switching off of fixture rows, parallel to windows that allows reducing electricity consumption by 5–10 %; in premises with combined lighting it is recommended to switch on and off specific groups of fixtures, depending on lighting level, created by daylight in different zones of the premises. This measure gives energy savings of 10–20 %. For outdoor lighting of industrial facilities, cities and settlements and indoor lighting of major production premises it is feasible to install centralized automatic control that provides savings in size of 10–15 %.

11. Voltage supply of 660/380 V (solidly earthed systems) of high power LI without intermediate transformation, including LI designed for phase voltage 380 V. Voltage supply 660/380 V can give electricity savings up to 12 %,

owing to increase of LS luminosity and decrease of losses in network and CG.

12. Application of LI, where HPML power is significant (hundreds of kilowatts and more), group three-phase compensating capacitor banks, which reduce electricity losses and need for cables, wires, switching and protective devices for lighting networks.

13. Use of devices and fittings for a convenient and safe access to LI for cleaning during operation process. Personnel for lighting servicing should also be defined at the design stage.

14. Cleaning of window glass and lantern lights in industrial and public buildings at least 2 times a year that will allow reducing work hours of artificial lighting and save 5–10 % of electricity in average.

15. Increase of natural and artificial lighting factor by using light colors for industrial and public buildings painting.

16. Reconstruction of old LI that do not meet the requirements to artificial lighting.

CHAPTER 7. ELECTRICAL ENERGY METERING AT INDUSTRIAL FACILITIES

According to [33], evaluation of consumption (generation) of electrical energy (power) in retails markets, provided services on electrical energy transmission, as well as actual losses of electrical energy in facilities of electricity supply network is done:

1. On the basis of data, obtained from electrical energy meters, including those in metering complexes and systems;
2. When there are no meters available – by calculation methods.

Metering complex is a set of meters and instrument transformers for current and (or) voltage, connected according to approved circuit, using which these meters are installed (connected), and designed for electrical energy (power) metering in one supply point.

Metering system is a set of metering complexes, connecting and computation components, data acquisition and transmission devices, software, designed for metering, storage, remote acquisition and transmission of meter readings for one and several points of supply.

Meters, readings of which according to [33] are used for determining the consumption (generation) of electrical energy (power) in retail markets, provided services on electrical energy transmission, actual losses of electrical energy in electricity supply network that are paid for in retail market, should meet the requirements of the Russian Federation legislation on uniformity of metering, as well as accuracy class requirements, be allowed for operation according to established procedure, have intact security seals and (or) visual control signs.

For electricity metering, consumed by residents, as well as for electricity supply network facilities and intra-building utility systems of apartment building in the boundary of attribution, meters of accuracy class 2.0 and higher are to be installed [33].

In apartment buildings, connected to electric network after entry into force of Government Resolution No. 442, on the boundary of electric network facilities attribution and intra-building utilities, collective (building) meters of accuracy class 1.0 and higher are to be installed.

For consumed electricity metering for consumers of the maximum power not less than 670 kW, meters of accuracy class 1.0 and higher are to be used – for connection points to electricity supply network of 35 kV and lower, accuracy class 0.5S and higher – for connection points to electricity supply network of 110 kV and higher.

For consumed electricity metering for consumers of the maximum power not less than 670 kW, meters of accuracy class 0.5S and higher are to be used, allowing for metering the hourly electrical energy consumption, and storing data about hourly electrical energy consumption for last 120 days and more or included in metering system.

For metering reactive power, consumed (generated) by consumers with maximum power not less than 670 kW, in case if the Agreement for electrical energy supply, concluded in respect of energy receivers of such consumers, according to Rules for non-discriminated access to services in electrical energy transmission and these services rendering, has a condition about a ratio of active and reactive power consumption; metering devices, allowing for reactive power metering or combining active and reactive power metering and measuring hourly consumption (generation) of reactive power are to be used. Here the stated meters should be of accuracy class not less than 2.0, but have accuracy class not more than one step lower for used meters, measuring active power.

Accuracy class of instrument transformers, used in metering complexes for installation (connection) of metering devices, should not be lower than 0.5. It is permitted to use voltage instrument transformers of 1.0 accuracy class for installation (connection) of metering devices of accuracy class 2,0 [33].

7.1. Electronic EE meters

EE accounting by electronic meters is based on conversion of alternating current and voltage analog input signals into the count pulse or code.

A structural diagram of electronic meter, based on the amplitude and pulse-width modulation is shown in Fig. 7.1.

There are no mechanical rotating parts in this meter, thereby friction is excluded. Consequently, better metrological specifications are achieved: measurement errors, sensitivity threshold, shunt running, etc.

LCD indicator is applied instead of a drum-type counter mechanism in the range of electronic meters. Application of specialized large-scale integrated circuit (LSI), microprocessors allowed development of multifunction meters. They meter active and reactive energy, as well as current, voltage, $\cos\varphi$, control and store load curves, display information about the meter connection diagram, etc. Electronic meters, produced in Russia, do not fully satisfy the operation requirements, such as:

- ✓ Reliability, dust- and water-resistance of casing;
- ✓ Reliability of electronic circuit components and quality of meter assembly;
- ✓ Security against switching and lightning overvoltage, especially in distribution systems of 380/220 V voltage;

✓ Security against unauthorized access and measuring of the meter connection circuit.

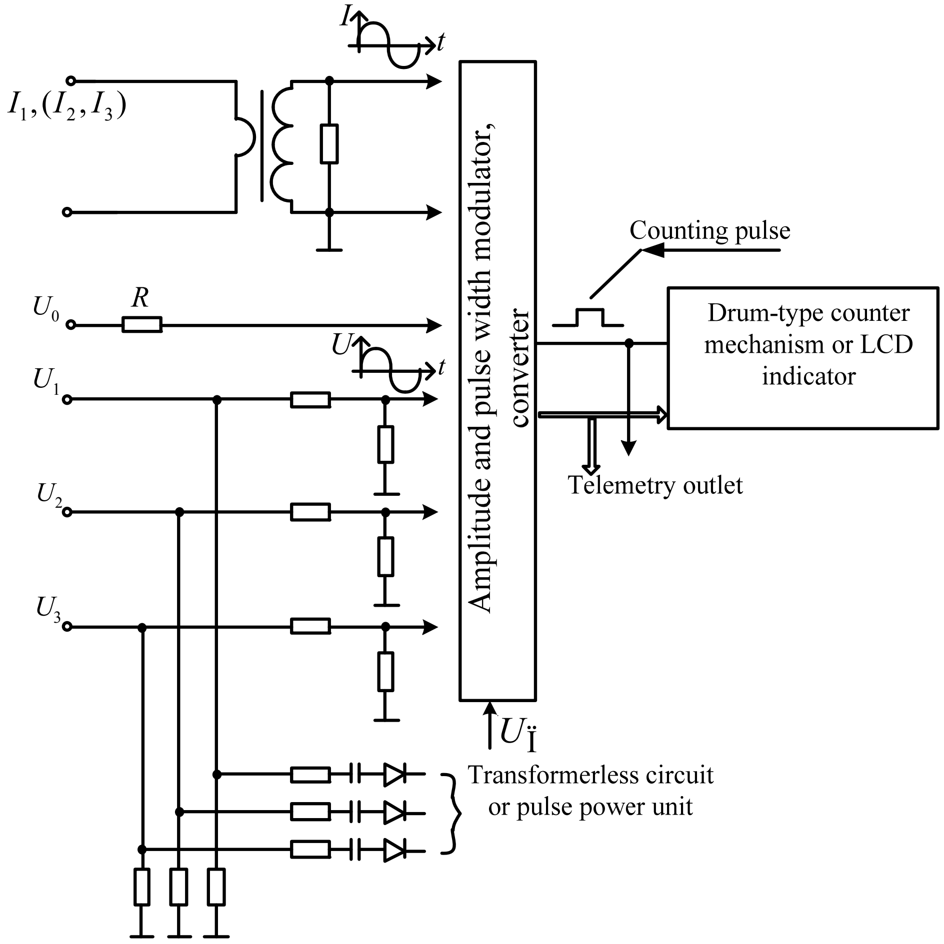


Fig. 7.1. Structural diagram of electronic meter

7.2. Accuracy of EE meter readings

Accuracy of electric power meter readings can be estimated by the meter error, which is found, according to its systematic component, sensitivity threshold, shunt running, accuracy of interior angle control, and additional errors.

Error of a meter δ_C depends on current and $\cos\varphi$ values. Error dependence on the current and $\cos\varphi$ is called a meter load characteristic.

When operating on connections with low $\cos\varphi$ (below 0.5 ind.) and low load currents (below 0.5 A), plus errors of metering by induction devices up to +30 % are observed during check-up with a standard meter of CE6806P type. Some meters give minus errors to –8 % in the same conditions. Such a wide scatter can be explained mainly by friction compensation adjustment in the induction meter.

Sensitivity threshold is the least power value, at which electricity is measured by a meter. For an induction meter of accuracy class 2 with the rated current of 5 A, the current sensitivity threshold limit is 25 mA at $\cos\varphi = 1$. It is much less for an electronic meter and practically reaches 1–5 mA. Sensitivity threshold of a meter can be estimated according to measurement error on 25 mA current, and $\cos\varphi = 1$, using the standard meter CE6806P.

Shunt running. When a meter is switched to voltage of 80–110 % from the rated (with $U_{\text{nom}} = 220$ V from 176 to 242 V) with disconnected current circuits, the induction meter disc shall not make more than one full turn during 10-minute observation. Indicators of the main and calibration transmitting devices shall not blink for an electronic meter.

Reasons, causing an induction meter shunt running during operation:

- ✓ A reverse order of voltage phase sequence;
- ✓ No voltage on one of the phases of the meter terminal block;
- ✓ Different values of phase voltages in terminal block of three-phase meter, for example $U_{\text{A}} = 220$ V, $U_{\text{B}} = 240$ V, $U_{\text{C}} = 260$ V;
- ✓ Diagram of a three-phase meter connection is done with compatible current and voltage circuits;
- ✓ Meter maladjustment.

Accuracy of interior angle control of the active energy induction meter is tested on the bench with the rated current, voltage and $\cos\varphi = 0$ for phase shift angles of 90 and 270°. Here the meter should not measure electricity.

7.3. Connection circuits for single-phase meters

Different meter types of both domestic and foreign manufacture are applied for electric power metering in single-phase systems of alternating current.

A single-phase meter connection diagram is shown in Fig. 7.2, *a*. The obligatory requirement for a meter connection is adherence to the connection polarity both for current and voltage.

An induction meter connection diagram with reverse polarity in the current system is shown in Fig. 7.2, *b*. In this case, current reversal in the system generates a negative torque, and the meter disc will turn in the opposite direction. An electronic single-phase meter in this case does not meter the power, and indicator blinking is not observed. New types of electronic single-phase meters measure the electric power regardless of current system connection polarity.

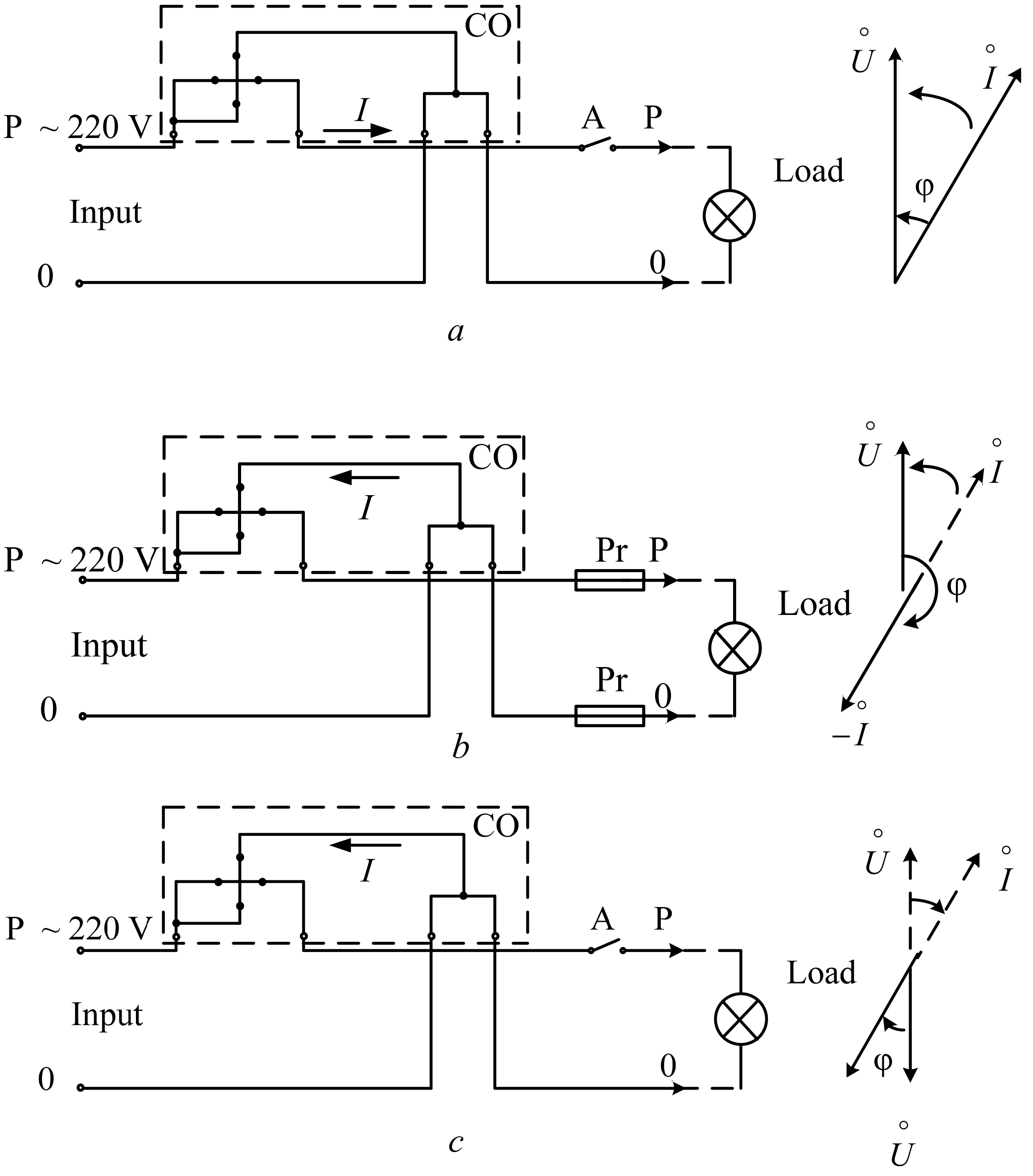


Fig. 7.2. Connection and vector diagrams of a single-phase meter (a), a single-phase induction meter with reverse polarity in current system (b) and a single-phase meter with reverse polarity in current and voltage system (c)

Connection of a single-phase meter with voltage and current reverse polarity is shown in Fig. 7.2, *c*. In this case current and voltage phases are simultaneously measured at 180°, and phase shift angle remains the same. Therefore, the meter measures electric power, according to its accuracy class. Use of meter connection diagram in Fig. 7.2, *c,* is not allowed in practice, as it permits power consumption without accounting.

To prevent an electricity theft, installation of the following is currently provided at the meter manufacturing factories:

- ✓ A reverse lock;
- ✓ Second (duplicate) jumper for voltage delivering to the coil, and its placement inside the case;
- ✓ Second current coil in the circuit of neutral wire.

Besides, a meter casing is made transparent.

7.4. Three-phase meter connection circuits in 380/220 V electrical installations

Meters of direct (immediate) connection are applied for electrical energy measuring in the three-phase four-wire systems of 380/220 V voltage. They are called straight-through. Besides, meters, connected to the system through current transformers (CT), are used. They are called universal or transformer.

Meters of direct connection are designed for the rated currents of 5, 10, 20, 50 A. Connection of these meters current circuit is done in series with the system conductors and obligatory polarity adherence (Fig. 7.3).

The metered energy is equal to difference of the metering device readings (R) during settlement (accounting) period: $\Delta W = R_{\text{f}} - R_{\text{i}} = \Delta R$.

Connection of one current circuit with reverse polarity results in a significant power undermetering. Adherence to the direct order of phase sequence in the terminal block is obligatory. Variation of phase sequence in the terminal block is provided by changing the connection point, accordingly of two wires of one element with two conductors of the other element.

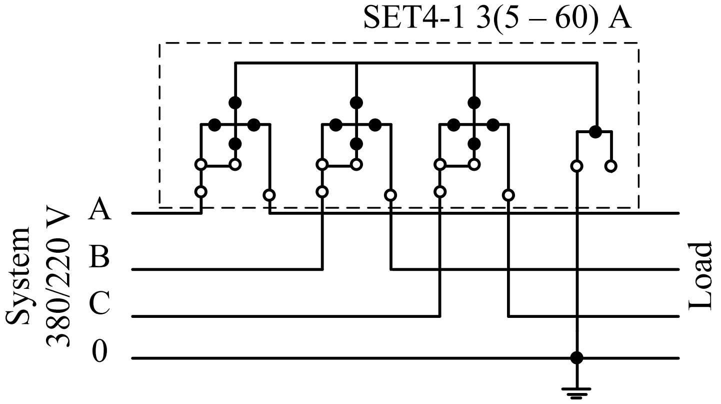
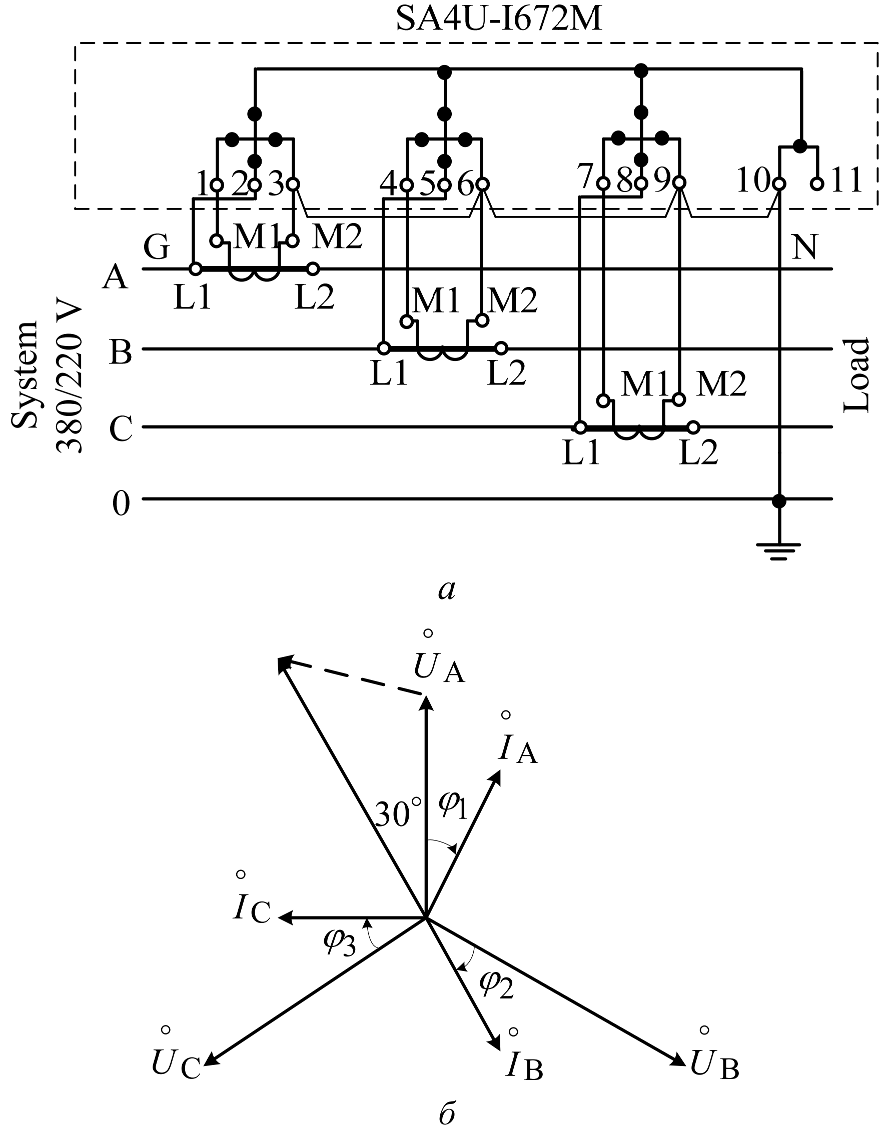


Fig. 7.3. Connection diagram of the straight-through meter SET4-1

Transformer meter connection diagram (*a*) and vector diagram (*b*), which corresponds to the inductive load type in case of phase shift, equal to 30°, are shown in Fig. 7.4. Connection diagram is done in ten-wire. Meter current circuits are not connected galvanically to voltage circuits, but separated. The measured electric power is equal to difference of the counter mechanism readings, multiplied by transformation factor:

$$W = (\mathrm{R_f} - \mathrm{R_i}) \cdot k_{\mathrm{U}} = \Delta R \cdot k_{\mathrm{U}} .$$



a

б

Fig. 7.4. Connection diagram of three-element meter SA4U-I672M in the four-wire system with separated current and voltage circuits (a) and vector diagram (b). Direct phase sequence is obligatory

Connection of each of the three meter elements requires an obligatory adherence to polarity of current circuit connection, and their voltage compliance. Reverse polarity of CT primary winding connection, or its secondary winding causes a negative torque, influencing on the meter disc. Diagram provides the rated error of measurement. Neutral wire connection is obligatory. The most common circuit disturbances are:

- ✓ Loosening or oxidation of CT screw terminals;

- ✓ Break (internal fracture) of voltage phase wires of the secondary circuits;
- ✓ CT breakdown.

Three wires of one element in the meter terminal block are interchanged with the corresponding three wires of the other element, when phase sequence changing is required.

Seven-wire connection circuit (Fig. 7.5) is often applied. Current and voltage circuit integration is done in this diagram. Alignment of current and voltage circuits is performed by installation of jumpers in the meter and CT. The circuit has the following drawbacks:

- ✓ Current circuits are under load;
- ✓ CT breakdown is not detected for a long period;
- ✓ Installation of jumpers I2-L2 on the CT, and 1–2 on the meter causes additional measurement error.

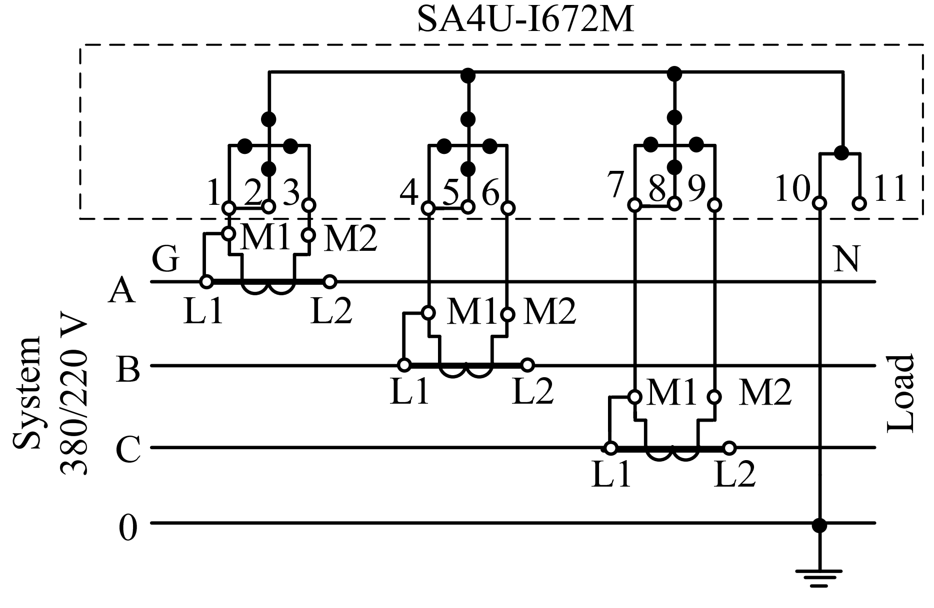


Fig. 7.5. Connection diagram of three-element meter of SA4U-I672M type in four-wire system with integrated current and voltage.
Direct phase sequence is obligatory: L1 – M1 – jumpers, installed in CT; 1–2; 4–5; 7–8 – jumpers, installed in the meter

The most universal is meter connection diagram with a test box (Fig. 7.6). The test box allows replacement of meters and check of connection circuit without load interruption.

The connection circuit of meters, shown in Fig. 7.7, is applied for active and reactive energy measurement. Connection diagrams of a reactive-type meter SR4U-I673 and active energy meter do not differ from each other. Current circuits of these meters are connected in series, voltage circuits – in parallel. The difference of reactive energy meter from active energy meter is in the internal wiring diagram. Due to internal wiring diagram of coils, designed for 380 V, an additional 90° phase shift is made between magnetic fluxes.

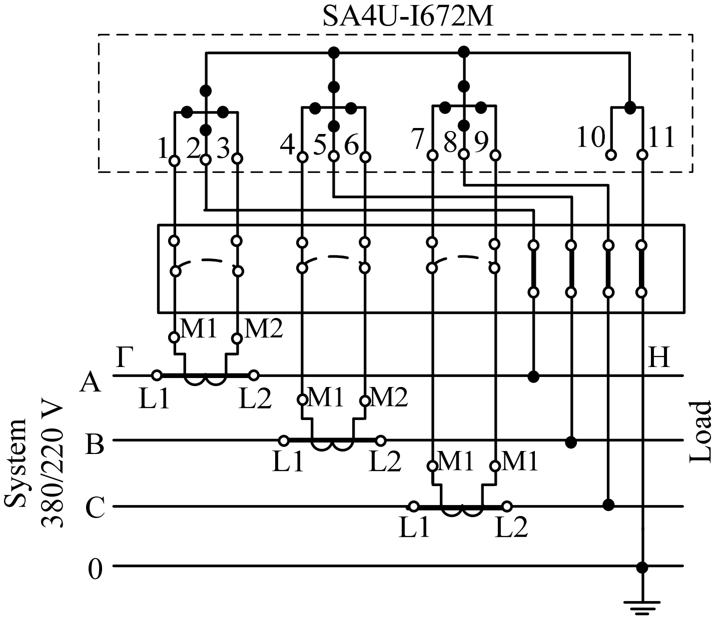


Fig. 7.6. Connection diagram of three-element meter SA4U-I672M in the four-wire system with the test box

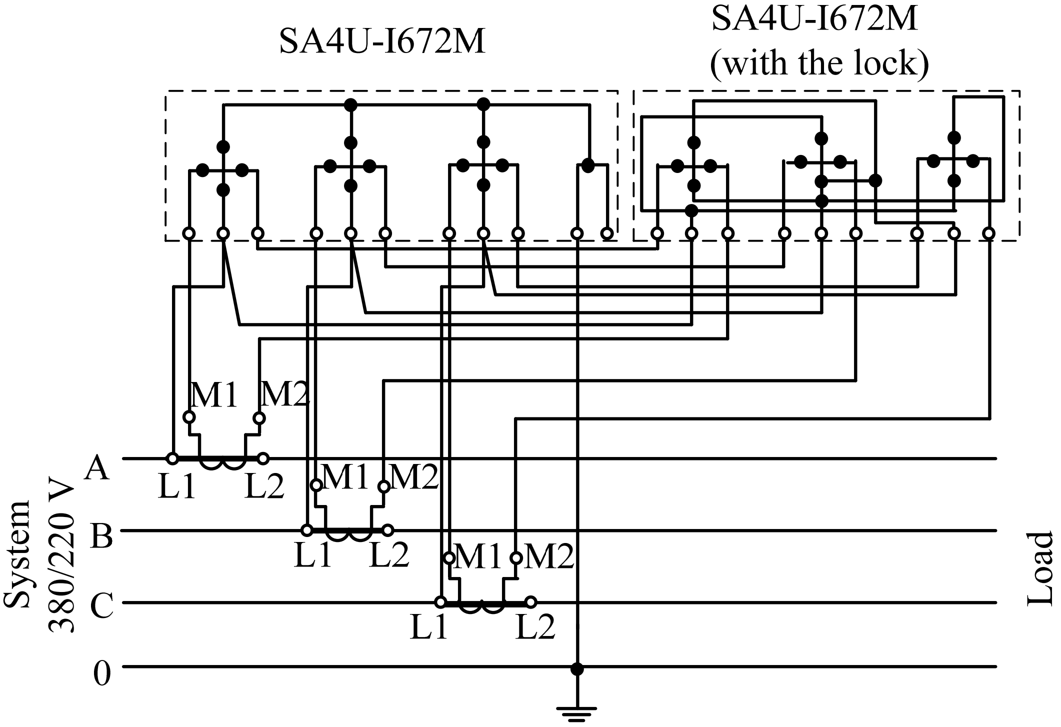


Fig. 7.7. Connection diagram of reactive and active energy meters in the 380/220 V system

7.5. Three-phase meter connection circuits in electrical installations over 1000 V

Two-element active energy meters of SA3U-I670M type, measuring CTs and voltage transformers (VT), connected according to the circuit in Fig. 7.8; are applied in three-phase three-wire systems of 6–10 kV and over for electric power measurement.

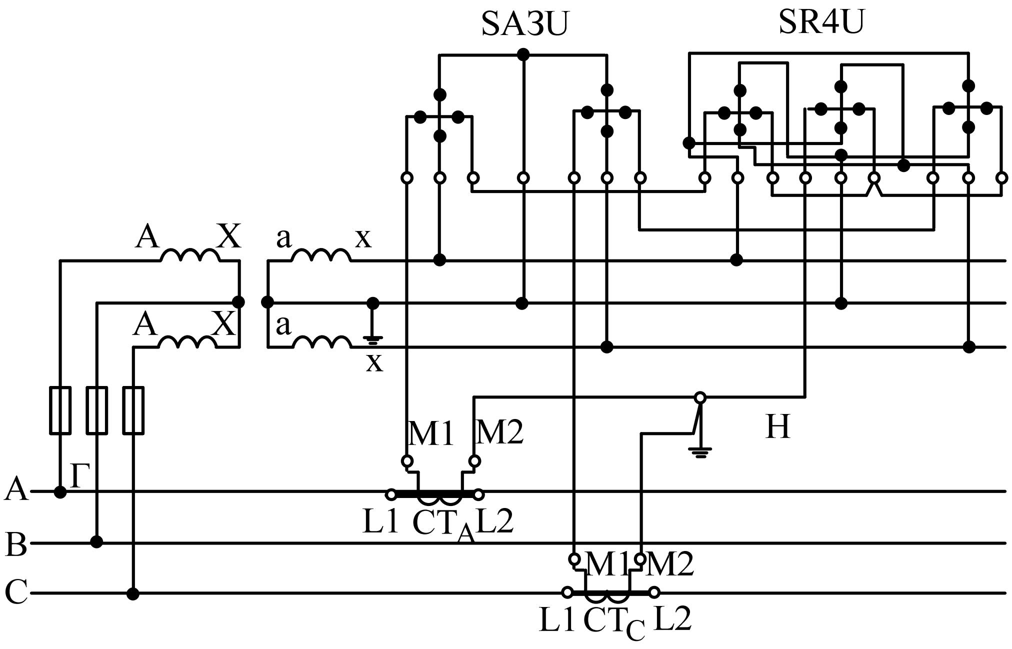


Fig. 7.8. Circuit diagram of two-element active energy meter and three-element reactive energy meter connection to the three-wire system with two measuring CT and VT. Direct sequence of ABC phases is obligatory

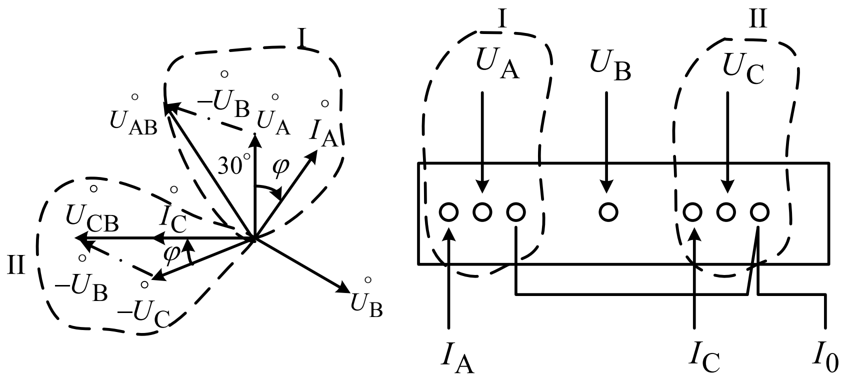


Fig. 7.9. Vector diagram of electric power measurement by a two-element meter

We will study power measurement by a two-element meter SA3U-I670M on the example of vector diagram (Fig. 7.9) of phase-to-phase voltages $U_{AB} = U_{CB} = 100$ V and currents $I_A = I_C = 1$ A with the phase shift angle $\varphi = 30°$.

The first metering element registers active power

$$P_1 = U_{AB} \cdot I_A \cdot \cos(30^\circ + \varphi) = 100 \cdot 1 \cdot 0.5 = 50 \text{ W}.$$

The second metering element registers active power

$$P_2 = U_{CB} \cdot I_C \cdot \cos(30^\circ - \varphi) = 100 \cdot 1 \cdot 1 = 100 \text{ W}.$$

Active power, measured by the meter is $P = P_1 + P_2 = 150$ W. Absolute error of electricity measurements δ_A will be 50 W or – 33 % with current I_A absence at U_A voltage on the first meter's measuring element.

Electricity measurements δ_C error will be 100 W or – 66 % with current I_C or voltage U_C absence on the second measuring element.

When phase B voltage is absent on the meter, electricity δ_B measurement error will be – 50 %.

If load on this connection is active ($\cos\varphi = 1$), then electricity measurement errors in the above cases are: $\delta_A = -50$ %, $\delta_B = -50$ %, $\delta_C = -50$ %.

During no-load operation of power transformer (inductive type of load at $\cos\varphi = 0{,}17$; $\varphi = 80^\circ$) the active power, measured by the first meter element is

$$P_1 = 100 \cdot 1 \cdot \cos 110^\circ = -34 \text{ W},$$

by the second meter element

$$P_2 = 100 \cdot 1 \cdot 0.64 = 64 \text{ W}.$$

Active power, measured by the meter, will be

$$P = 64 - 34 = 30 \text{ W}.$$

In this mode with U_C voltage absence due to VT fuse blowing or secondary circuit failure, a meter disc will rotate in the opposite direction, distorting the measurement results.

According to standard guidelines on electric power metering [34], it is recommended to apply three-element meters. The connection diagram for these meters (Fig. 7.10) provides their operation, according to the accuracy class, in different conditions of the system. Connection of earthed phase B to the middle element provides an opportunity to install the direct voltage phase sequence and test the connection diagrams.

Active power, measured by a metering device,

$$P_1 = U_A \cdot I_A \cdot \cos\varphi_1 + U_B \cdot I_B \cdot \cos\varphi_2 + U_C \cdot I_C \cdot \cos\varphi_3.$$

Besides, it is required to check the compliance of measuring CT and VT transformation factors, specified on the plates, with their certification data and, finally, the meter error.

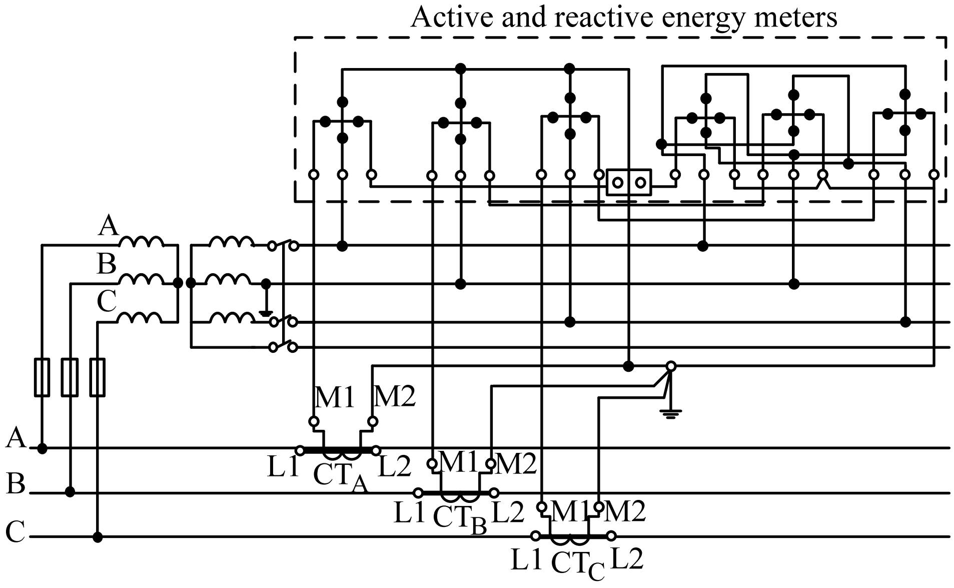


Fig. 7.10. Circuit of three-element active and reactive energy meters connection in the four-wire system with three CT and VT earthed B-phase. Direct sequence of ABC phases is obligatory (voltage circuits of electronic meters are conventional)

Based on these data analysis, a conclusion on correctness of connection diagrams and preliminary conclusion on electricity measurement reliability are made.

Vector and wiring diagrams for three-element meter measurement is shown in Fig. 7.11.

To prevent mistakes in meter connection diagram, it is required to specify the direction of active and reactive power of the tested connection with the power-system operator and by switchboard instrumentation indications at the substation before testing.

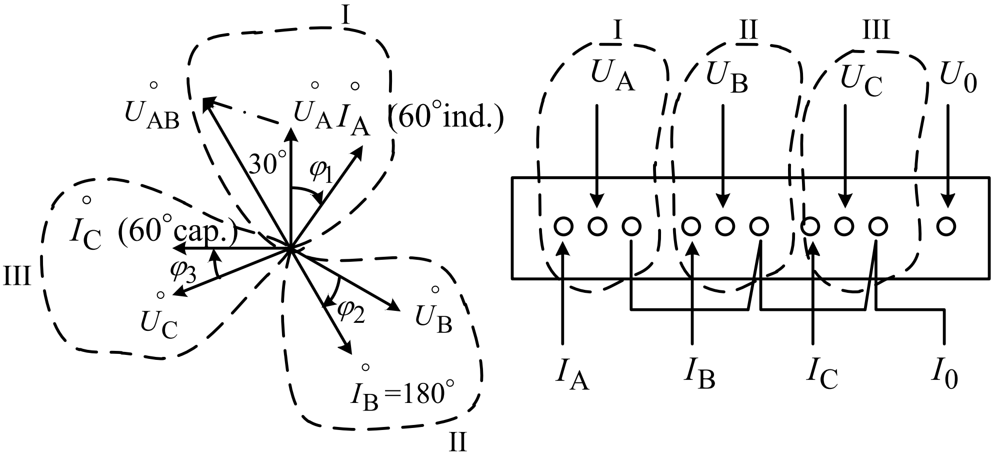
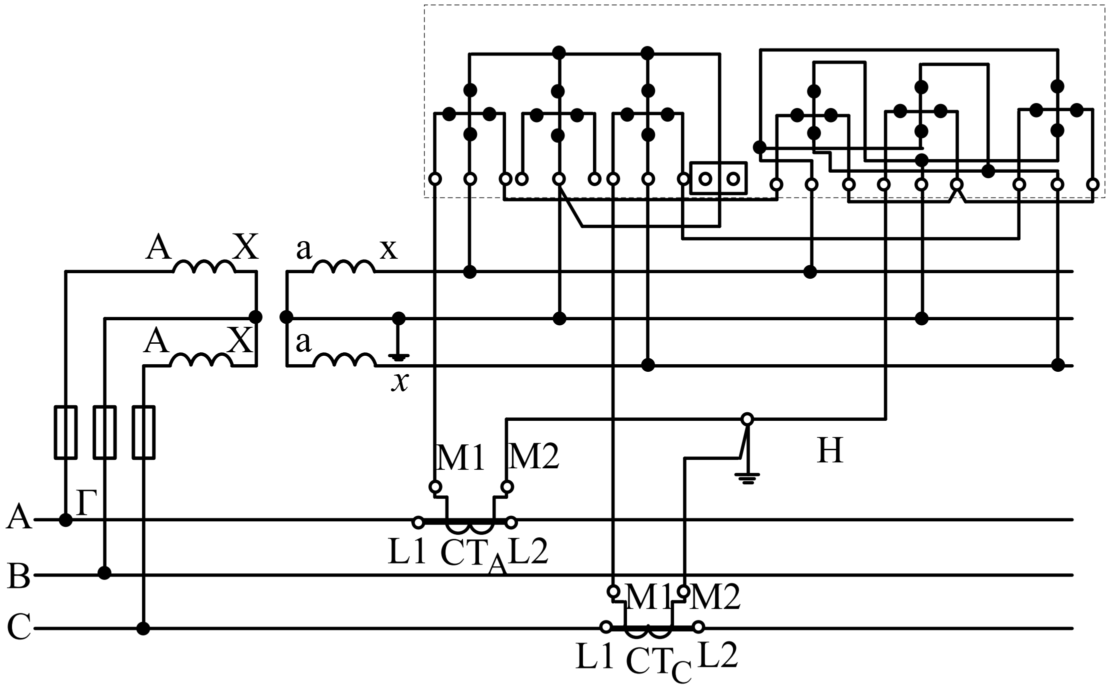


Fig. 7.11. Vector and wiring diagrams for electricity registration by three-element meter

Despite that, when connecting a meter (connecting wires to the meter), a mistake can be made. For example, an additional phase shift, differing from the actual one by 60°, can be made.

Connection of three-element electronic meters in the circuit with two CT is done in two ways:

1. Installation of an external jumper on the terminal block between voltage terminal of the middle element and general terminal of the meter (Fig. 7.12).



Active and reactive energy meters

Fig. 7.12. Circuit diagram of active energy meter connection and three-element reactive energy meter connection in the three-wire system with two measuring CT and VT. Direct sequence of ABC phases is obligatory

The first and third metering elements are transformed to phase-to-phase voltage U_{AB} and U_{CB} by this jumper. It should be mentioned that such jumper installation is allowed not for all types of three-element meters.

2. Connection of the middle meter element current circuit for the sum of A and B phases current with reverse polarity (Fig. 7.13).

To provide the required accuracy of electricity metering, it is necessary to adhere to PUE requirements (Regulations for Electrical Installations) [35], standard instructions for electricity accounting [34], methods for electricity metering [36], regulations and standards of accounting devices application [37–41] and other.

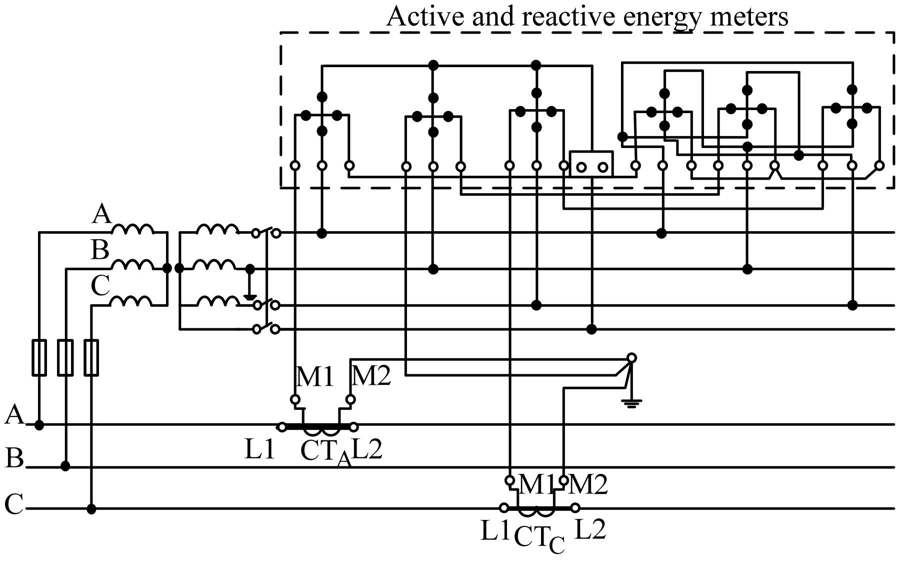


Fig. 7.13. Circuit diagram of three-element active and reactive energy meters connection in four-wire system with two CT. Direct sequence of ABC phases is obligatory (voltage circuits of electronic meters are shown conventionally)

According to requirements of Standard guidelines for EE metering during its generation, transmission and distribution, the EE metering system should be protected against electromagnetic fields effect (more than established by specifications for elements), mechanical damage and unauthorized access.

Every meter should have two types of seals: manufacturer seal on enclosure fitting (seal of verifying organization), forbidding the access inside a meter mechanism and seal of energy-selling organization on cover of terminal block, forbidding the access to incoming and outgoing terminals.

Energy-supplying organization should seal the CT terminal boxes, change-over box terminals, where circuits to electricity meters are, current circuits of meters in case when measuring instruments and protection devices are connected together with meters to CT; testing terminal boxes with shunt terminals for CT secondary winding and connections of voltage circuits during meter shutoff for replacement or verification; protective screen and doors of chambers, where meters, fuses on low and high voltage side of VT, to which meters are connected; fittings on handles of VT disconnector drives, to which meters are connected.

CHAPTER 8. GENERAL INFORMATION ABOUT COMMERCIAL RELATIONS MANAGEMENT IN THE OREM MARKET

New energy policy of the State implements the controlled energy market concept.

Main directions of the energy policy are developed by the RF Government and approved by the President's Decree No. 472 dated 07.05.95. According to the Decree, the Federal target program "Fuel and Energy" was developed and approved by the Government.

8.1. Wholesale market of EE and power (OREM)

OREM peculiarities, which make it different from other markets, are continuity of operation and irregular schedule of power and electricity supply, depending on the consumers to a considerable degree. This irregularity is defined by life cycles of the society functioning and has the following periods: 24 hours, a week, a month and a year.

The OREM market, where wholesale electricity suppliers and consumers interact, usually deals with high and ultra-high voltage. EE suppliers also deal with major industrial (final) consumers at the OREM, which are supplied by such systems.

Commercial relations between OREM entities are regulated by:

- ✓ long- and medium-term bilateral agreements for electricity and power supply (receiving);
- ✓ short-term operating agreements (bilateral and multilateral), concluded under guidance of the OREM operators.

Types of electric power and energy supply vary quite widely. Along with that they can be classified by the following main categories:

- ✓ According to a kind of the supplied "goods":
  - – Power supply;
  - – Electricity and corresponding power supply;
- ✓ According to the purpose of delivery for EC-buyer – additional (balance, deficit), cost-effective;
- ✓ According to the reliability (readiness) of supply – guaranteed (firm), non-firm (possible for cancellation at the supplier initiative).

Power supply (without accompanying energy) mean delivery of backup operating power, which can be sold if necessary during a specific period (within 10 or 30 minutes).

Supply of electricity and respective power stipulate for payment for both electricity and power, received by a consumer.

Balance (deficit, additional) delivery of electric power and electricity is performed when buyer has a shortage of power and/or electricity and it is fraught with limitation of consumers.

Economy supplies of electric power and electricity can be performed in case, when a buyer, capable to provide a power and electricity balance by their own energy system, purchases a cheaper power and/or electricity from the neighbouring EC and unloads their own equipment.

Delivery, providing a specific reliability level due to reservation of generating equipment by an EC seller, is called firm. According to agreements, a different degree of "firmness" can be provided, depending on the situation in delivering and receiving EES and industry in general.

8.2. OREM Agreements

Speaking of commercial relations at the OREM, two groups of participating entities should be differentiated: manufacturers–producers (EC, IPP) and final consumers of electricity; businessmen–traders, brokers, wholesale buyers of electricity.

Load schedules of final consumers are specified and forecasted with a quite high accuracy, allowing consumers to plan their strategy in the market.

Structure of electricity supply agreement is free, but its text shall comply with the trade and commercial legislation of the country.

Bilateral agreements are usually long-term (for a season and longer), as both parties (producers and consumers) are interested in the steady long-term relations.

Many of the bilateral agreements can be based on exchange market prices and on operating market prices, giving an opportunity for a market entity to protect itself against risk by concluding agreements at the futures (long-term) market. Firm Electricity Supply Agreements is the agreement, in which a level of power to be supplied is fixed. Such agreements are concluded mainly for covering a basic load. Some agreements for firm power delivery can be used for provision of the required load schedule or, on the contrary, one agreement can include different power values for different time periods.

Electricity Supply Agreement is determined by the following factors: fixed value of electricity, supply duration, and the maximum (minimum) power value. In accordance with this agreement, consumers can use electricity at their own discretion within stipulated range; however, the agreed electricity amount shall be taken by the consumer. Its implementation plan and the dates of agreeing are also specified in the agreement.

Financial agreements for EE supply, which are concluded for different future time periods, are called futures. Basic agreements are concluded for the basic power (for a week), day-time and night power. Two OREM entities conclude an agreement for the future to smooth the price difference, which can arise in the market. Different futures agreements can be combined in more complex blocks. Besides risk smoothing, futures trading helps to stabilize the electricity prices.

Agreement of “Take and Pay” type means that consumer can receive electric power and energy by free schedule. The payment will be according to the agreed tariff. This type of agreement can be used in combination with other agreements, but consumer has the right to work only by one such agreement in every time period. Using this type of agreement allows a consumer to enter the OREM in the easiest manner.

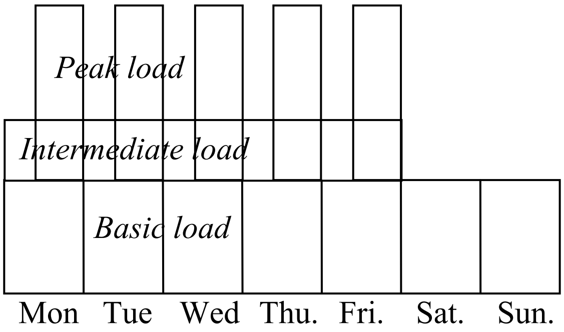


Fig. 8.1. An idealized consumer load diagram

Usually a consumer weekly load diagram is considered a model (Fig. 8.1), where three zones are differentiated: basic load – constant load during all seven days of the week; peak load – from 7:00 till 22:00 during five working days per week (from Monday till Friday); intermediate load – from 22:00 till 7:00 during five working days and twenty-four-hour from 00:00 till 24:00 during holidays and weekends.

According to the OREM rules, every consumer can provide covering of his load schedule, using agreement portfolio. Thus, for example, in the given case (Fig. 8.1) a consumer can solve problems by concluding three agreements (not necessarily with the same supplier of electricity): for basic EE supply, for peak power supply and accompanying EE, for covering of the intermediate part of the diagram. It is convenient to use “Take and pay” agreement exactly for such situation. Electricity supply under such agreement is not related to certain load diagram points: consumer can take the required EE at any moment. Only its effect duration is provided for in the agreement (1 week, 2 weeks, etc.), cost and total EE amount to be supplied. Here the consumer should choose the OREM entity, i. e. EE supplier.

Agreement portfolio. If consumer’s load is quite high, it can be feasible to purchase EE by several agreements. Portfolio usually consists of one or several agreements for firm power supply and one agreement like “Take and pay". The first two agreements cover need for the basic load, and the latter – in the most indefinite, peak load. Such portfolio can be called passive, because consumer, having signed the agreements, can stop worrying further about future.

Major consumers often add to the above-stated "portfolio" an agreement for electricity supply to have some flexibility in their consumption management. Having an electricity supply agreement, a consumer can choose in some cases, by which out of two agreements (electricity supply or "Take and pay") it is more profitable to get electricity at the OREM market. It is natural that consumers should demonstrate some activity, i. e. watch the OREM prices and regularly inform the EE producer of their plans. Such agreement portfolio is called "active".

Consumers can also buy all electricity by market prices at the exchange and use futures and alternative agreements to protect themselves against risks. All of it allows a consumer to avoid abrupt price fluctuations and consume electricity at a steady price.

Wholesale buyer of EE, supplying it to several (many) consumers, should develop a summary load diagram, similar to the one given in Fig. 8.1. It gives an OREM entity (reseller, broker) opportunity to get an additional effect due to load schedule leveling.

Various ES, differing by operating conditions, can be electricity suppliers at the OREM:

✓ NPP, operating mainly in the basic part of diagram (first of all it refers to domestic NPP);

✓ HPP, capable and sometimes forced to operate in the basic, peak and intermediate modes;

✓ Various TPP, designed for basic load and peak covering.

Agreements, concluded at the OREM, significantly differ in duration. The longest of them, concluded for 10–30 years, are defined by future development plans of EC or the State and related to construction of major ES and electric grids.

Agreements for one or two years are concluded between the OREM entities during development of integrated plans for energy resources use. Agreements, concluded for shorter periods, can be conditioned by emergency maintenance of the main energy equipment and other reasons, having a considerable impact on power and electricity and the existing OREM entities. Agreements are concluded by means of bilateral negotiations, in which every owner of the electric grid participates, if necessary, or by means of the energy exchange.

Long-term agreements, referring to the firm supply, are concluded for a period about 10 years. Such agreements are provided for when EC-buyer counts on the long-run use of new ES capacity, which is commissioned by EC-seller. Annual payment here is based on the necessity to reimburse the costs for ES construction (considering operating power backup) and power transmission lines, by which electricity is transmitted. Here, costs for maintenance and operation of respective energy equipment and transmission lines are also accounted.

Agreements for a limited time period, usually applied for 6–12 months, are meant to eliminate difficulties, caused by seasonal reasons or delay in new equipment commissioning. Payment for power supply under such agreement also provides for some costs compensation to EC-seller for ES and power lines construction. Electricity cost under this agreement provides for a payment at the cost price (maintenance, repairs, electricity losses, taxes, fuel, etc.) plus 10–15 %.

Seasonal electricity supplies are profitable for neighboring EC, the maximum loads of which do not coincide in time.

Short-term supply is provided for one or several weeks or longer, and is usually applied for elimination of forecasted power deficit, related to equipment service maintenance. In this case, power supply is paid at the price, which is a partial compensation to EC-seller for electrical plants and power lines construction without power backup. Electricity is supplied at the cost price plus 10 %.

Supply, performed according to agreement between system dispatch operators for a short period (about 1 hour), and is paid for in a similar way.

Emergency supply, caused by emergency failure in the EES, either paid by the cost price, possibly with markup about 10 %, or mutually compensated.

Along with the above stated power supply in energy consolidations, an economic electricity exchange is in practice. This category includes supplies for a short period, promptly coordinated by system operators, when one of EC or EI assumes the purchase of some electricity amount to be more profitable than its production at their own less-efficient ES.

During economic exchange the supplier is usually paid the cost price of supplied electricity and plus half of economic effect, obtained from intersystem electricity supplies, which is found by difference of electricity cost price during exchange (considering the electricity losses in the intersystem power lines).

If exchange of electricity and power is done by two EC via the system of the third EC, its share in profit is also stipulated.

8.3. Electrical energy market structure analysis

There are the following forms of the energy supply sector arrangement:

1. **Monopoly** is a vertically integrated model, where only one company provides the electricity generation, transmission and distribution, and it is responsible for a reliable electricity supply of consumers in the specific territory.
2. **A single-buyer model** is based on the competition among electricity suppliers and monopoly for its transmission and distribution provided that competitive market is controlled by an independent system operator.
3. **Competitive wholesale market model** is based on a free access to the main system and competition among electric power producers;
4. **Competitive retail market model** is based on competition among producers and free access of all buyers to suppliers.
5. **Competitive wholesale model** is based on a free access to the main system and competition in the area of electricity generation with partial monopoly of distribution power companies and (or) energy resellers to final consumers in the specific territory.
6. **Competitive retail model** is based on competition in the generation area and free access of all consumers to electricity suppliers.

It should be mentioned that competition is possible and urgent in the area of electricity production; however, there is no unanimous option regarding the issues of actual competitive market sale.

When monopoly is at all levels, competition among electricity producers is absent, and consumers have no right of choosing them. EE production and delivery along the transmission system to distribution EC (if available), or to final consumers, are concentrated and controlled by one energy company, which is entrusted with these responsibilities. Such vertically integrated organization allows development of large-scale transmission systems and construction of major power stations by establishing the economic advantages, and that was a convincing argument for benefit of this model for a long time.

A single-buyer model is based on the statement that market relations solely cannot provide satisfaction of economic interests of all parties to electricity production, transmission and distribution. Therefore, necessity in the state control over energy system functioning and development arises. This model (Fig. 8.2) operates in conditions when there is only one buyer in the market and several generating companies, which compete for electricity and power supply. A parallel free market remains limited and cannot influence on a single buyer's concept objectives that need to be settled.

According to the competitive wholesale market model, distribution power companies, which trade in retail, buy EE directly from producers and deliver it through transmission system to consumers. Competition has an opportunity to expand because all producers can sell EE to multiple consumers.

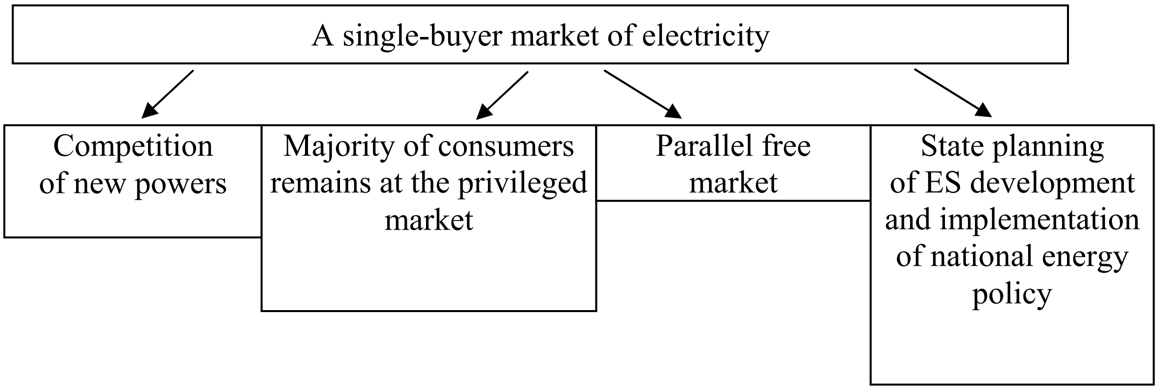


Fig. 8.2. A single-buyer model

In the models of free access to the system (Fig. 8.3) producers compete in respect of final EE consumers. They are independent in their decision-making on investment projects and can directly supply final consumers, using general-purpose transmission lines, which remain a natural monopoly. Thus, this model works best when market operators have neither engineering, nor organizational limitations on direct agreements conclusion, i. e. the systems are available and the access is free.

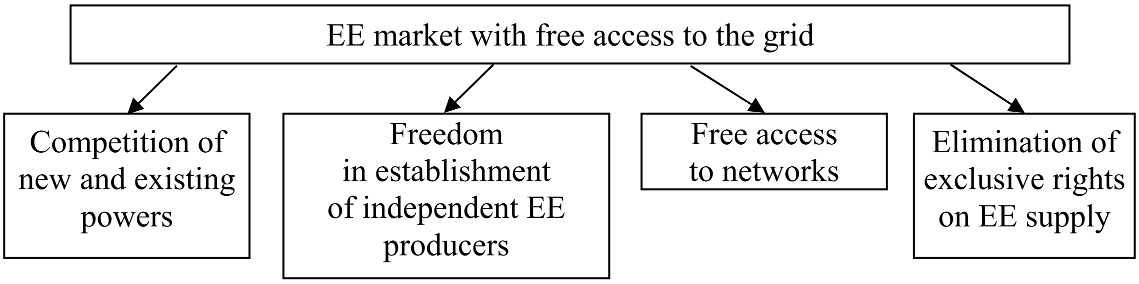


Fig. 8.3. Model of free access to the system

Imminence of market relations development in the power engineering industry of Russia is determined by the following reasons:

✓ Change of external economic conditions in respect of energy industry;

✓ Imminence of industry participating as a consumer at the established energy markets of fuel, equipment and services;

✓ Availability of quite rigid industrial relations as an EE supplier with consumer industries, already operating on the basis of market relations;

✓ Necessity of EI departments subordination to general public laws on market relations establishment;

✓ Necessity to review the conception of electric power engineering industry as a natural monopoly.

Effectiveness of ongoing reorganization is directly related to economic and energy security of the country and its regions, and shall be based on maintaining the engineering integrity of unique UES. Favorable conditions, providing competition of market entities, are established and developed along with the expected increase of electricity supply reliability to consumers, and reduction of EE production and distribution costs. Generalized structure of the existing wholesale electricity and power market is given in Fig. 8.4.

Changes, occurring in the power industry management and control during the last decade, are aimed at reduction of monopolism level in the industry with some reduction of state control over prices, tariffs, subsidies and investments.

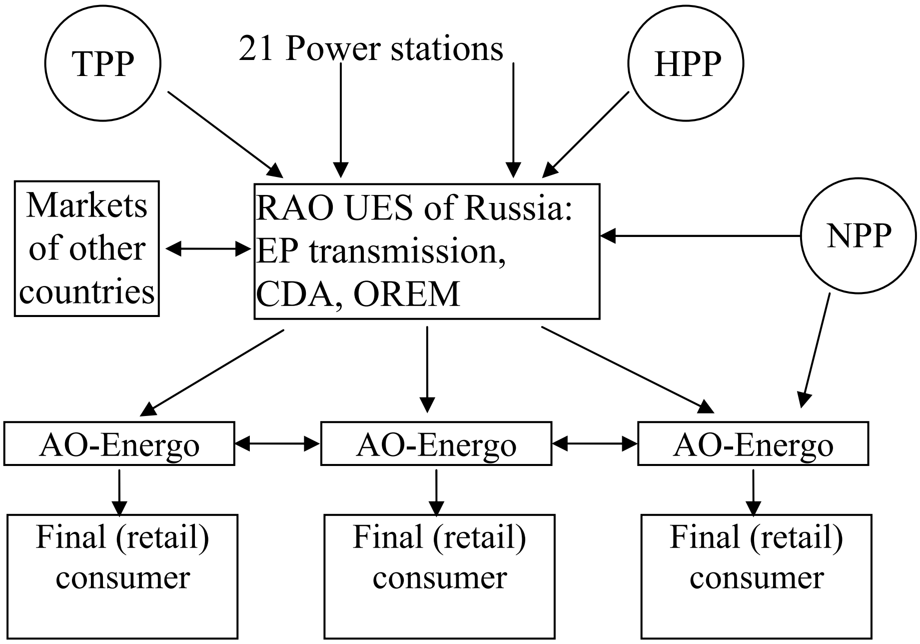


Fig. 8.4. A simplified OREM structure

Structural changes are described mainly by production separation from transportation, sale distribution when providing guarantee of a free access to transportation systems of all independent electricity producers. A simplified general diagram of electric power engineering industry, showing changes, typical for transition to market relations, is given in Fig. 8.5.

A traditional EES does not depend on economic structure (public of private property): it is completely integratable and controlled.

As it is shown in Fig. 8.6, Company A provides all services to consumers. It possesses the generating capacities, transmission and distribution systems. When integrated EES is available (for example, Company B in Fig. 8.6), electricity exchange is performed on the basis of long – and short-term agreements. Essentially, structure of Fig. 8.6 develops the diagram, presented in Fig. 8.5, *a*.

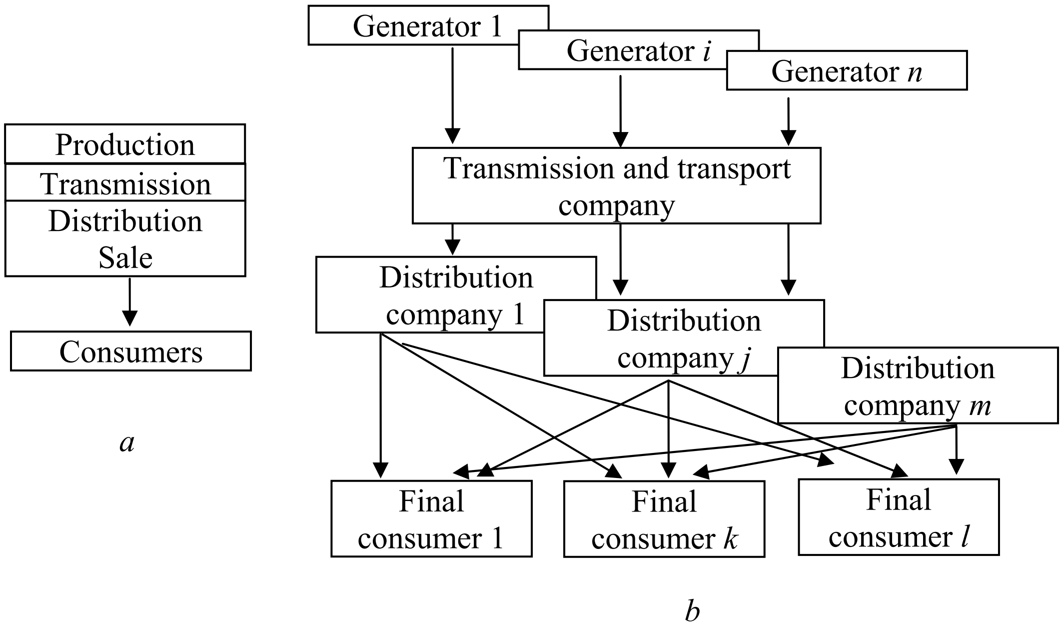


Fig. 8.5. An enlarged simplified diagram of electric power industry restructuration: prior to (a) and after (b) reforming

A future transition diagram in Fig. 8.7 includes two new components: independent generating companies (not utility generators); direct supply of some consumers of utility companies B or independent companies by utility companies A. Electrical energy utility system A will try to operate according to the integration principle, but some of its consumers will buy electricity from other companies. The company, consumers and controllers will attempt to coordinate their relations and costs during this period. Electrical energy utility system B and independent electricity-supplying companies can rent transmission lines from Company A or organize electricity supply in a different way.

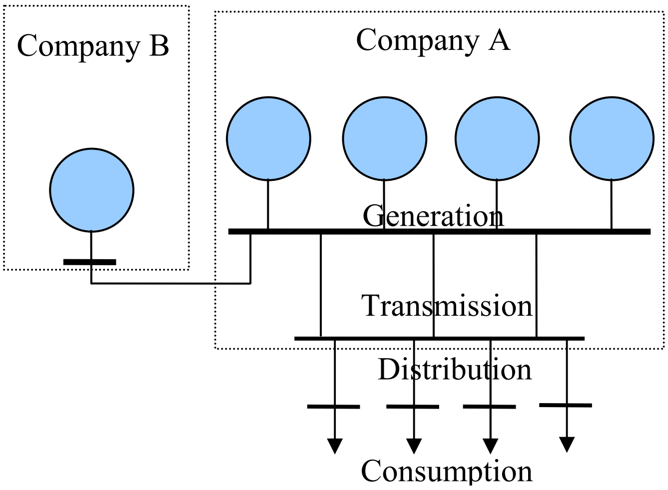


Fig. 8.6. Traditional structure of a completely integrated system of companies electricity supply

Unlinked structure of EES without state control is similar to the diagram, given in Fig. 8.5, *b*. All generating sources do not depend on transmission companies. Companies, producing EE, sell it through network companies to distributing companies and consumers.

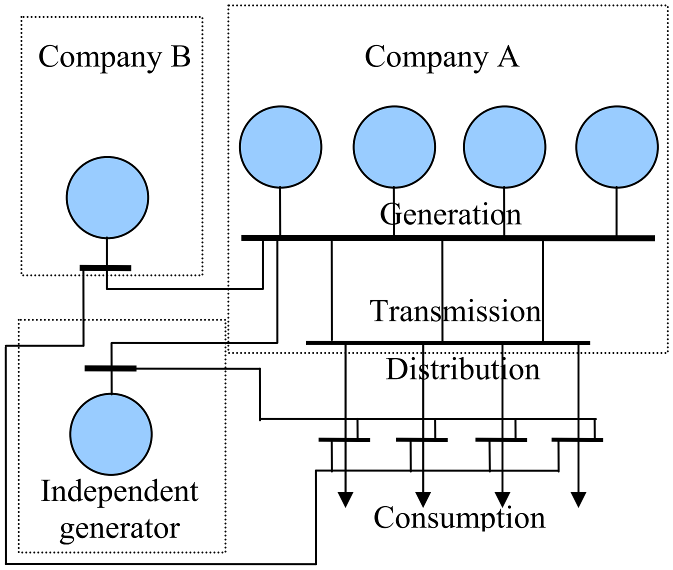


Fig. 8.7. Transitional structure of electricity supplying companies

A network company is the market where flexible prices are set. Dispatch operators of these companies also decide, which electric plants shall operate to provide an economically efficient system. Distribution company gives in rent its transmission lines for EE transmission, buys it for selling to consumers and provides other services.

Strategy of current reforms in the electric power engineering industry includes:

1. Functional division of the industry, based on subsystems of EP production, transportation, distribution and sale with a guarantee on the State's part of fair participation of all power enterprises in these activities;
2. Gradual deregulation of electric power industry with elimination or weakening of the state control by replacing it with competition elements both in the wholesale, and retail level.

Functional division is reached by restructuring programs and privatization of the sector with establishment of competitive power companies and approximately equal starting conditions for them. Management efficiency is improved here by newly established structures. Along with that, competition elements are to be implemented at the stages of electricity production and sale, as possible duplication of capital investments in different voltage systems construction is deemed unfeasible. Optimization of investment process is expected due to wider opportunities of attracting private and foreign capital.

Competition among generating sources refers to the OREM prerogatives and is implemented on the basis of contracting parties' freedom to conclude bilateral agreements either directly, or within the civilized market framework – an association of two or more interconnected energy systems, which concluded the agreement for activities (pools) coordination. The defining specifications for such competition origin and development are availability of generating capacities and free access of consumers to the electric grid, which should provide the required capacity for electricity and power supply and exchange. Sale competition is determined by a consumer's freedom to choose an EE supplier and refers to conditions of regional market functioning.

Analysis of market structures, existing in the world electric power industry, has shown that there are several variants of market relations models:

1. Centralized or monopolized model includes the dispatch and engineering process management of energy system modes and coordination of market entities development. An effect of electricity production cost reduction, as a result of regional AO-Energo joint work, is demonstrated in the most evident way. At the same time, it doesn't have stimulating mechanisms, aimed at profits maximization of market entities. Besides, it contains an opportunity to obtain an ungrounded profit by certain entities due to rigid centralized management.
2. Competitive model of centralized market (pool) – compulsory or voluntary, is based on competition among generating entities – competitive markets where the required volumes of goods are formed by producers first, demanding the minimum price for their goods. Peculiarity of competitive electric power markets functioning is their orientation to a competitive consumer, which is suggested different schemes of services, revised within relatively small time intervals.
3. Decentralized market model is based on the information about possible EE and power supply volumes, demand for them, capacity resources of system-forming and distribution networks, as well as about the maximum prices of supplied and purchased products.

Analyzed models of market relations demonstrate a vast diversity of research methods, using the game approaches. Different modifications of the maximum profit principle are preferred to costly criteria; and control measures consistency is the most important condition of market leverage steady effect in the power sector. Power companies have the exclusive rights for monopoly electricity supply to consumers in the specific territory practically in all countries. Electricity supply efficiency is increased by competition among fuel suppliers. For major consumers, having their own ES, limitations are implemented for the power, generated by them to the market. A developed structure of market relations provides for unconditional freedom in electricity supplier selection.

Despite the differences, every model includes the market relations entities, which are legal entities, performing purchase-sale of electricity and power and/or providing transit services, such as:

- ✓ Competing enterprises-producers (generating, mainly, private energy companies); independent private sources (mainly, block-stations);
- ✓ Private and municipal power distribution companies – electrical system enterprises;
- ✓ Enterprises, providing a connection of legal entities (national grid companies) and performing functions of the market operator;
- ✓ Private power companies, which do not own the sources and/or grids and resell electricity;
- ✓ Major enterprises-consumers of electricity and power, for which limiting indices are specified at the estimated time interval (industry, agriculture, transport, utility and consumers equated to them).

A company, representing the management chain on the basis of dispatch management bodies; performing operating and engineering process management of security, sustainability, cost-effectiveness, viability, reliability and EES modes; as well as accounting, analysis and development of commercial relations improvement measures among market entities; acts as the market operator. It should be mentioned that implementation of competition elements results in a significant increase of market entities number. It causes necessity to determine special groups of experts, involved in operating-commercial activity, forming the concept of the market commercial operator. The area of their activity is as follows:

- ✓ Organization of centralized operation of electricity and power market;
- ✓ Work on commercial documentation development;
- ✓ Execution of agreements and invoice billing for EE supply and process services;
- ✓ Control over payments;
- ✓ Suggestions on tariff policy forming.

Along with that, the activity of a market commercial operator should be related to work of dispatch management bodies, i. e. with process operator of the market.

Thus, an operator of electricity and power market performs functions of commercial and process operators, which can work jointly as departments of one company or separately.

The required condition for effective functioning of electricity market operator is provision of their independence. It is in opportunity of making decisions on the load of generating sources, based only on the minimum declared price and process requirements to operating conditions and/or provision of consumers with free access to transportation system. Independence of the market operator is usually provided by functional division of the industry and operator binding to the national grid company in the world electric power engineering industry.

The element of market relations control is the state licensing of electricity production, transmission activities and distribution services. Control over functioning and relations among market entities, development of tariffs in those areas, where competition is not defined, hindered or impossible, and also justification of payment amount to the market operator should be performed at the state level.

Control and coordination of economic relations among the OREM entities is performed by controlling committees. Their powers are quite wide and include issues of tariff approval with differentiation according to various parameters, control over the commissioned power units condition, and monitoring of consumer service quality.

Analysis of needs and consequences of management reorganization in the electric power industry allowed specifying a range of main problems:

✓ Selection of a model, compatible with specific nature of organizational, production and dispatch-process structure of energy sector;

✓ Functional division of industry;

✓ Establishment of energy pools;

✓ Establishment of independent system operators;

✓ Weakening of the state control;

✓ Control over prices and tariffs through limitation from the top;

✓ Establishment of competitive generation market;

✓ Allowing a consumer to select a supplier;

✓ Gradual establishment of competition conditions in the area of EE trading;

✓ Analysis of possible admittance of foreign investors in the national energy sector.

A technical aspect, related to operation of high-voltage transportation grids in the real-time mode, as well as power system dispatching, cannot influence on the dynamics of competitive market development. The following is required for its infrastructure establishing:

1. To fulfill the requirements, related to division of monopoly functions from the competitive block. EP transmission in the grid is considered a natural monopoly, while generation – the area of competitive relations.

2. To provide a free access of market participants to the power system. Tariff for EP transmission shall facilitate the EP free trade, but not limit it.

The tariff should be such that market entities could select partners freely and conclude trade deals.

3. To adjust the system of losses compensation. The owner is responsible for losses in the system, as they refer to electricity consumption by the system enterprise. Compensating volumes are bought in addition by network owner on the basis of bilateral agreements or the exchange. Cost of losses is compensated by tariff.

4. Solution of the problem, related to process limitations and system overload, is provided either by establishing special prices for different energy zones and regions, or using the EE barter method and mutual compensation of supplies, based on commercial offers from generating companies.

5. Balance closing between actual meter readings and contractual commitments for EE supply. To establish the market or introduce compensations, stimulating producers to maintain production capacity reserves.

6. Introduction of an independent system operator, managing the process of generating substations dispatch in the real-time mode, based on the offers from the physical delivery market.

Thus, electric power market should be an adaptive mechanism in the area of physical, financial and information flows management among the entities during balancing their interests, based on contractual relations, reliable technical and economic information and tooling.

CHAPTER 9. ENERGY COMPONENT OF CONSUMER BASKET FOR TOMSK REGION

Fuel and energy balance is formed by two constituents: energy, consumed for production of production means, and required for goods production. Volume of each constituent is unknown and can only be estimated approximately.

The method for calculation of consumer basket (CB) energy intensity allows for evaluating the energy input, required goods production (CB constituents), as well as energy input, required for auxiliary processes: heating, ventilation, processes forming in machine engineering, chemistry, petrochemistry and etc. Thereby energy CB acts as an indicator of electrical energy and fuel-energy resources use efficiency, as it reflects the work of all industrial sectors. Economically it developed in such way that energy efficiency is very low in Russia.

Assuming that at the stage of economy revival from crisis, an energy-intensity of material production in Russia will result in limitation of energy resources. Due to this fact an estimation of some average value of energy consumption by region's population can by of interest, for example, for Tomsk city or Tomsk region. Here the objective is not only limit the energy resources use, but also estimate the fuel-energy resources input per unit of produce. Energy consumption analysis allows for differentiated establishment of direct and indirect energy input for final product, as it does not depend on currency exchange rate, inflation, market conditions, prices for raw and materials.

9.1. Justification of CB data for calculation of energy demand per capita

To carry out an analysis of a person's energy demand, the main set of food products, indispensable-to-life things and housing-and-utility services should be considered. Statistical data of such kind are given in consumer basket, developed for basic social-demographic groups of population by the Government of the Russian Federation according to the Federal Law "On Subsistence Minimum Wage of the Russian Federation" [40, 41, 42].

According to definition [40], consumer basket is an estimated scope of products and other consumption articles, applied for analysis and evaluation, both as qualitative indicators of consumption and quantitative. It is usually calculated per capita or family and is of regional or structurally social nature.

Calculation of energy intensity of the minimum product and services set for every socially-demographic group of population is an elaborate and labor-consuming task. At the first stage it is reasonable to do such calculation for an “average” person with needs, corresponding to consumer basket data. In this case, doing calculations based on one person’s needs, we determine a “lower” boundary of energy consumer basket for the entire region.

9.2. Estimation of energy input, required for manufacture of CB product set

Method of total energy input summing for consumer basket components was used for energy consumption analysis. Analysis of direct and indirect input was done simultaneously. Advantage of this approach consists in that in conditions of strict limitation for energy resources production, it is a tool for purposeful specifying of proportions and volumes of energy resources consumption. Using this method, energy consumption for the region can be done and calculated threshold values for energy resources production, based on it. The method basis is evaluation of total energy input for consumption goods production, as in this case it is only possible to find energy inputs in the sector of consumption goods production, according to consumer basket data:

$$E_{\text{full}} = E_{\text{dir}} + E_{\text{indir}}. \tag{9.1}$$

Direct energy input E_{dir} includes energy consumption for production and consumption of ready-made produce. In this case this is input for successive processing stages, preceding the final product:

$$E_{\text{dir}} = \sum_{i=1}^{n} e_{ik} Z_k = \sum_{i=1}^{n} x_{ik}, \tag{9.2}$$

where $I = 1, 2, ..., n$ – number of processing stages of the k-th of consumer basket component; $k = 1, 2, \ldots, 26$ – amount of components, according to CB data; e_{ik} – specific energy consumption of the i-th processing stage in production of the k-th CB component; Z_k – volume of k component consumption (as per CB data).

Indirect input E_{indir} includes energy consumption for functioning and development of all adjacent productions by means of inter-industry relations system, involved for final product manufacture: water supply, heating, lighting, construction and maintenance of buildings and facilities:

$$E_{\text{indir}} = \sum_{j=1}^{n} a_{jk} Z_k = \sum_{j=1}^{n} x_{jk}, \tag{9.3}$$

where $j = 1, 2, \ldots, n$ – number of inter-industry relations stages, participating in a final product processing and production process; a_{jk} – specific energy consumption of the j-th stage of inter-industry relations in production of k-th of CB component; Z_k – volume of consumption component k (as per CB data).

For evaluating the significance of energy intensity of each processing stage ($e_{ik}Z_k$, $a_{jk}Z_k$) in total amount of energy input, consumed for CB component (E_{full}) production, we calculate its actual share W_{ik} , using the formula

$$W_{1k} = \frac{x_{1k}}{\sum_{i=1}^{n} x_{ik} + \sum_{j=1}^{n} x_{jk}}; \quad W_{2k} = \frac{x_{2k}}{\sum_{i=1}^{n} x_{ik} + \sum_{j=1}^{n} x_{jk}}; \quad W_{nk} = \frac{x_{nk}}{\sum_{i=1}^{n} x_{ik} + \sum_{j=1}^{n} x_{jk}}, \tag{9.4}$$

where x_{1k}, x_{2k}, x_{nk} – energy intensity of the 1-st, 2-nd, n-th processing stage in production of k-th component of consumption volume Z_k; $\sum_{i=1}^{n} x_{ik} + \sum_{j=1}^{n} x_{jk} = E_{\text{full}}$ – total energy inputs for production of the k-th CB component.

With account for accumulation, ordered series can be presented as a distribution function [43].

$$\begin{gathered} F\left(W_{1k}\right) = \frac{x_{1k}}{E_{\text{full}}}; \quad F\left(W_{1k} + W_{2k}\right) = \frac{\sum_{i=1}^{2} x_{1k}}{E_{\text{full}}}; \\ F\left(\sum_{i=1}^{2} W_{ik}\right) = \frac{\sum_{i=1}^{n} x_{1k}}{E_{\text{full}}} = \frac{E_{\text{full}}}{E_{\text{full}}} = 1. \end{gathered} \tag{9.5}$$

Distribution function analysis was done for level of significance level $\alpha = 0.05$ or probability $P = 0.95$, as taken for technical problem solution [43].

It is worth mentioning that other energy inputs are also partially accounted in all calculations, which take place in industry then producing means of production and are mainly formed in metallurgy, chemistry, petrochemistry and machine engineering. Other energy inputs are directed to provide the industry functioning and development. These are the energy inputs, which cannot be evaluated precisely and by expert estimation make 10–15 % from total energy input [43].

In below tables the most significant production processes are given from the point of their contribution to energy input value during each CB component creation. Energy intensity of production processes were calculated, found by inquiries sent to an enterprise and from reference sources [44–47]. As an example, in Table 9.1 are given actual energy resources inputs for bread production for all chain elements of a final product.

According to data in Table 9.1, an ordered series is developed, using which an actual value of energy consumption is found.

Table 9.1

Estimated electricity input for bread production
(for 115.4 kg of bread a year)

Name of process	X_{ik}, kgrf	W_{ik}, r. u.
Direct energy input		
1. Soil preparation	0.001	$2 \cdot 10^{-5}$
2. Seeding and crop tending	0.005	$9.86 \cdot 10^{-5}$
3. Harvesting	0.96	0.02
4. Equipment for final product manufacture	21.77	0.43
	$\mathbf{E_{pr} = 22.74}$	
Indirect energy input		
1. Ventilation	8.11	0.16
2. Lighting and heating	8.09	0.16
3. Construction of buildings, facilities	5.24	0.1
	$\mathbf{E_{indir} = 21.44}$	
Other energy inputs (0.15* E_{full})	$\mathbf{E^{*} = 6.63}$	0.13
	$\mathbf{E_{full} = 50.71}$	1

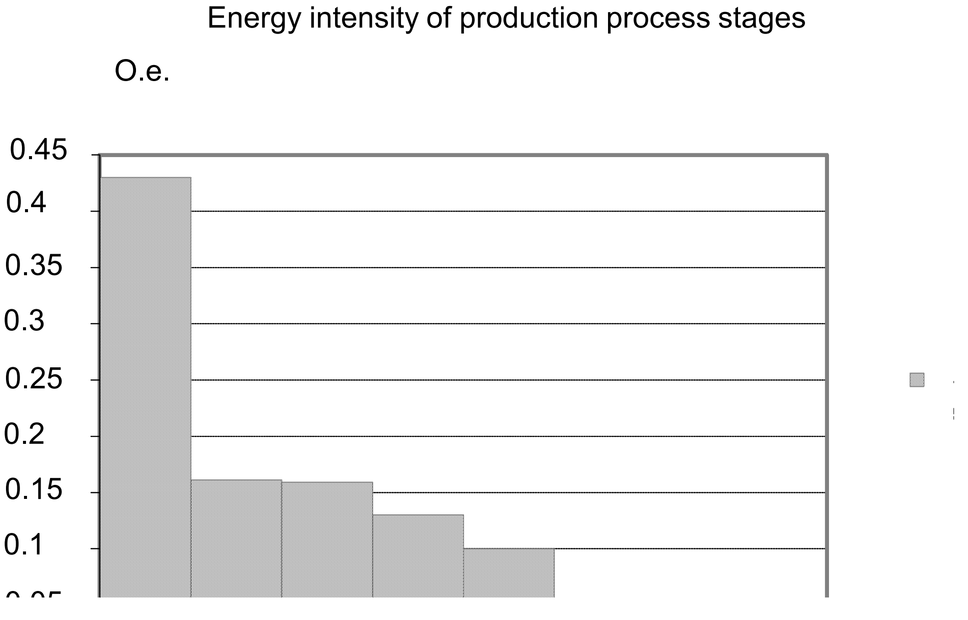


Fig. 9.1. Function of energy input distribution during bread production (production process stages are put in energy intensity decreasing order)

In Fig. 9.1, 9.2 are given functions of energy input distribution for components, taking part in bread production. Here the function of distribution probability F ($P = 0.95$) in Fig. 9.2 limits the insignificant processes, energy intensity of which does not usually exceed the allowable error value.

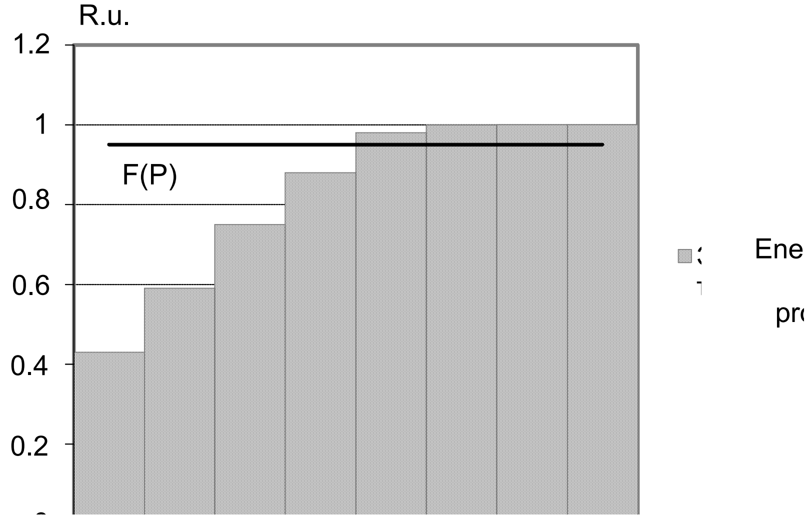


Fig. 9.2. Function of EE input distribution during bread production (energy intensity of production process stages are summed up) – by X axis we plot processes of the inter-industry relations chain, summed up in the order of energy volume decreasing (see Table 9.1)

A similar calculation is done for every of consumer basket constituents. The results are given in Table 9.2.

Table 9.2

Estimated electricity input for consumer basket goods production

Name of final product	Data according to CB	Actual total energy input, kg r.f. per year
Bread products (in terms of flour)	115.4 kg per year	50.71
Milk and dairy products (in terms of milk)	227.9 kg per year	271.98
Meat products	27.38 kg per year	1712.34
Potatoes	110.5 kg per year	14.80
Vegetables and melons	98.1 kg per year	13.10
Fresh fruit	23.8 kg per year	4.03
Sugar, confectionery (in ters of sugar)	21 kg per year	0.15
Fish products	13.2 kg per year	0.47
Eggs	141.8 pcs. per year	199.95
Vegetable oil, margarine and other fats	10.8 kg per year	0.46
Salt, tea, spices	4.2 kg per year	0.001
Outer coat group	3 pcs. per year	29.41
Outer suit-dress group	9 pcs. per year	89.06
Underwear	10 pcs. per year	98.96

Continuation of Table 9.2

Name of final product	Data according to CB	Actual total energy input, kgrf per year
Hosiery	6 pcs. per year	34.90
Headgear and smallwear	4 pcs. per year	23.26
Footwear	6 pcs. per year	2.39
Bed linen	14 pcs. per year	81.43
Articles of daily necessity and medications	61 pcs. per year	0.008
Cultural-general and households goods	19 pcs. per year	0.005
Housing	18 m^2	1720
Central heating	8 Gcal per year	1376
Cold and hot water supply and water disposal	275 l per day (100 375 l per year)	439.053
Gas supply	10 m^3 per month (120 m^3 per year)	164.4
Energy supply	54 kW · h per month (648 kW · h per year)	202.176
Transport services	619 trips per year	138
Total		**6692**

Evaluation of limit indicators of energy consumption can be done by summing up total energy input components of “consumer basket”. At level of significance $\alpha = 0.05$ the value of energy input per capita makes 6.7 trf.

Calculation of consumed energy resources by a municipality is done by means of a ratio

$$E_{\mathrm{M}} = E \cdot N, \tag{9.6}$$

where N – number of residents in the municipality.

For Tomsk region this value is 6708.240 thous. trf, while (according to FEB) the energy consumption value for the region is 7439.8 thous. trf.

Analysis of energy input along the entire chain of product manufacture allows evaluation of integrated influence of these or those processing or structural transformation in the regional economy. Thus, area of energy use analysis for region’s economy extends considerably, and also includes analysis of interterritorial and inter-industrial relations.

9.3. Variation of energy demand, depending on factors, effecting its value

The minimum food product sets, non-food goods and services for basic social-demographic population in the Russian Federation (RF) entities are recommended to form on the basis of the RF territory zoning depending on the factors, effecting the consumption peculiarities.

The RF territory zoning (to form a minimum set of consumer basket components) is founded on two basic factors: nature-climatic and economic conditions; social-demographic structure of regional population.

The RF entities are divided into 16 zones, depending on peculiarities of food product consumption, which are effected by nature-climatic and economic conditions, national and local tradition in meals of population, the established food structure with account for actual consumption of food products in low-income families, necessity to satisfy needs of basic social-demographic population in nutrients, based on chemical composition and caloric value of foods, as well as higher caloric value of the minimum foods set for basic social-demographic population, living in northern regions [40, 42].

Depending on consumption of non-foods and services, all RF entities are divided into 3 zones (Table 9.3, 9.4).

Table 9.3

Enlarged zoning of the RF territory depending on climate features of regions

Zone No.	I	II	III
Climate	Cold and sharply continental	Moderate	Warm
Representatives	the Komi Republic, the Republic of Sakha, the Tomsk region, the Tyumen region and etc.	the Republic of Mordovia, Tatarstan, the Moscow region, the Sverdlovsk region and etc.	the Republic of Adygeya, Dagestan, the Krasnodar region, the Rostov region and etc.

Let's consider influence of natural-climatic conditions on energy consumption value.

According to data of minimum consumer basket (MCB), a recommended minimum set of housing and utility services by zones in head is the following (Table 9.4) [42].

For a convenient comparison the housing and utility services are converted into reference fuel by means of conversion factors.

Proportion of electricity supply and central heating in total scope of services for every zone is given in Table 9.5.

According to data in Table 9.5, difference in proportion of electrical energy, required for illumination, cooking and other household needs per capita, living in different climatic zones, is insignificant. A wider variation is observed in heat energy values, required for residential premises heating.

Table 9.4

The minimum set of housing and utility services for the RF climatic zones per capita, kgrf

Service, kgrf	Consumption standard		
	Zone I	Zone II	Zone III
Housing	1720.2	1720.2	1720.2
Central heating	1376	1152.4	929
Cold and hot water supply and water disposal	439	457	472
Gas supply	164.4	164.4	164.4
Electricity supply	202.2	187.2	172.3
Total	**3900**	**3700**	**3500**

Table 9.5

Proportion of electricity supply and central heating from total housing and utility services

Name of service, %	Zone I	Zone II	Zone III
Electricity supply	5.2	5.1	5
Central heating	35.3	31.3	26.9

The next factor, defining a personal energy consumption value, is belonging to a specific social-demographic group, namely:

1) Able-to-work population (men, women);
2) Retire people;
3) Children (from 0 to 6 years, from 7 to 15 years).

This factor influences mainly on foods consumption and demand for non-food goods. Tomsk region refers to VII zone by features of foods consumption and to I zone by non-food goods.

Based on energy demand of a person, defined in previous section, it is possible to calculate energy consumer baskets (ECB) for every social-demographic group. Difference in energy demand of population depending on social status is relatively low (Table 9.6).

Data in Table 9.6 do not differ with common views of consumption, able to work population requires more energy to stay in a regular physical condition, the retired and small children – less by physiological reasons, children from seven to fifteen – consumption is higher as they grow and develop.

Table 9.6

Energy consumer baskets for social-demographic population, kgrf per capita a year

No.	Description	Able to work population		Retired	Children	
		Men	Women		0–6 years	7–15 years
1	Food part	2781.4	2261.1	1797.7	1791.5	2773
2	Non-food part	329.7	359.8	329.8	403	414.7
3	Housing and utility services	3900	3900	3900	3900	3900
	Total	**7011.1**	**6520.9**	**6027.5**	**6094.5**	**7087.7**

Number of people in every social-demographic group for the period of 1996–2002 is given in Table 9.7 [42].

Table 9.7

Number of people in every social-demographic group

Year	Men	Women	Retired	Children 0–6 years	Children 7–15 years	All population of region
1996	314 411	333 860	108 074	138 239	117 124	1 011 708
1997	315 638	336 507	108 840	127 720	119 602	1 008 307
1998	318 677	339 747	142 584	118 186	154 412	1 073 606
1999	322 308	344 997	141 454	110 101	153 352	1 072 212
2000	325 998	348 946	139 604	103 875	149 570	1 067 993
2001	328 734	353 287	138 299	99 928	144 561	1 064 809
2002	330 203	356 290	138 604	97 660	138 083	1 060 840

Statisitcs, given in Table 9.7, demonstrates that number of able to work population increased during the considered period (and number of women, able to work, is slightly higher than men), number of retired people increased, reduction of birth rate in the region shows decrease of children.

Averaged boundary by social-demographic factor looks as follows (Table 9.8):

Table 9.8

Averaged boundary for social structure of population per capita and in terms of all popultion in the region

	1996	1997	1998	1999	2000	2001	2002
ECB per capita, kgrf	6627.9	6634.3	6635.5	6640.4	6643.9	6645.1	6643.5
ECB for region's population, thous. trf	6705	6689	7124	7120	7096	7076	7048

Income level also provides influence on energy consumption rate. According to income level, all population is divided into 10 groups (see Table 9.9) [42].

Table 9.9

*Number of people in ten-percent groups, divided by income level, thous. persons**

Group	1	2	3	4	5	6	7	8	9	10
1996	1.3	0.9	421.1	285.5	167.2	139.3	41.3	18.3	2.4	0.7
1997	1	1.7	279.7	242.3	180.1	201.1	87.8	59.1	14.9	7.2
1998	1.4	0.9	275.8	256.3	188.7	203.2	82.3	50.1	10.9	4.1
1999	0.3	0.8	72.2	146.1	168.5	280.1	173.1	153.1	49.2	28.8
2000	0.2	1	23	72	109.1	241.4	198.5	234	102.4	86.4
2001	0.4	1.8	15.1	44.2	70.1	173.2	167.4	247.1	143.3	202.2
2002	1.4	2.6	4.1	16.1	30	103	124.6	233.2	173.2	372.6

*1 group – population with the lowest income; 10 group – population with the highest income.

From statistical reference books we know about structure of consumer expenses of population for every group [42]. Earlier, by means of MCB data processing, were estimated energy demand of average person, which is 6.7 trf and their distribution structure (services, foods and non-food goods). Recalculating known energy intensity to income level, we obtain structure of energy needs distribution, depending on 2002 income level, as follows (Fig. 9.3):

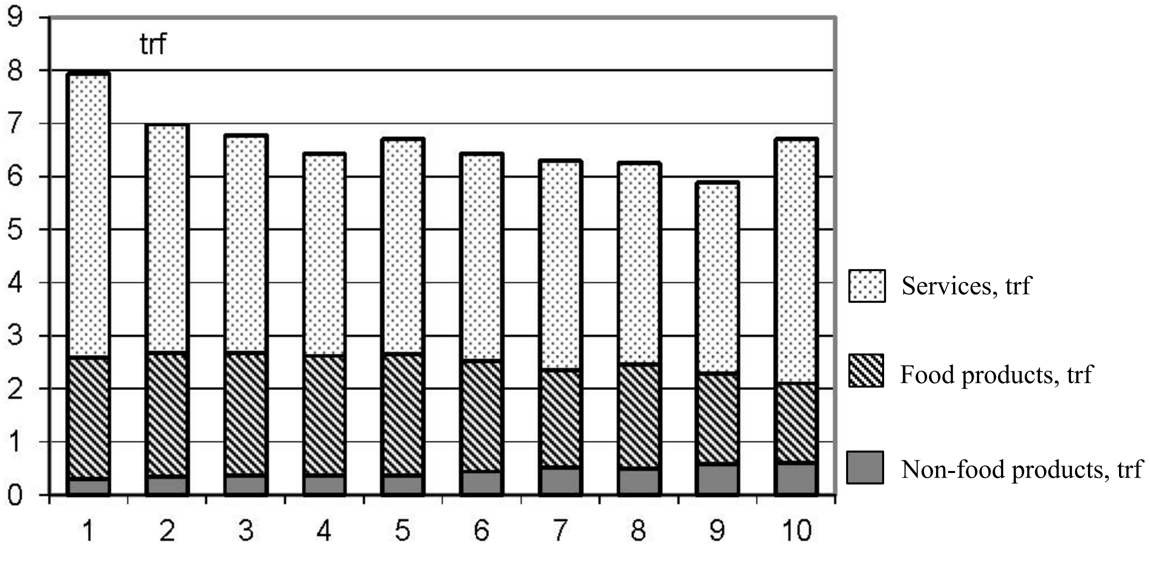


Fig. 9.3. Energy intensity of consumer basket for 10 % groups of population, reflecting each category proportion in total amount

Averaged boundary for Tomsk region population using income level factor is as follows (see Table 9.10):

Table 9.10

Averaged boundary for income level structure per capita and for entire region's population

	1996	1997	1998	1999	2000	2001	2002
Per capita, kgrf	6595.2	6537.4	6541.9	6430.1	6377.7	6368.7	6392.3
For population, thous. trf	6781	6781.4	6803.7	6894.4	7024	7027	7109.7

With income increase a person cannot consume more foods physiologically. The reason for this component decrease (Fig. 9.4) is that they can afford services and eating out.

Non-food proportion increase is natural (therefore, and energy intensity) for a person with high income. Expenses for housing and utility services are maximum for population with the lowest income, decreases for part of population with medium income and also grows with income increase (10 group). Due to this a curve of energy demand of population on income level has a shape of parabola (Fig. 9.4).

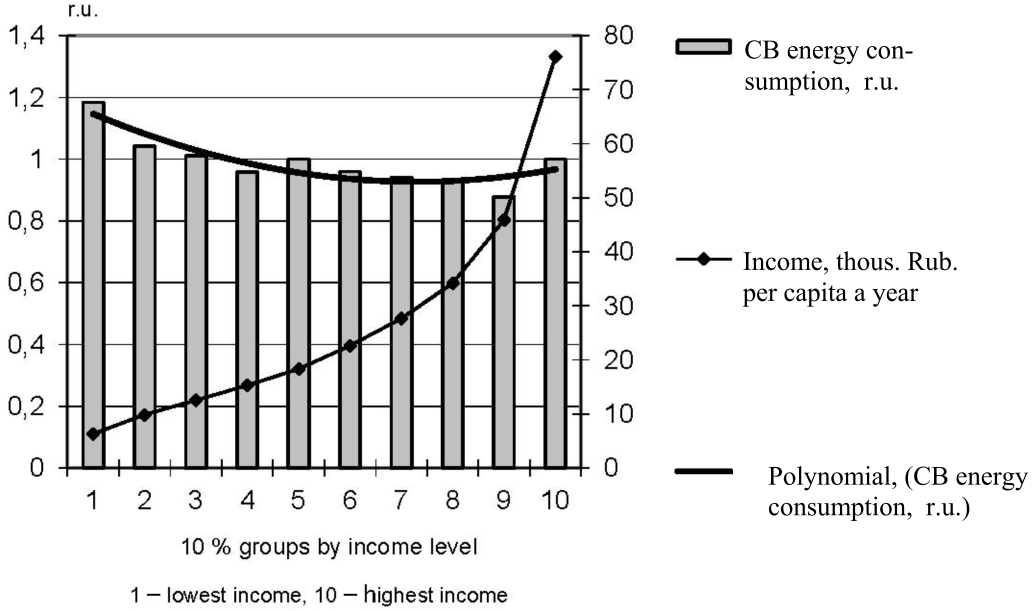


Fig. 9.4. Variation of energy consumption of population and income level

Data in Tables 9.8, 9.10 show variation of energy consumption by a person, depending on social-demographic group and income level. Distribution of boundaries is insignificant, and comparison with energy demand of an 'average person' allows defining boundaries of energy demand both per capita and for entire population of Tomsk region (Fig. 9.5).

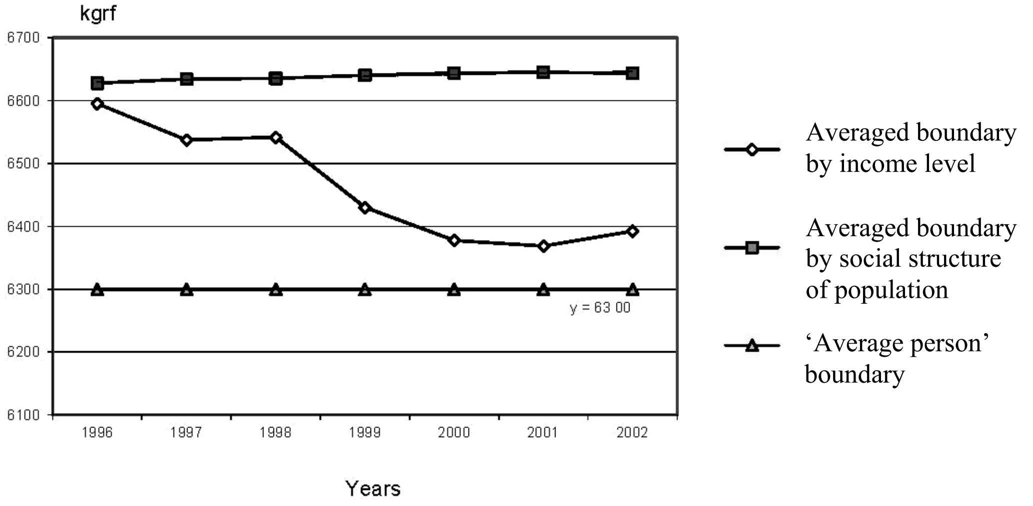


Fig. 9.5. Simultaneity of energy consumption boundaries, depending on the factors influencing its value, kgrf per capita a year

Considering demographic situation in Tomsk region, energy consumer basket for region's population acquires the following boundaries (Fig. 9.6).

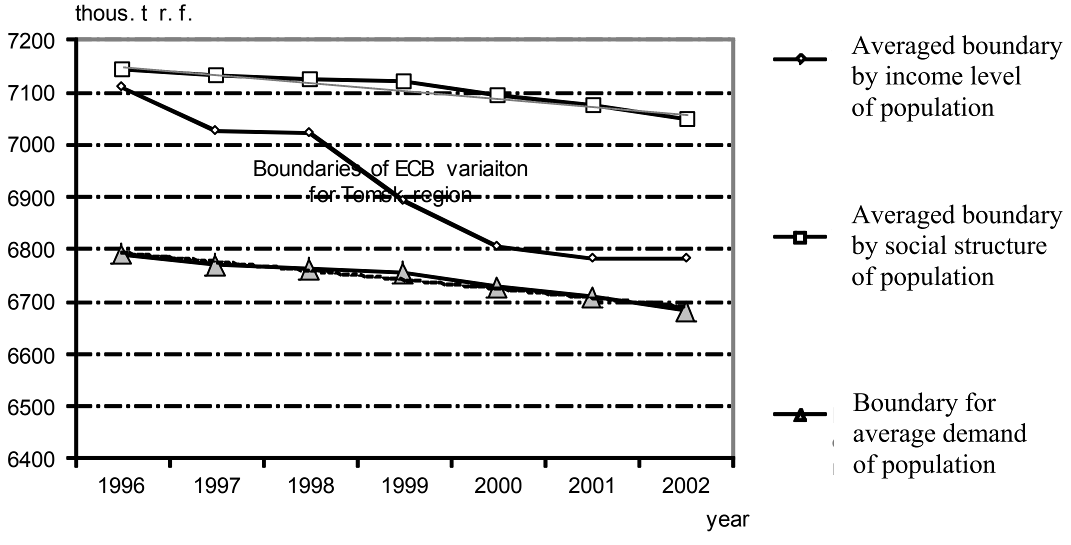


Fig. 9.6. Simultaneity of energy consumption boundaries, depending on the factors influencing its value, thous. trf for entire population of Tomsk region

The fact that energy CB boundaries, defined for the region, coincide with energy consumer basket (ECB) per capita, is conditioned by the dependence on demographic trends, namely:

1. Growth of total population, which is caused by migration increase, and then reduction, caused by birth rate decrease and death rate increase;
2. Increase of able-to-work proportion among population;

3. Decrease of children number in families;

4. Growth population income level, that effects change of people in ten-persent groups, classified by income level.

By energy-saving programs implementation in sectors, related to production and processing of food products, and thus reducing the energy content in product cost, and especially saving energy in housing and utility area, there is a real opportunity to, at least, stabilize the cost of minimum consumer basket, approved by the RF Government for basic social-demographic population, or fill it with a wider range of consumer goods.

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Annex 1

Table P 1.1

Example of efficiency calculation of seasonal shutoff of one operating transformer in a two-transformer substation (transformers operate to different buses) (to Chapter 6, item 6.1.2)

Number	Rated power S_R, kV·A	Current, A		Load factor, K_L	Number of hours, h		Power losses, kW		Energy losses, kW·h	
		Rated, I_R	Maximum operating, I_M		Maximum load, T	Maximum losses, τ	No-load, ΔP_{NL}	Short circuit, ΔP_{SC}	No-load, ΔW_{NL}	Short circuit, ΔW_{SC}
T = 8760 h										
1	100	144	110	0,76	6789	5650	0.6	2,4	5256	7915
2	100	144	85	0.59	6789	5650	0.6	2,4	5256	4720
T = 6760 h (transformers shutoff for summer)										
1	100	144	110	0.76	5540	4000	0.6	2.5	4056	5603
2	100	144	85	0.59	5540	4000	0.6	2.4	4056	3342
T = 2000 h (summer)										
1	100	144	53.3	0.37	1250	500	0.6	2.4	1200	164

As a result of the first transformer shut-off for summer, total EE losses decrease by 3512 kW·h, that in monetary equivalent at tariff T = 3 Rub./kW·h results in reduction of operating costs for 10 536 Rub.

Table P 1.2

Example of calculation of efficiency from low-loaded transformers replacement with transformers of a lower power

TS No.	Rated power of transformer, kV·A		No-load losses, kW		Short circuit losses, kW		Rated current, A		Max. current, I_M, A	Load factor		Number of hours of max. losses, h τ	Reduction of losses δA = Δ*W*1 – Δ*W*2, kW·h
	S_R1	S_R2	$\Delta P_{NL}1$	$\Delta P_{NL}2$	ΔPsc1	Δ*P*sc2	I_R1	I_R2		β1	β2		
1	2	3	4	5	6	7	8	9	10	11	12	13	14
51/1	320	250	1.6	0.82	6.07	3.7	462	361	185	0.4	0.51	5650	5339
51/1	320	250	1.6	0.82	6.07	3.7	462	361	150	0.32	0.41	5650	5111
59/1	320	100	1.6	0.365	6.07	1.97	462	144	85	0.184	0.59	5650	5664
59/2	320	100	1.6	0.365	6.07	1.97	462	144	100	0.216	0.7	5650	4522
60	320	250	1.6	0.82	6.07	3.7	462	361	225	0.487	0.62	4550	4600
66	320	250	1.6	0.82	6.07	3.7	462	361	190	0.411	0.53	2650	3278
116/1	180	100	1	0.365	4	1.97	260	144	110	0.423	0.764	5650	4331
116/2	180	100	1	0.365	4	1.97	260	144	85	0.327	0.59	5650	2848
													Total 35 693

For a feasibility analysis of these measures, a comparison of costs is required, needed for purchase of transformers of lower power, disassembly of previous transformers and assembly of new ones with the value, for which operational costs decrease, related to payment for electricity.

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