Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Economics, Management & Humanities

Comparison of methods for calculating parameters of a power supply system

Master’s Thesis

Study program: Electrical Engineering, Power Engineering & Management

Field of study: Management of Power Engineering and Electrotechnics

Scientific supervisor: Mgr. Sherzod Tashpulatov, M.A., Ph.D.

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Prague 2020

MASTER‘S THESIS ASSIGNMENT

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Department / Institute: **Department of Economics, Management and Humanities**

Study program: **Electrical Engineering, Power Engineering and Management**

Specialisation: **Management of Power Engineering and Electrotechnics**

II. Master’s thesis details

Master’s thesis title in English:

Comparison of methods for calculating parameters of a power supply system

Master’s thesis title in Czech:

Comparison of methods for calculating parameters of a power supply system

Guidelines:

1) Description of parameters of a power supply system
2) Computation methods of parameters of a power supply system
3) Modelling a power supply system using the ETAP software
4) Comparison of results obtained by different methods

Bibliography / sources:

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Date of master’s thesis assignment: **17.01.2020** Deadline for master's thesis submission: **22.05.2020**

Assignment valid until: **30.09.2021**

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Declaration:

I hereby declare that this master's thesis is the product of my own independent work and that I have clearly stated all information sources used in the thesis according to Methodological Instruction No. 1/2009 – "On maintaining ethical principles when working on a university final project, CTU in Prague."

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Abstract

This paper discusses two methods for calculating the parameters of a power supply system – paper based approach (PBA) and computer based approach (CBA). We study the load data of the metallurgical plant. PBA and CBA results are modeled in the ETAP software program. The output data from this program are the power losses in the transformer-line section and the voltage level after the transformers. These output data are needed for estimating the energy and economic efficiency based on the two approaches. Using power losses, the energy losses are found. Energy losses and equipment cost are used in the economic analysis of projects by NPV criterion. This paper can help to understand whether there is a significant difference in energy and economic efficiency following from the PBA and CBA results, and also how to improve and update the PBA.

Key words

Power supply system, paper based approach, computer based approach, Newton-Raphson method, net present value, profitability index, internal rate of return

Content

List of abbreviations

General abbreviations

AC	Alternative Current
CAPM	Capital Asset Pricing Model
CBA	Computer Based Approach
CNC	Computer Numerical Control
DC	Direct Current
DF	Duty Factor
ETAP	Electrical Power System Analysis Software
IDD	Input Distribution Device
MSDS	Main Step-Down Substation
PBA	Paper Based Approach
RAPFM	Rated Active Power Factor Method

Cable abbreviations

AAAC	All Aluminum Alloy Conductor
AAC	All Aluminum Conductor
AACSR	Aluminum Alloy Conductor Steel Reinforced
ACAR	Aluminum Conductor Alloy Reinforced
ACSR	Aluminum Conductor Steel Reinforced
EPR	Ethylene Propylene Rubber
MI	Mass Impregnated
MIND	Mass Impregnated Non-draining
PE	Polyethylene
PVC	Polyvinylchloride
XLPE	Cross-Linked Polyethylene

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1. Introduction

A power supply system is a network of electrical components designed for supply, transfer, and use of electric power. Main parameters of such systems are voltage, loads, overhead, and cable lines, transformers, switch-gears, and others.

Computation of parameters of a power supply system is the most important part in designing an electrical system. Assumptions and errors made at these designing stage can lead to critical consequences in the economic and electric segment of the project. They can lead to overstatement or understatement of the project cost, improper loading of transformers and cable lines, deterioration in the quality of electricity supply, lifetime reduction of electric equipment and elements of the power supply system.

The reason for making various assumptions at the stage of calculating the electrical load lies in the random, probabilistic nature of the load. Electric load cannot be perfectly predicted. Real load in the form of current or power does not remain unchanged during an hour or minute or even second. There are several computational methods which solve these problems differently: each of them makes assumptions depending on the type of load, the nature and accuracy of the calculation.

Each of these methods, nevertheless, has errors. In addition, most methods of calculating the load were developed in the end of the 20th century, and do not take into account both the nature of the change in the present load and the possibility of special software programs computing power supply systems. Before computing power increased, accurate calculations of complex electrical systems were practically impossible. Nowadays, various programs could provide very accurate estimations on the planned supply system without simplifying assumptions. However, manual documents indicate the need to apply methods developed in the late 20th century. Therefore, there is an actual problem of the difference between the estimations obtained using software and various calculation methods.

Based on these facts, we can establish two approaches for calculating parameters of a power supply system. The first method is a *paper based approach* (PBA), which is a combination of various historical and statistical methods. The second method is a *computer based approach* (CBA). There are a lot of software to design power supply of enterprises. One could use MATLAB, RastrWin, ETAP to get load flow data and analyze a power supply system.

We will analyze flow data using Electrical Power System Analysis Software (ETAP). Our results will be compared with results based on a paper based approach. Thus, the goal of the master’s thesis is to compare the economic efficiency for computer based and paper based approaches for calculating parameters of a power supply system. For this purpose, we first model a power supply system using a software package. Then, we optimize the simulated power supply system. Finally, comparative economic analysis of the data will be conducted.

Designing a power supply for industrial enterprises in Russia is based on norms of technological design from 1994 [1]. This document is not up to date due to reasons listed above. All industrial spheres anyway are influenced by this norms, but I will analyze power supply system for metallurgical plant. The share of the metallurgical industry in Russia's GDP is about 5%, in industrial production is about 18% and in exports is about 14% [2].

2. Parameters of a power supply system

In this chapter, we will give an overview of the power supply system starting from the medium voltage transmission line through the transformers into the low voltage switchboard. Figure 1 represents typical power supply system. It could have different parts after switchboard, for instance, sub distribution board, loads such as the pieces of machinery, lighting, heating, ventilation, air conditioning, and control panels.

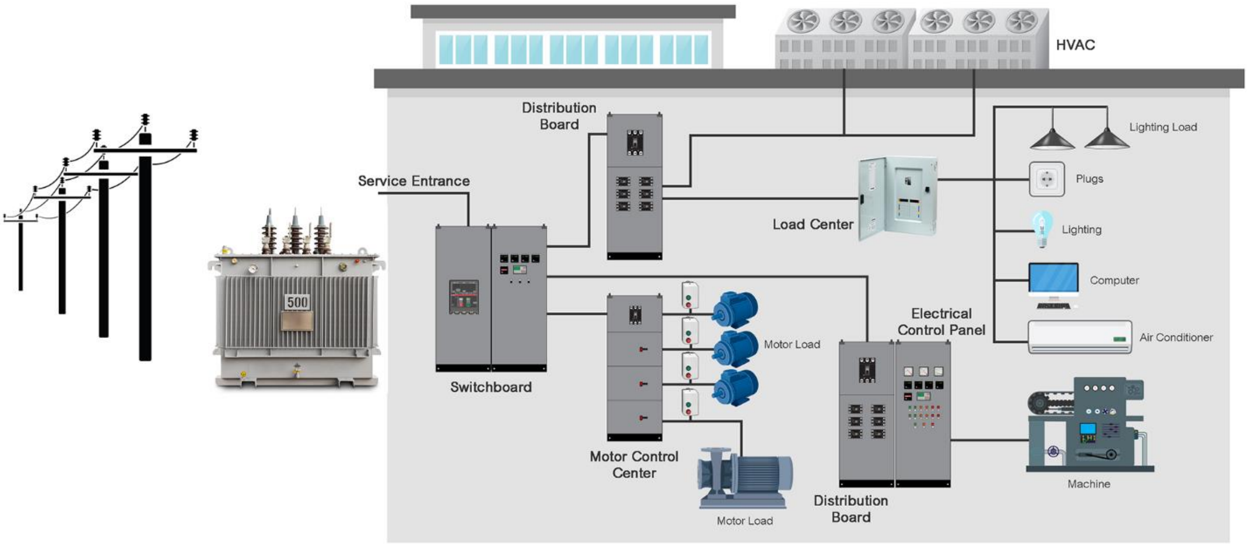


Figure 1 – Typical power supply system [3]

Power supply system consists of a lot of equipment that characterizes it. Depending on the equipment, it is possible to estimate the reliability of the system, safety and satisfaction of the end-use energy consumer. Therefore, I will term the elements of the power supply system as *parameters* of such system.

Main parameters of electric power supply system are:

- power consumers;
- power lines;
- power transformers.

These three parameters are the most expensive and necessary for each power system. Power consumers are special parameter of a power system from point of view of electrical engineer. Usually, power consumers are already installed and their selection is impossible. They are the starting point for calculating the electrical load and designing the supply system. Power consumers do not directly affect the price of a power supply system. The value of the electrical load of the consumer affects the choice of transformer and the line to it. However, the cost of the consumer will not be reflected on the cost of the line and the transformer.

Power lines and transformers are intended for the distribution and transmission of electricity to consumers. Of course, other parameters like switchboards, protection elements are responsible for the security and ability to control the system. However, energy will be transferred through existing cable lines and transformers; other devices only allow you to regulate and protect this process.

Transformers and lines determine most of the cost of the power supply system. It is necessary to accurately and correctly calculate and select these elements. All other parameters could be neglected due to significantly lower price and role in energy distribution.

In the following chapters we will consider the main parameters of the power supply system in more detail.

2.1 Power consumers

An *electric receiver* is an apparatus, an assembly, a mechanism, designed to convert electrical energy into another kind of energy. The *consumer* of electric energy is an electric receiver or a group of power receivers united by a technological process and located in a specific territory. [4]

Power consumers are power supply endpoints. They could not be chosen by power supply specialist; the whole power supply system adapts to them. Concerning this fact, we should know about types, specialties and features of power consumers.

Power consumers are categorized according to the following main features based on [5]:

1. by voltage and power;
2. by type of current;
3. by reliability of power supply;
4. by duty types.

We will consider features of power consumers in Chapters 2.1.2 – 2.1.4.

Main parameter of power consumer is nominal electrical load. Nominal electrical load is a such load, which set by the equipment description for long-term operation. But the real load may differ from nominal. We will consider it in next chapter.

2.1.1 Electrical loads

According to [5], the first and main stage of designing a power supply system is to determine the expected (calculated) values of electrical loads. They are not a simple sum of the installed (nominal) loads. Main reasons for this are incomplete loading of some power consumers, the non-symmetric work, the probabilistic random nature of turning power consumers on and off, etc.

The concept of “calculated load” follows from the definition of calculated current I_{calc}, by which all network elements and electrical equipment are selected. If the load is constant over time, then the network flows constant current, which is taken as calculated $I_{nom} = \text{const} = I_{calc}$.

When load constantly changes (when the change in current over time is random) the calculated current can be determined by the expression:

$$I_{calc} = \frac{1}{T}\int_0^T I(t)dt, \qquad (1)$$

where $T = 3 \cdot \tau_0 = 30\ \text{min},$ is the average interval;

$\tau_0 = 10\ \text{min},$ it is the heating time constant,

I_{nom}, I_{calc} – currents described before formulas, A.

The calculated current I_{calc} is such a constant average (for a 30-minute time interval) current that leads to the same maximum heating of the conductor or causes the same thermal wearout of the insulation that and real constantly changed load. [5]

2.1.2 Voltage levels and current types of power consumers

According *to voltage and power*, the electric consumers are divided into two groups [4]:

a) Power consumers that can be powered directly from the 6 and 10 kV buses (large electric motors, powerful arc furnaces) with power from hundreds of kilowatts to hundreds of megavolt-amperes;

b) Power consumers, the power of which is economically feasible at a voltage 380-660 V, with a capacity of up to hundreds of kilowatts.

According to the *type of the current*, power consumers are divided into three groups [4]:

a) operating from an industrial network with a frequency of 50 Hz;

b) operating from an alternating current mains at a frequency different from the standard;

c) working from a direct current network.

2.1.3 Reliability categories for power consumers

There are three category of power supply reliability based on [5]. They are dependent by the importance of the power consumer, the complexity of the technological process, and the impact on life safety.

Power consumers of the 1st category. Power consumers, whose work interruption can lead to a threat to people's lives, a threat to state security, significant material damage (equipment damage, mass reject products), a breakdown of complex technological process, disruption of the functioning of particularly important elements of public utilities, communication facilities and television.

Power consumers of the 1st category in normal conditions should be provided electricity from two independent, mutually redundant power sources, and interruption of their power supply in case of power failure from one of the power sources can only be allowed while the backup power is automatically turned on.

Power consumers of the 2nd category. Power consumers, whose work interruption leads to a massive shortage of products, to mass downtime of workers, machinery and industrial transport, disruption of the normal activity of a significant number of urban and rural residents. It is the most numerous category. Power consumers of this category should be provided with electricity from two independent, mutually redundant power sources. Power interruption is acceptable for the time required for turn-on backup power by operational personal.

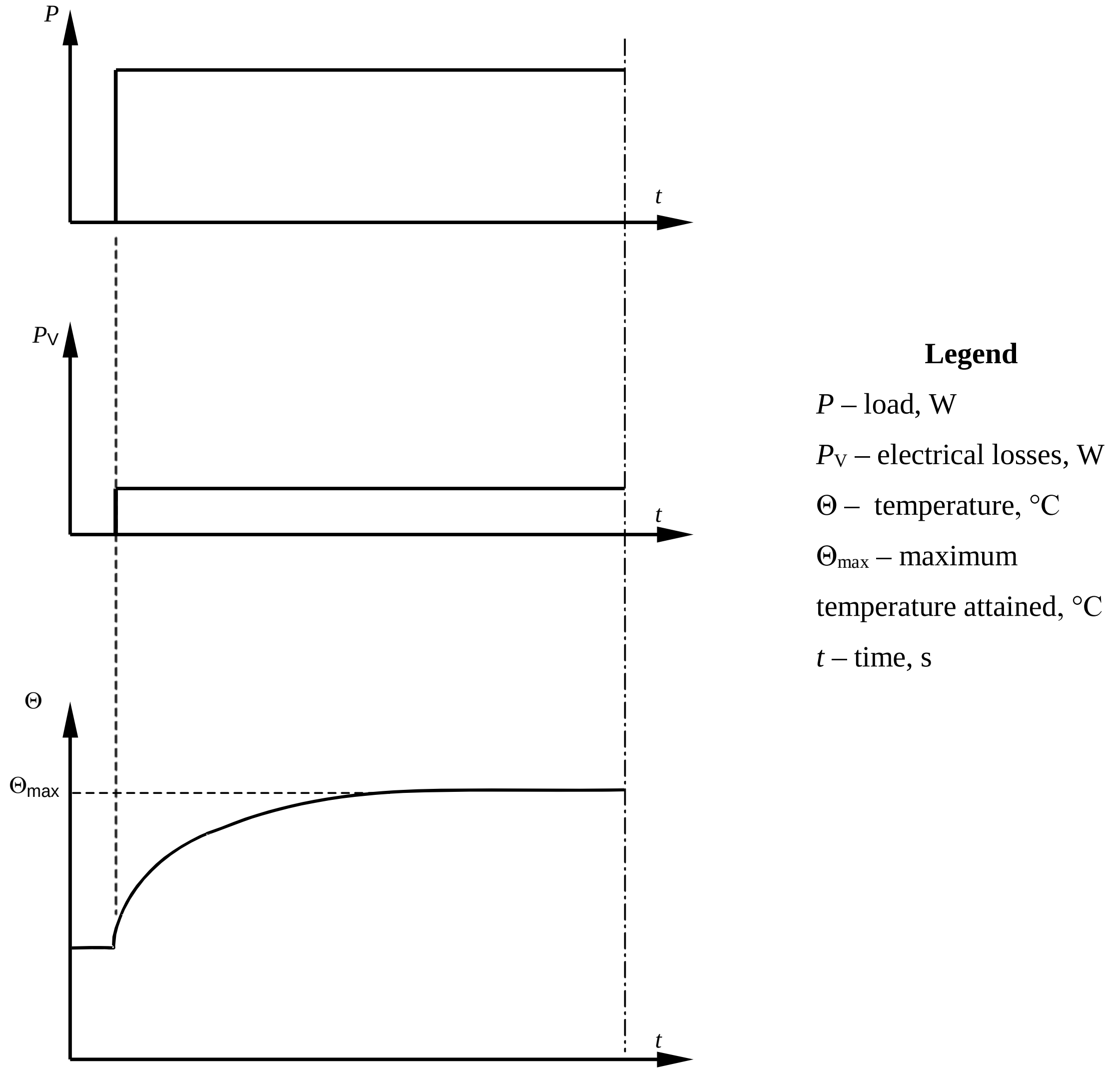
Power consumers of the 3rd category. All others power consumers which are not included in the first and second category. These include power consumers in workshops, in non-responsible warehouses, in non-serial production workshops, etc. For electric power consumers of the 3rd category, it’s enough one power source, provided that interruptions of the electric power needed for repair or replacement of a damaged item do not exceed 1 day.

2.1.4 Duty types of power consumers

The term “duty” defines the load cycle to which the machine is subjected, including, if applicable, starting, electric braking, no-load and rest de-energized periods, and including their durations and sequence in time. There are several duty types of power consumers.

Duty type S1 – Continuous running duty

Operation at a constant load maintained for sufficient time to allow the machine to reach thermal equilibrium as represented at Figure 2. [6]



Legend

P – load, W

P_V – electrical losses, W

Θ – temperature, °C

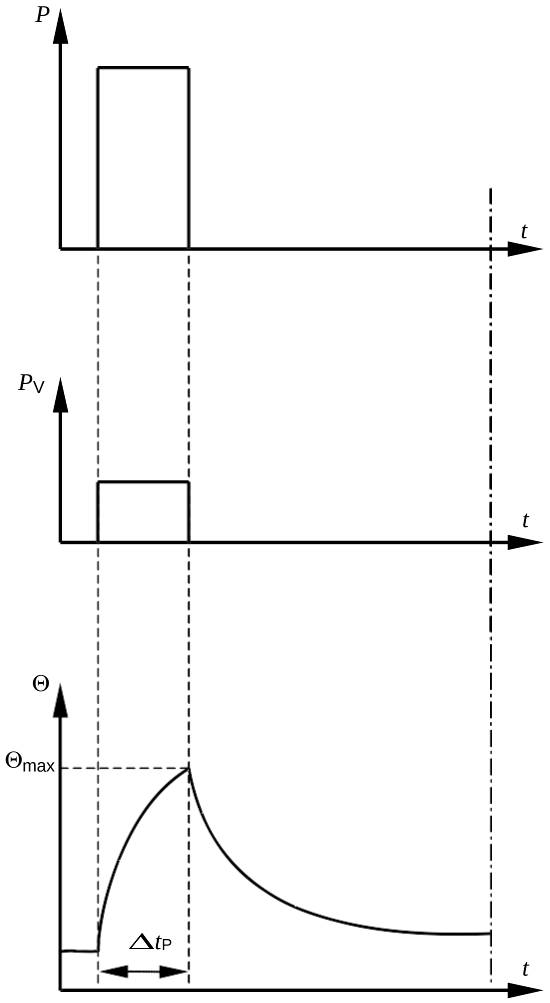
$Θ_{max}$ – maximum temperature attained, °C

t – time, s

Figure 2 – Continuous running duty [6]

Duty type S2 – Short-time duty

Operation at constant load for a given time, less than that required to reach thermal equilibrium, followed by a time de-energized and at rest of sufficient duration to re-establish machine temperatures within 2 K of the coolant temperature. Such mode represented at Figure 3. [6]



Legend

P – load, W

P_V – electrical losses, W

Θ – temperature, °C

Θ_{max} – maximum temperature attained, °C

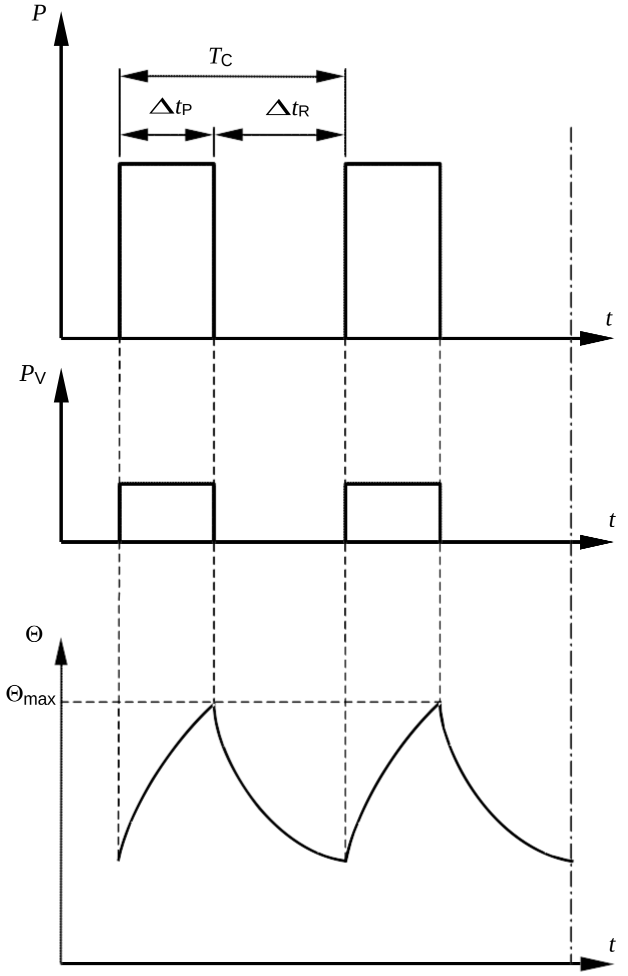
t – time, s

Δt_P - operation time at constant load, s

Figure 3 – Short-time duty [6]

Duty type S3 – Intermittent periodic duty

A sequence of identical duty cycles, each including a time of operation at constant load and a time de-energized and at rest represented at Figure 4. In this duty, the cycle is such that the starting current does not significantly affect the temperature rise. [6]



Legend

P – load, W

P_V – electrical losses, W

Θ – temperature, °C

Θ_{max} – maximum temperature attained, °C

t – time, s

T_C – time of one load cycle, s

Δt_P – operation time at constant load, s

Δt_R – time de-energized and at rest, s

Figure 4 – Intermittent periodic duty [6]

There are 3 main duty types. Other duty types could be described by first or third, mathematically.

Summarize, we can have different load characteristics. Differences in quantity of power, duty types, operation times, etc. lead to high difficulty in load computation.

Determination of expected (calculated) values of electrical load is first stage of supply system designing. There are several ways how to find expected electrical load which we will consider in Chapter 3.

All of this power consumer's specialties should be taken into account in the calculation. Otherwise, power consumers will work incorrectly or even do not work. Features of main power consumers of industrial enterprises define power supply system. We need different number of transformers if we have first or second category of reliability; we need special equipment (rectifiers) if we have direct current consumer, etc. Difference in duty type and work modes of power consumers complicates the task of accurate load computation. We should make some assumption to find real electric load or have some strong mathematical base to solve large number of equations. These two different ways described in Chapter 3.

2.1.5 Impact of voltage on power consumers

As stated earlier, power consumers are the starting point for designing a power supply system. Nevertheless, they are also the final point for designing. After all calculations and equipment selection, in order to evaluate the energy efficiency of the power supply system, it is necessary to evaluate the quality of operation of the end-use power consumers. One of the important quality indicators is voltage [7]. In this subchapter, the effect of voltage on the operation of a power consumer will be considered.

When transmitting electric power, voltage deviations are inevitable. Voltage deviation is the algebraic difference between the actual mains voltage and the rated voltage at the terminals of the power consumer, referred to the rated voltage [7]:

$$\delta U,\% = \frac{U_{real} - U_{nom}}{U_{nom}} \cdot 100\%, \qquad (2)$$

According to state standard GOST 32144-2013 [8] the voltage deviation from the nominal should be:

- for electrical motors – from +5 to -2.5% U_{nom};

- for lighting networks of industrial enterprises and public buildings – from +5 to -2.5% U_{nom};

- for most of power consumers – no more ± 5% U_{nom}.

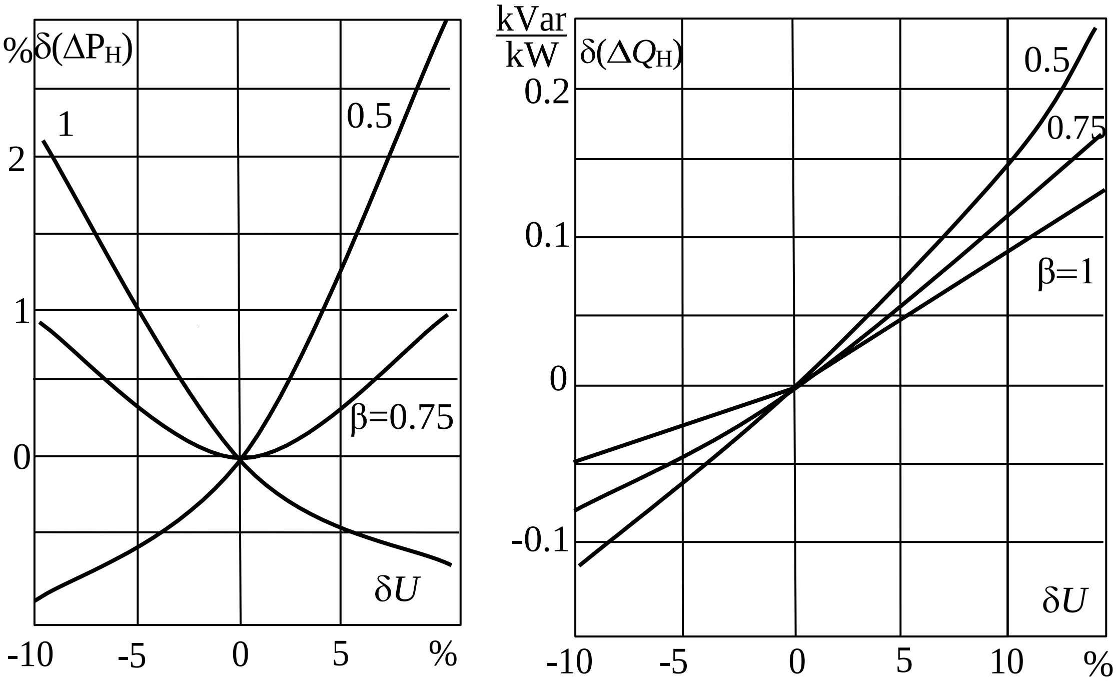
where U_{nom}, U_{real} – nominal and real voltage, V.

The deviation of energy quality indicators from standard values leads to economic damage among power consumers. This damage can be divided into electromagnetic and technological component. The electromagnetic component is determined mainly by additional losses of active power and energy and a reduction in the lifetime of electrical equipment due to accelerated aging of the insulation. The technological component of the damage is associated with an increase in the duration of the production process, with a decrease in the productivity of electrical equipment, which leads to an increase in the specific energy consumption per unit of production. [7]

Next step is to consider the operation of typical power consumers for voltage deviations.

Induction motors. The vast majority of motors in industrial plants are induction motors. As studies show [7], voltage deviations significantly affect the energy performance of motors. For instance, Figure 5 shows the dependences of additional losses of active power $\delta(\Delta P_{nom})$ and reactive power $\delta(\Delta Q_{nom})$ with respect to the nominal losses depending on voltage deviations.

As presented on the Figure 5, the change in active losses in motors with voltage deviations within ± 10% in is relatively small (no more than 0.03 ΔP_{nom}), but they turn out to be of the same order as losses in the supply networks.



a) b)

Figure 5 – Changes in power losses depending on voltage deviations at various load factors: a) active power losses; b) reactive power losses [7]

Undervoltage has a significant effect on the service life of an induction motor. This is due to accelerated aging of the insulation with increasing motor current. So, with 10% voltage deviations and rated engine load, its *lifetime is halved*. The approximate data of the influence of deviations of the supply voltage of induction motors on their characteristics are given in Table 1 [7].

Table 1 – Changing the parameters of induction motors with voltage deviation [7]

Characteristics of induction motors	Change in characteristics when voltage changes by	
	-10%	+10%
Starting and maximum torque	**-19%**	**21%**
Synchronous speed	const	const
Slip	**23%**	**-17%**
Speed at nominal load	-1,5%	1%
Power factor under load:		
- nominal	1%	-3%
- 75%	2...3%	-4%
- 50%	4...5%	-5.-6%
Rotor current at nominal load	**14%**	**11%**
Stator current at nominal load	**10%**	**-7%**
Starting current	**-10...-12%**	**10…12%**
Winding temperature increase	5...6°	const

According to the data in Table 1, voltage changes significantly affect the current and torque of the motors. These two parameters characterize the useful operation of the engine. Changes in the moment affect the production process. Current changes negatively affect aging insulation. To summarize, we can say that voltage deviation leads to a significant imbalance in the operation of the induction motors.

Technological equipment. In production line installations, automated machines, etc., voltage deviations can significantly affect the productivity of technological equipment. Let's consider this position on examples [7].

Experimental studies carried out on rolling machines of a metal-smelting plant, showed that the average minute productivity of these machines is 0.275 kg at a voltage $U = 1.05U_{nom}$ at the motor terminals and 0.236 kg at $U = 0.9U_{nom}$. During three-shift operation of the enterprise, the undersupply of products on one machine at $0.9U_{nom}$ is about 5000 kg per year. An increase in voltage in excess of $1.05U_{nom}$ leads to a decrease in product quality.

A voltage reduction of 1% for the transfer pumps of a pulp-and-paper mill leads to a decrease in mill productivity by 0.1%. In a common case decrease in machine productivity and an increase in power losses lead to an increase in energy consumption per unit of output up to 0.3% for each percentage of voltage deviation. With positive voltage deviations, the specific energy consumption decreases to 0.2% for each percentage deviation.

Research conducted on weaving machines establish that for every percent of voltage reduction, the productivity of mechanisms decreases by 0.2%, and with voltage deviations above 5%, the decrease in productivity for each percent of deviation increases. With increasing voltage, the increase in machine performance is negligible.

A significant effect is exerted by voltage deviations on the course of technological processes in electroheat. With a decrease in voltage, the duration of the process increases, and in some cases its complete upset can occur. So, with a voltage reduction of 8 ... 10%, the technological process in resistance furnaces and induction furnaces cannot be brought to an end.

All these cases indicate that the magnitude of the voltage has a finite effect on the volume and quality of the product. Voltage changes lead to tangible monetary and energy losses in production.

Lighting equipment

An important characteristic of a light source is the dependence of the light output on the magnitude of the supply voltage and, accordingly, the power consumed by the lamp. The power consumed by the lamp with increasing supply voltage increases significantly. The increase in power consumed by various types of lamps, as a percentage of the nominal, is given in Table 2. [9]

Table 2 – The increase in power consumed by lamps [9]

Lamp type	Overvoltage, %					
	1	2	3	5	6	10
Filament lightbulb	1.6%	3.2%	4.7%	8.1%	11.5%	16.4%
Fluorescent lamp	2.4%	4.9%	7.2%	12.2%	17%	24.3%
Sodium-vapor lamp	2%	8%	11%	18%	23%	34%

In addition to a significant increase in the energy consumed for lighting, with an increase in the supply voltage the number of lamps required for the operation of lighting and operating cost increases. The relations between supply overvoltage, relative lamp lifetime and the number of lamps of various types required for operation are shown in Table 3. [10]

Table 3 – The dependence of lamps parameters on voltage deviation [10]

Parameter	Overvoltage, %						
	0	1	2	3	4	5	6
Lifetime compared to nominal, %:							
• Filament lightbulb	100	87.1	75.8	66.2	50.5	38.7	7.8
• Fluorescent lamp	100	95	93	90	85	80	73
The required number of lamps for same light output, %:							
• Filament lightbulb	100	114	132	151	198	258	284
• Fluorescent lamp	100	105	108	111	118	125	137

The data presented convincingly show that for the rational use of electricity for lighting and reducing operating costs, it is necessary to effectively stabilize the voltage at the terminals of the light sources.

Summing up, the effect of voltage on the work of electricity consumers is very significant. The voltage value of the final conductor should be in accordance with state standard [8]. In the following chapters we use voltage as an assessment of the quality of the technological component of the power supply system.

2.2 Power supply lines

Power supply lines could be overhead and cable lines. It depends on voltage level, energy distribution level and amount of transmitted energy.

Before considering application features of overhead lines and cable lines, we should find out difference between wire and cable. Wire and cable are two terms that are used in electrical and communication fields. They are often confused, but in fact, they are quite different. A wire is a single conductor (material most commonly being copper or aluminum) while cable is two or more insulated wires wrapped in one jacket. Multiple conductors that have no insulation around would be classified as a single conductor. There are two main types of wires: solid or stranded.

A solid wire is a single conductor that is either bare or insulated by a protective colored sheath. It offers low resistance and are perfect for use in higher frequencies. When inside a covering there are many thin strands of wires twisted together, it is called a stranded wire. Stranded wires are used where flexibility is important because which the wire can be used for a longer period. This type of wire has larger cross-sectional area than solid wires for the same current carrying capacity [11].

Main task of power supply engineer is to choose right conductor and its cross section. The selection of the most appropriate conductor at a particular voltage level must take into account both technical and economic criteria as listed below [11]:

1. The maximum power transfer capability must be in accordance with system requirements.
2. The conductor cross sectional area should be such as to minimize the initial capital cost and the capitalized cost of the losses.
3. The conductor should conform to standard sizes already used elsewhere on the network in order to minimize spares holdings and introduce a level of standardization.
4. The conductor thermal capacity must be adequate.
5. The conductor diameter or bundle size must meet recognized international standards for radio interference and corona discharge.
6. The conductor must be suitable for the environmental conditions and conform to constructional methods understood in the country involved.

Then we can consider features of overhead and cable lines in power supply cases.

2.2.1 Overhead lines

An overhead line is a device for transmitting energy through wires in the open air, attached with insulators and fittings to transmission tower.

Wires. According to the design of the wire can be one- and multi- trailing. The minimum diameter of the wires is set depending on the transmitted power, the required safety margins, losses on the “crown”. For overhead lines, mainly copper, aluminum, steel-aluminum and steel wires are used. In overhead lines and flexible conductors, aluminum is mainly used as a conductive material, which possesses the properties necessary for a conductive material (specific conductivity, necessary mechanical strength). To further increase the mechanical strength of aluminum wires and chemical resistance in contact joints, apply:

- steel-aluminum wires with the ratio of the cross sections of the steel core and the multi-wire aluminum outer layer 0.2–0.24;
- aluminum wires coated with bituminous particles to protect against corrosion;
- welded and pressed joints. [5]

Overhead lines are, in essence, air-insulated cables suspended from insulated supports with a power transfer capacity approximately proportional to the square of the line voltage. Overhead lines are more economic than cable feeders. For the transmission of equivalent power at 11 kV a cable feeder would cost some 5 times the cost of a transmission line, at 132 kV 8 times and at 400 kV 23 times. Such comparisons must, however, be treated in more depth since they must take into account rights of way, amenity, clearance problems and planning permissions associated with the unsightly nature of erecting bare conductors in rural and urban areas.

Environmental conditions [11]

1) Temperature. The maximum, minimum and average ambient temperature influences conductor current rating and sag. For temperate conditions typically 20°C with 55°C temperature rise. For tropical conditions 35°C or 40°C with 40°C or 35°C temperature rise. Maximal conductor operating temperature should not exceed 75°C to prevent annealing of aluminum.

2) Wind velocity. Required for structure and conductor design. Electrical conductor ratings may be based on cross wind speeds of 0.5 m/s or longitudinal wind speeds of 1 m/s.

3) Solar radiation. Required for conductor ratings but also for fittings such as composite insulators which may be affected by exposure to high thermal and ultraviolet radiation. Typical values of 850W/m and 1200W/m may be assumed for temperate and tropical conditions respectively.

4) Rainfall. Important in relation to flooding (necessity for extension legs on towers), corona discharge and associated electromagnetic interference, natural washing and insulator performance.

5) Humidity. Effect on insulator design and lifetime.

Types of conductor [11]

For 36 kV transmission and above both aluminum conductor steel reinforced (ACSR) and all aluminum alloy conductor may be considered. Aluminum conductor alloy reinforced (ACAR) and all aluminum alloy conductors steel reinforced (AACSR) are less common than AAAC and all such conductors may be more expensive than ACSR. Historically ACSR has been widely used because of its mechanical strength, the widespread manufacturing capacity and cost effectiveness. For all but local distribution, copper-based overhead lines are costlier because of the copper conductor material costs. Copper has a very high corrosion resistance and is able to withstand desert conditions under sand blasting. All aluminum conductors (AAC) are also employed at local distribution voltage levels.

From a materials point of view the choice between ACSR and AAAC is not so obvious and at larger conductor sizes the AAAC option becomes more attractive. AAAC can achieve significant strength/weight ratios and for some constructions gives smaller sag and/or lower tower heights. With regard to long-term creep or relaxation, ACSR with its steel core is considerably less likely to be affected. Jointing does not impose insurmountable difficulties for either ACSR or AAAC types of conductor as long as normal conductor cleaning and general preparation are observed. AAAC is slightly easier to joint than ACSR.

2.2.2 Cable lines

A cable line or cable is one or several insulated cores twisted together, enclosed in a common hermetic sheath (rubber, plastic, aluminum, lead).

The cable consists of conductors having core insulation and belt insulation. To protect against mechanical damage, the cable structure includes armor, a protective sheath, etc.

The following factors govern the design of power cables [11]:

1. The cross-sectional area of the conductors chosen should be of the optimum size to carry the specified load current or short circuit short term current without overheating and should be within the required limits for voltage drop.

2. The insulation applied to the cable must be adequate for continuous operation at the specified working voltage with a high degree of thermal stability, safety and reliability.

3. All materials used in the construction must be carefully selected in order to ensure a high level of chemical and physical stability throughout the life of the cable in the selected environment.

4. The cable must be mechanically strong, and sufficiently flexible to withstand the re-drumming operations in the manufacturer's works, handling during transport or when the cable is installed by direct burial, in trenches, pulled into ducts or laid on cable racks.

5. Adequate external mechanical and/or chemical protection must be applied to the insulation and metal or outer sheathing to enable it to withstand the required environmental service conditions.

Types of cables are detailed in Table 4.

Table 4 – Types of cables [11]

Voltage level	Usage	Voltage range	Insulation
Low voltage	Telephone	50 V	PVC or PE
	Control	600 – 1000 V	PVC
	Solid dielectric	600 – 1000 V	XLPE, EPR
	MI or MIND	600 – 1000 V	
Medium voltage	Solid dielectric	3 kV – 7.2 kV	PVC, PE, XLPE, EPR
	MI or MIND 3 kV	3 kV – 7.2 kV	Paper
	Solid dielectric	10 kV – 50 kV	XLPE, EPR
High voltage	MIND	10 kV – 36 kV	Paper
	Oil filled, gas pressure	80 kV – 100 kV	XLPE, Paper

Next types of cables insulation (paper, PVC, XLPE, EPR) will be described based on [11]

Paper insulation

Oil-impregnated, paper-insulated cables have a history of satisfactory use at all voltage levels. They are nowadays rarely specified for new installations except at voltage levels of 66 kV and above or for reinforcement of existing installations where standard cable types are required throughout the network.

Until the development of XLPE or EPR cables paper tape insulation was the most stable form at high temperatures and better able to withstand the stresses occurring under short circuit conditions. However, paper insulation deteriorates rapidly because of its hygroscopic nature if exposed to moisture. In order to prevent this, the paper layers are protected against ingress of water, usually by a lead/lead alloy or corrugated aluminum alloy metal sheath.

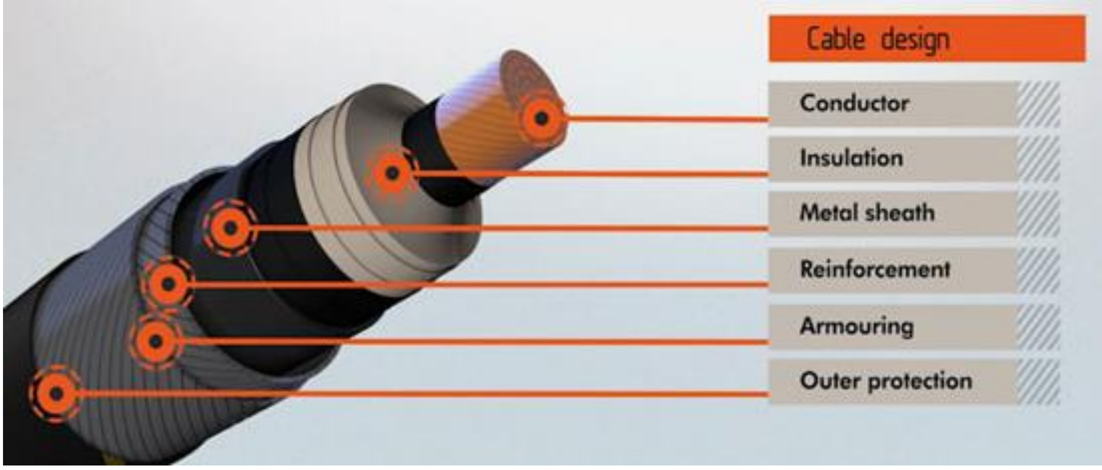


Figure 6 – Paper insulated cable [12]

PVC insulation

PVC has the advantage over paper insulation in that it is non-hygroscopic and does not therefore require a metallic sheath. The absence of such a sheath simplifies jointing by the elimination of plumbing operations on the lead sheath. Moreover, it is both lighter and tougher and inherently more flexible than paper. Therefore, PVC-insulated cables may be bent through smaller radii than paper-insulated cables thus easing installation problems. PVC is resistant to most chemicals although care must be taken with installations in petrochemical environments. It is a thermoplastic material which softens at high temperatures and therefore cannot withstand the thermal effects of short circuit currents as well as paper insulation. The maximum conductor temperature is 65°C to 70°C. Multicore cables are generally armored when laid direct in ground. At low temperatures PVC hardens and becomes brittle and installations should not be carried out at temperatures below 0°C.

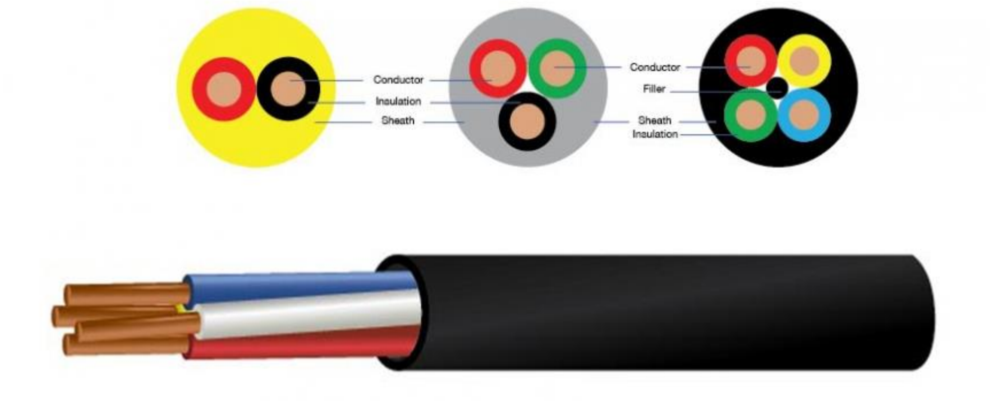


Figure 7 – PVC insulated cable [13]

XLPE insulation

XLPE is a thermosetting material achieved by a process akin to the vulcanization of rubber. The resulting material combines the advantages of PVC insulation (high dielectric strength, good mechanical strength and non-hygroscopic nature) with thermal stability over a wide temperature range.

XLPE has no true melting point and remains elastic at high temperatures therefore permitting greater current carrying capacity, overload and short circuit performance in comparison with PVC and paper-insulated cables. XLPE cables have greater insulation thickness than their equivalent paper-insulated cables. This results in XLPE cables having larger overall diameters and for a given cable drum size slightly less overall cable length can be transported. This factor may be reduced by specifying segmental-shaped conductors instead of the typical circular conductor shaping. The power factor of XLPE cables is very low compared to paper-insulated cables; 0.001 at the nominal system voltage to earth.

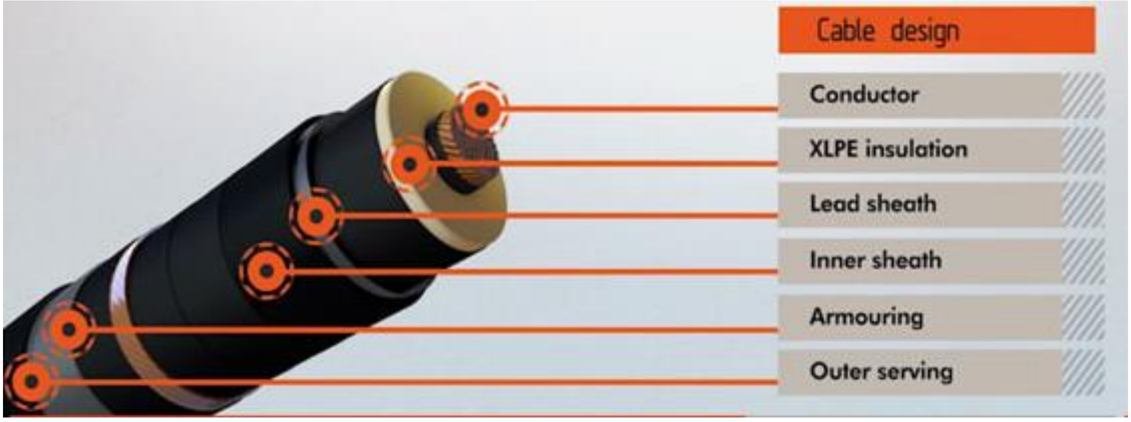


Figure 8 – XLPE insulated cable [12]

EPR insulation

Ethylene propylene rubber cables have a cross-linked molecular structure like XLPE and are produced by a similar process. Both EPR and XLPE have the same durable and thermal characteristics but EPR has a higher degree of elasticity which is maintained over a wide temperature range. This EPR flexibility characteristic is somewhat mitigated when such cables are used in conjunction with steel armoring. Between six and twelve ingredients are used in the production of EPR which necessitates great care to maintain purity and avoid contamination during the production process. For this reason, EPR insulation tends to be more expensive than XLPE insulation but such cables should be considered where handling ability is important.

All these types of cables are not perfect and cause loss of energy and voltage in the electrical network. The influence of the cable cross-section and the type of insulation on the operation of the electrical system will be discussed in more detail in Chapter 3.

2.2.3 Supply lines losses

Each electricity supply line has voltage and power losses. Losses of voltage on the line affect the end-use power consumers (as described in Chapter 2.1.5). Power losses affect energy losses, which reduces the energy intensity of the enterprise and increases electricity bills. First consider the origins of these losses.

Dielectric losses

Cables of the same conductor diameter, insulation material and similar construction from different manufacturers will have similar, small dielectric losses which may be compared when buying cable during the tender adjudication stage. The larger the conductor diameter, the greater the losses for a given insulating dielectric material. Dielectric losses in XLPE-insulated cables will be appreciably lower than in oil-filled paper-insulated types which have a higher capacitance per unit length. [5]

Screen or sheath losses

Screen or sheath/metallic layer losses will be proportional to the current carried by the cables and will be approximately the same for standard cables of the same types and size. If the cables are to be installed on systems with high earth fault levels the sheath or metallic layer cross-sections will have to be increased. In particular, care should be taken regarding possible future network expansion and interconnections which might involve increasing fault levels over the lifetime of the cable installation. Losses may be reduced in the case of circuits employing single core cables by single point bonding on short cable routes (<500 m) and cross-bonding on longer routes. [14]

Load losses

When current flows through the wires of a three-phase line with active resistance R, the power loss occurs. The reason for such losses lies mainly in the heating of the conductor. The power of heating generated by an electrical conductor is proportional to the product of its resistance and the square of the current:

$$\Delta P = I^2 \cdot R\,[W], \tag{3}$$

where I, A – current which flows through the conductor, R, Ohm – conductor’s active resistance.

This is Joule–Lenz law [15]. These losses are the predominant losses in conductors. To simplify the calculations and the concept of influencing factors, use the following formula for these losses [16]:

$$\Delta P_{line} = \frac{P^2 + Q^2}{U^2} \cdot R\,[W], \tag{4}$$

where P, W and Q, Var – active and reactive power which flows through the line, U, V – value of voltage in the beginning of conductor.

All of the above losses are included in the energy losses of the enterprise and you need to pay for them. In addition to power losses, these factors play a role in voltage losses that are critical for power consumers. Line voltage losses could be found as [16]:

$$\Delta U_{line} = \frac{P \cdot R + Q \cdot L}{U^2} \cdot 100\,[\%], \tag{5}$$

where *R* and *L* (Ohm) – resistance and inductance of the line, *U* – value of voltage in the beginning of line.

We will need the values of power and voltage losses later. Voltage losses will be used to assess the quality of the electricity of the supply system, power losses will be used as an estimate of economic efficiency (Chapter 7).

2.3 Power supply transformers

Any transformer that takes voltage from a primary distribution circuit and "steps down" or reduces it to a secondary distribution circuit or a consumer's service circuit is a distribution transformer. Although many industry standards tend to limit this definition by kVA rating (e.g., 5 to 500 kVA), distribution transformers can have lower ratings and can have ratings of 5000 kVA or even higher, so the use of kVA ratings to define transformer types is being discouraged. [14]

In this subsection we will consider definition of transformer, types of supply transformers, transformer model for computation and power and voltage losses in transformer.

Following chapters 2.3.1-2.3.4 are based on [14].

2.3.1 Theory and principles

Transformers are devices that transfer energy from one circuit to another by means of a common magnetic field. In all cases except autotransformers, there is no direct electrical connection from one circuit to the other.

When an alternating current flows in a conductor, a magnetic field exists around the conductor, as illustrated in Figure 9. If another conductor is placed in the field created by the first conductor such that the flux lines link the second conductor, as shown in Figure 10, then a voltage is induced into the second conductor. The use of a magnetic field from one coil to induce a voltage into a second coil is the principle on which transformer theory and application is based.

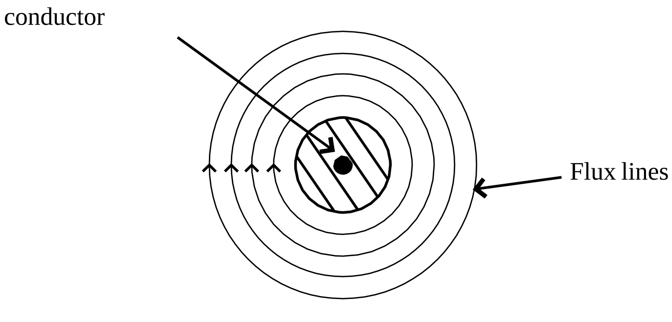


Figure 9 – Magnetic field around conductor [14]

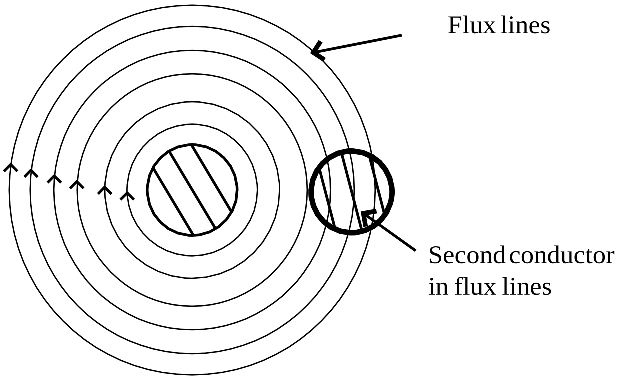


Figure 10 – Magnetic field around conductor induces voltage in second conductor [14]

This is the case of air core transformer. Air is conductor for magnetic flux.

However, the ability of iron or steel to carry magnetic flux is much greater than air. This ability to carry flux is called permeability. Modern electrical steels have permeabilites in the order of 1500 compared with 1.0 for air. This means that the ability of a steel core to carry magnetic flux is 1500 times that of air. Steel cores were used in power transformers when alternating current circuits for distribution of electrical energy were first introduced. When two coils are applied on a steel core, as illustrated in Figure 11, almost 100% of the flux from coil 1 circulates in the iron core so that the voltage induced into coil 2 is equal to the coil 1 voltage if the number of turns in the two coils are equal.

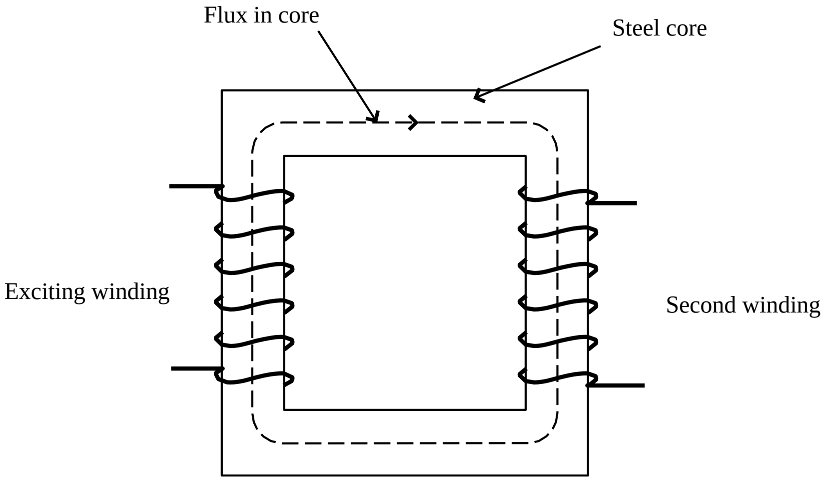


Figure 11 – Two coils applied on a steel core [14]

In supply transformers the core, which provides the magnetic path to channel the flux, consists of thin strips of high-grade steel, called laminations, which are electrically separated by a thin coating of insulating material. The strips can be stacked or wound, with the windings either built integrally around the core or built separately and assembled around the core sections. Core steel can be hot- or cold-rolled, grain-oriented or non-grain-oriented, and even laser-scribed for additional performance. Thickness ranges from 0.23 mm to upwards of 0.36 mm. The core cross section can be circular or rectangular, with circular cores commonly referred to as cruciform construction. Rectangular cores are used for smaller ratings and as auxiliary transformers used within a power transformer. Rectangular cores use a single width of strip steel, while circular cores use a combination of different strip widths to approximate a circular cross-section. The type of steel and arrangement depends on the transformer rating as related to cost factors such as labor and performance.

Just like other components in the transformer, the heat generated by the core must be adequately dissipated. While the steel and coating may be capable of withstanding higher temperatures, it will come in contact with insulating materials with limited temperature capabilities.

Therefore, it is necessary to cool the transformers. Depending on the type of cooling, different types of transformers are distinguished. We will consider them in the next subsection.

2.3.2 Types of supply transformers

No transformer is truly an 'ideal transformer' and hence each will incur some losses, most of which get converted into heat. If this heat is not dissipated properly, the excess temperature in transformer may cause serious problems like insulation failure.

All supply transformers need a cooling system. Transformers can be divided in two types as dry type transformers and oil immersed transformers. Different cooling methods of transformers are:

- for dry type transformers:

1. Air Natural
2. Air Blast

- for oil immersed transformers:

1. Oil Natural Air Natural
2. Oil Natural Air Forced
3. Oil Forced Air Forced
4. Oil Forced Water Forced

Air Natural or Self Air Cooled Transformer

This method of transformer cooling is generally used in small transformers (up to 3 MVA). In this method the transformer is allowed to cool by natural air flow surrounding it.

Air Blast

For transformers rated more than 3 MVA, cooling by natural air method is inappropriate. In this method, air is forced on the core and windings with the help of fans or blowers. The air supply must be filtered to prevent the accumulation of dust particles in ventilation ducts. This method can be used for transformers up to 15 MVA.

Oil Natural Air Natural

This method is used for oil immersed transformers. In this method, the heat generated in the core and winding is transferred to the oil. According to the principle of convection, the heated oil flows in the upward direction and then in the radiator. The vacant place is filled up by cooled oil from the radiator. The heat from the oil will dissipate in the atmosphere due to the natural air flow around the transformer. In this way, the oil in transformer keeps circulating due to natural convection and dissipating heat in atmosphere due to natural conduction. This method can be used for transformers up to about 30 MVA.

Oil Natural Air Forced

The heat dissipation can be improved further by applying forced air on the dissipating surface. Forced air provides faster heat dissipation than natural air flow. In this method, fans are mounted near the radiator and may be provided with an automatic starting arrangement, which turns on when temperature increases beyond certain value. This transformer cooling method is generally used for large transformers up to about 60 MVA.

Oil Forced Air Forced

In this method, oil is circulated with the help of a pump. The oil circulation is forced through the heat exchangers. Then compressed air is forced to flow on the heat exchanger with the help of fans. The heat exchangers may be mounted separately from the transformer tank and connected through pipes at top and bottom. This type of cooling is provided for higher rating transformers at substations or power stations.

Oil Forced Water Forced

This method is similar to previous method, but here forced water flow is used to dissipate hear from the heat exchangers. The oil is forced to flow through the heat exchanger with the help of a pump, where the heat is dissipated in the water which is also forced to flow. The heated water is taken away to cool in separate coolers. This type of cooling is used in very large transformers having rating of several hundred MVA.

The vast majority of distribution transformers on utility systems today are liquid-filled. Liquid-filled transformers offer the advantages of smaller size, lower cost, and greater overload capabilities compared with dry types of the same rating.

2.3.3 Transformer model

A simple two-winding transformer is shown in the schematic diagram of Figure 12. A primary winding of N_P turns is on one side of a ferromagnetic core loop, and a similar coil having N_S turns is on the other. Both coils are wound in the same direction with the starts of the coils at $H_1, \{A/m\}$ and $X_1, \{Ohm\}$ respectively. When an alternating voltage $V_P, \{V\}$ is applied from H_2 to H_1, an alternating magnetizing flux $\varphi_m, \{Wb\}$ flows around the closed core loop. A secondary voltage $V_S = V_P \cdot N_S / N_P$ is induced in the secondary winding and appears from X_2 to X_1 and very nearly in phase with V_P. With no load connected to $X_1 - X_2$, $I_P, \{A\}$ consists of only a small current called the magnetizing current. When load is applied, current I_S flows out of terminal X_1 and results in a current $I_P = I_S \cdot N_S / N_P$ flowing into H_1 in addition to magnetizing current. The ampere-turns of flux due to current $I_P \cdot N_P$ cancels the ampere-turns of flux due to current $I_S \cdot N_S$, so only the magnetizing flux exists in the core for all the time the transformer is operating normally.

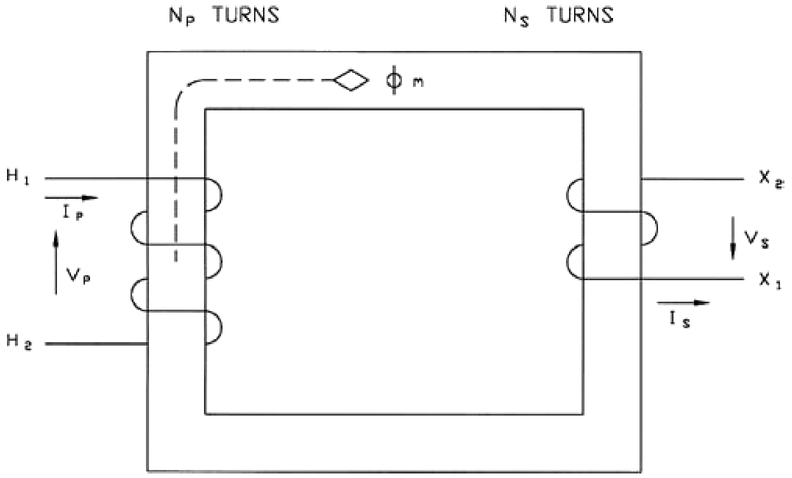


Figure 12 – Two-winding transformer schematic diagram [14]

Figure 13 shows a complete equivalent circuit of the transformer. An ideal transformer is inserted to represent the current- and voltage-transformation ratios. A parallel resistance and inductance representing the magnetizing impedance are placed across the primary of the ideal transformer. Resistance and inductance of the two windings are placed in the H_1 and X_1 branches, respectively.

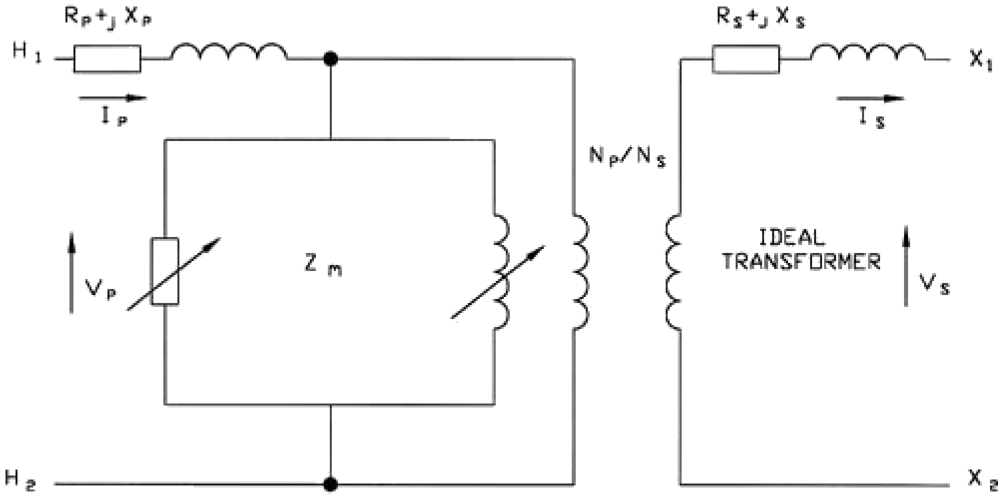


Figure 13 – Complete transformer equivalent circuit [14]

We use such transformer model for computation and simulating of real transformers in electrical network. Such model allows us to consider all parameters of transformers. One of main transformer parameters is losses. They affect lifetime of equipment and total consumed energy which defines electricity charge.

2.3.4 Transformer losses

Each transformer has power and voltage loses. Consider the types of losses and the causes of their occurrence.

No-Load Loss and Exciting Current

When alternating voltage is applied to a transformer winding, an alternating magnetic flux is induced in the core. The alternating flux produces hysteresis and eddy currents within the electrical steel, causing heat to be generated in the core. Heating of the core due to applied voltage is called no-load loss. Other names are iron loss or core loss. The term “no-load” is descriptive because the core is heated regardless of the amount of load on the transformer. If the applied voltage is varied, the no-load loss is very roughly proportional to the square of the peak voltage, as long as the core is not taken into saturation. The current that flows when a winding is energized is called the “exciting current” or “magnetizing current,” consisting of a real component and a reactive component. The real component delivers power for no-load losses in the core. The reactive current delivers no power but represents energy momentarily stored in the winding inductance. Typically, the exciting current of a distribution transformer is less than 0.5% of the rated current of the winding that is being energized.

Load Loss

A transformer supplying load has current flowing in both the primary and secondary windings that will produce heat in those windings. Load loss is divided into two parts, I^2R loss and stray losses.

I^2R *loss*

Each transformer winding has an electrical resistance that produces heat when load current flows. Resistance of a winding is measured by passing DC current through the winding to eliminate inductive effects.

Stray Losses

When alternating current is used to measure the losses in a winding, the result is always greater than the I^2R measured with DC current. The difference between dc and ac losses in a winding is called “stray loss”. One portion of stray loss is called “eddy loss” and is created by eddy currents circulating in the winding conductors. The other portion is generated outside of the windings, in frame members, tank walls, bushing flanges, etc. Although these are due to eddy currents also, they are often referred to as “other strays.” The generation of stray losses is sometimes called “skin effect” because induced eddy currents tend to flow close to the surfaces of the conductors. Stray losses are proportionally greater in larger transformers because their higher currents require larger conductors. Stray losses tend to be proportional to current frequency, so they can increase dramatically when loads with high-harmonic currents are served. The effects can be reduced by subdividing large conductors and by using stainless steel or other nonferrous materials for frame parts and bushing plates.

Harmonics and DC Effects

Rectifier and discharge-lighting loads cause currents to flow in the distribution transformer that are not pure power-frequency sine waves. Using Fourier analysis, distorted load currents can be resolved into components that are integer multiples of the power frequency and thus are referred to as harmonics. Distorted load currents are expected to be high in the 3rd, 5th, 7th, and sometimes the 11th and 13th harmonics, depending on the character of the load.

Even-Ordered Harmonics

Analysis of most harmonic currents will show very low numbers of even harmonics (2nd, 4th, 6th, etc.) Components that are even multiples of the fundamental frequency generally cause the waveform to be nonsymmetrical about the zero-current axis. The current therefore has a zeroth harmonic or dc-offset component. The cause of a dc offset is usually found to be half-wave rectification due to a defective rectifier or other component. The effect of a significant dc current offset is to drive the transformer core into saturation on alternate half-cycles. When the core saturates, exciting current can be extremely high, which can then burn out the primary winding in a very short time. Transformers that are experiencing dc-offset problems are usually noticed because of objectionably loud noise coming from the core structure. Industry standards are not clear regarding the limits of dc offset on a transformer. A recommended value is a dc current no larger than the normal exciting current, which is usually 1% or less of a winding’s rated current.

All these losses increase the amount of energy consumed. Accordingly, this increases the charge for electricity. Losses in transformers is an important parameter that is taken into account both in technical and economic calculations.

2.4 Summary

In this chapter, we consider the main parameters of the power supply system. Transformers and supply lines are selected by load calculation results. The initial data for the calculation are information about power consumers.

Transformers and lines are designed to deliver energy to end users. If these parameters are chosen incorrectly, then the consumer's work may be disrupted or even terminated. In addition, these parameters are not ideal and have power losses. These losses are recorded in electricity bills. The purpose of the optimal design is to reduce the value of such losses.

Thus, in this chapter we gained knowledge of *what* the parameters of the power supply system are. The next chapter will consider *how* to select the parameters of the power supply system.

3. Paper based approach

As mentioned earlier, power consumers have a decisive role in determining the parameters of the power supply system. To be more precise, the value of the electrical load of the receiving energy determines the choice of all parameters of the power supply system: power transformers, power and distribution cables. Therefore, the correct evaluation of electrical loads is a decisive factor in the design and operation of electrical networks.

The question of determining the electrical load appeared with the advent of electricity in the early twentieth century [17]. The complexity of calculating the electrical load was in several aspects. Firstly, low computing power at that time. Secondly, the nature of the electrical load. The electrical load changes very quickly, depending on the equipment, its efficiency and the work performed on it. In addition, the simultaneous operation of multiple power consumers must be considered. Since each of them in each unit of time has different parameters, this gives a system of nonlinear algebraic equations. This problem is called

Load Flow problem. Thirdly, the uniqueness of each object being developed, since even two identical engines will have slightly different parameters.

All these factors lead to the creation of various methods and approaches used in determining the expected load. The first methods that appeared were associated with statistical data and mathematical simplifications of some aspects. All of them were calculated manually, so in this work I combined them under the name of the *paper based approach* (PBA). With the development of computer technology new ways to solve the Load Flow problem have appeared. These new ways of solving this problem with the help of technologies are presented in this paper as a *computer based approach* (CBA).

This chapter will consider the history of approaches and the methods of calculation and computing that are used in this work. PBA methods will be described in Chapter 3. CBA methods will be described in Chapter 4.

3.1 Overview of paper based approach

Paper based approach (PBA) is a combination of various historical and statistical methods. These methods were based on the analysis of established enterprises to facilitate the calculation of new enterprises. They are still used as the main calculation approach in many countries of the world. [1]

The task of designing a power supply system begins with determining the electrical load. Most load calculation algorithms consist of a set of different statistical actions. There are methods for calculating the load, in which the calculation of electrical loads is based on changes in the load and stands out as the basic component. In addition, there are methods in which the characteristic of the load change is taken as a random process, that is, the application of each method depends on the nature of the load and the operating mode of the enterprise. Moreover, each method has its advantages and disadvantages. [17]

A wide variety of mathematical methods for calculating electrical loads can be reduced to two main types: analytical and numerical. Analytical methods are applicable for the simplest models, while numerical methods, on the contrary, are more general.

Numerical methods are more accurate, but more demanding on calculations. The results obtained are a quantitative assessment of the process and the state of the system, however, in order to assess the quality of calculation and its profitability, a knowledge and calculation base is needed that enables analysis and applicability of certain calculation methods.

Analytical methods are based on analytical transformations and on the classical laws of physics. They allow you to unify the calculations of electrical loads to a single form. These methods have found great application and played an important role in the design of power supply systems. However, due to changes in production conditions and a number of calculation assumptions, such as scalar addition of current values, analytical methods lead to overstated design loads, and, consequently, to increased capital costs in power supply systems, which affects the operation of the system and its development. [17]

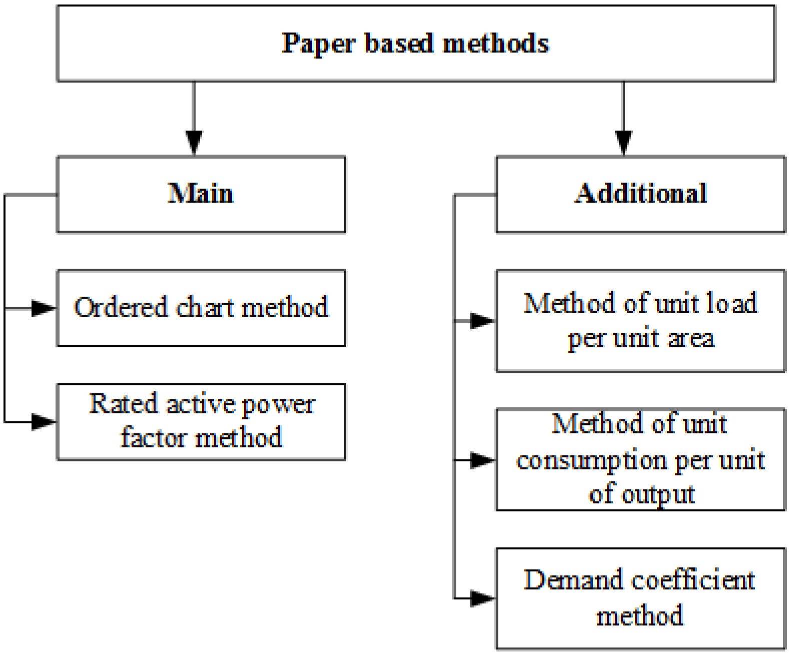


Figure 14 – Paper based methods of load calculation

We give a brief info about all these methods and more detailed information about methods which used in calculations.

3.2 Load calculation methods and concepts

Electric load is the first parameter for designing a power supply system. The first principles of load calculation appeared with the widespread distribution of electricity in the early 20th century. This chapter discusses methods for calculating the electrical load that are currently used in Russia.

3.2.1 Ordered chart method

The method is based on the research of G.M. Kayalov in the field of ordered diagrams of individual indicators of the operating mode of the electric drive and laid the foundation for guidelines for determining the electrical loads of industrial enterprises. [17]

Experimental studies of electrical loads in existing industrial plants have shown that individual and group load schedules of electric drives of the same profile are different, because depend on many random factors. The generalization of these characteristics is difficult. But if on their basis to build ordered charts by duration, then they closely coincide. This property serves as the starting point for the ordered chart method for determining design loads.

This method is no longer used for calculations. It was improved and rated active power factor method was created on its basis. Design of power supply systems is based on it [18]. We consider the rated active power factor method further.

3.2.2 Rated active power factor method

RAPFM is based on a modified method of ordered charts based on the normal distribution law. Since 1993, it has been the main and mandatory regulatory method for determining the electrical loads of industrial enterprises in Russia [1]. The definition of this method is given below and is based on [19]

The nature of the electrical load is probabilistic. Therefore, any mathematical method for describing the electrical load is based on probability theory and normal distribution.

The continuous random variable X has a *normal law distribution* (Gauss law) with parameters μ and σ, if its probability density has the form:

$$\varphi(x) = \frac{1}{\sigma\sqrt{2\pi}} \cdot e^{-\frac{(x-\mu)^2}{2\sigma^2}}, \qquad (6)$$

where μ is the mean or expectation of the distribution (and also its median and mode); and σ is its standard deviation.

The normal distribution curve is called normal curve or Gaussian curve.

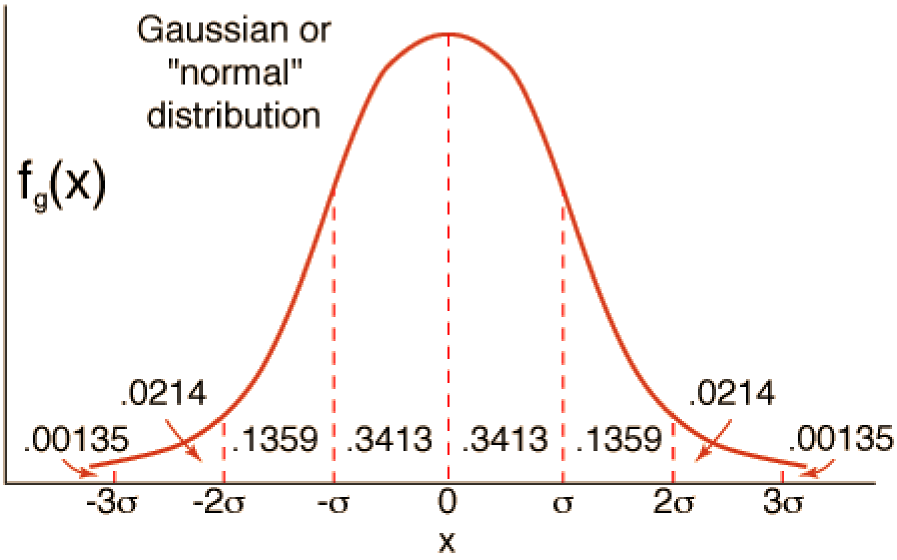


Figure 15 – Gaussian curve [20]

The problem is to understand in what range of values is the actual electrical load of the power consumer. For the solution, the Laplace formula is used. With its help, the probability of belonging of a value to a certain interval is determined. The probability of belonging to the interval (x_1, x_2) of a random variable X, subject to the normal law, is determined by the formula:

$$P(x_1 < X < x_2) = \Phi_0\left(\frac{x_2-\mu}{\sigma}\right) - \Phi_0\left(\frac{x_1-\mu}{\sigma}\right), \qquad (7)$$

where $\Phi_0(x) = \frac{1}{\sqrt{2\pi}} \int_o^x e^{-\left(\frac{x-\mu}{2\sigma}\right)^2} dt$ – Laplace’s law, probability density function.

The following assumptions are considered. We want to find an interval in which the value is 100% likely. However, this is not possible, therefore, we use the three sigma rule (rules for normally distributed data [20]) which provides a probability of 99.73%.

Under the normal distribution law, the design load and the probability of exceeding it are determined from the equation:

$$P_{rated} = P_{average} \cdot K_{rated}, \tag{8}$$

where K_{rated} is rated coefficient of active power, which gave name to this method. It is chosen in such a way that the power value satisfies the three sigma rule. These calculations are based on statistical data on power consumers, their operating time and loading.

The complexity of the analytical calculation of K_{rated} consists in the fact that its value depends on the number of power consumers in the group (sample size), their operating modes, and the load averaging interval.

For example, for small samples, the value of the calculated coefficient K_{rated} can be determined using Student's distribution coefficients using the following expressions:

$$K_{rated} = \frac{0.6 \cdot K_u + t \cdot \left(\frac{0.23}{\sqrt{n-1}} + \frac{0.3 - 0.25 \cdot K_u}{\sqrt{n-1} \cdot T} \right)}{K_u}, \tag{9}$$

where $K_u = \frac{P_{average}}{P_{nom}}$ – utility coefficient, relation between average and nominal power of power consumer, t – Student's distribution coefficient, n – number of power consumers working together, T - load averaging interval.

At the moment, there are many tables with a rated coefficient of active power for a different type and number of power consumers. This table data is used for calculation.

3.2.3 Statistical methods

Statistical methods are based on measuring the loads of lines supplying similar groups of power consumers, without resorting to the operation modes of individual electric drives and the numerical characteristics of individual schedules. The method considers that even for one group of mechanisms operating in a given production sector, coefficients and indicators are different.

The method uses two integral characteristics: the general average load and the general standard deviation, where the variance is taken for the same averaging interval.

Additional methods for calculating loads based on [4]:

1) *the demand coefficient method* is based on the calculation of maximum loads using the demand coefficient. It is used when the rated capacities of power consumers are known, as well as the demand coefficient and power factor. It is mainly used for factory-wide loads, as well as the calculation of lighting loads up to 1000 V.

The value of demand coefficient is assumed to be the same for electric consumers of one group (operating in the same mode) regardless of the number and power of individual consumers. Physical meaning is the fraction of the sum of the rated capacities of power consumers, which statistically reflects the maximum expected and encountered mode of simultaneous operation and loading of some indefinite combination (implementation) of installed consumers.

The reference data for demand coefficient correspond to the maximum value, and not to the mathematical expectation. The summation of maximum values, not average values, inevitably overstates the load.

2) *the method of specific consumption of electric energy per unit of production* is an approximate method of calculating loads and is based on the calculation of maximum loads for the annual consumption of active electric energy and the annual number of hours of use of the maximum active power. It was proposed in 1936 for the design of universal electrical networks for small and medium-sized engineering [16]. This method of calculating loads is used for the approximate determination of loads at the facility, since the issue of specific electricity consumption has not yet been resolved uniquely for all power receivers. However, the loads of pumping, compressor, and excavators can be determined by the specific energy consumption per unit of developed products. If there is data on the specific energy consumption and the lack of information on the installed capacity of the current collectors, this method is acceptable for rough calculations.

3) *the method of specific load per unit of production area* is an approximate method of calculating loads. It is based on the calculation of maximum loads according to specific design power per square meter of production area or the area of electric power receivers. The method is applicable for approximate calculations, however, it has been widely used in calculating the power of lighting loads of individual buildings of enterprise units, as Lighting load is evenly distributed over the area of the unit. Specific load power is determined by statistical data or reference literature for homogeneous production. This method requires a uniform distribution of electrical energy over the area of the room, and the specific power of the load depends on many factors.

At this moment in Russia, it is recommended to use the *rated active power factor method* to determine the electrical loads of industrial enterprises with voltages up to 1000 V. The *demand coefficient method* is used for objects with voltages above 1000 V. [21]

This chapter presents the basics of calculation methods. According to them, we get data on real electrical load. However, PBA does not end there. Now, according to the received electrical load data, equipment is selected. Laws and regulations for the selection of equipment are provided in Chapters 3.3 and 3.4.

3.3 Calculation of power supply lines

Calculation and selection of networks up to 1000 V

For electric networks with voltages up to 1000 V, technical requirements and conditions are decisive in the choice of conductor cross-section: heating conductors, mechanical strength, voltage loss, thermal resistance to short-circuit currents.

The choice of wire and cable sections is made by:

1) maximum allowable load current under heating conditions;

2) economic current density;

3) voltage loss.

Next Chapters 3.2.1-3.2.3 are based on [5].

3.3.1 Selection of the cross-section of wires, cables and busbars by heating

The current flowing along the conductor for a long time, at which the highest long-term admissible heating temperature of the conductor is established, is called the maximum allowable heating current I_{adm}.

The heating of conductors should not exceed the limit values of the long-term admissible temperatures (Table 5), in accordance with which the values of I_{adm} are set in the [5] (Table 6). Exceeding these temperatures leads to premature aging of the insulation of the conductors and reduces the reliability of the contacts.

Table 5 – Maximum allowable heating temperature of conductors [5]

Type of conductor (all of them are aluminum)	Continuous heating temperature, °C	Overload temperature, °C	Short circuit temperature, °C
Without insulation	70	125	200
PVC, PE, XLPE	55	110	150
EPR with voltage level, kV:			
6	65	110	200
10	60	90	200
35	50	75	125

The table is compiled for the following conditions:

1) the air temperature both indoors and outdoors is 25°C;

2) the soil temperature at a depth of cable laying is 15°C;

3) one cable is laid in the trench.

If the ambient temperature or the actual conditions for laying the conductor differ from those then appropriate amendments are introduced. First, the type of the conductor is selected depending on the characteristics of the environment of the room, its configuration and the method of laying the network.

Then choose the cross-section of the conductors under the condition of long-term permissible currents for heating. In this case, the calculated I_{calc} and admissible I_{adm} currents for the conductor of the accepted brand and its laying conditions are compared. The next relation must be satisfied:

$$I_{adm} \geq I_{calc} , \tag{10}$$

If the laying conditions differ from normal, then the admissible current is determined as

$$I'_{adm} = K_1 \cdot K_2 \cdot I_{adm} , \tag{11}$$

where K_1 - adjustment temperature coefficient which depends on outside temperature, dimensionless quantity;

K_2 - adjustment factor, depending on the number of cables laid in parallel and on the distance between them, dimensionless quantity;

I_{calc}, I_{adm}, I'_{adm} – different currents described before, A.

In the conditions of a two-transformer substation and several cables of one line, the conductor cross-section (selected for heating by continuous current) is checked by heating with current after the emergency mode:

$$I_{adm} = \frac{I_{a.emergency}}{K_1 \cdot K_2 \cdot K_{overload}}, \qquad (12)$$

where $K_{overload}$ is the coefficient of admissible short-term overload, dimensionless quantity;

$I_{a.emergency}$ - current after the emergency mode, A.

Table 6 – Continuous admissible current for wires and cables [5]

Cross-section, mm^2	PVC, PE, XLPE insulation		EPR
	Open	In conduit	In air
	Continuous admissible current, A		
2.5	24	19	-
4	32	23	-
10	60	39	45
16	75	55	60
35	130	85	95
50	165	120	110
70	210	140	140
95	255	175	165
120	295	200	200
150	340	255	230

This value of admissible current is approximate. Special adjustment tables are used to accurate this values. These adjustments depend on: temperatures of ground and air; number of wires lying together in the ground (with or without conduit).

3.3.2 Selection of the cross-section of conductors by economic current density

Electricity losses during transmission along the line and their cost increase with increasing line resistance, which is determined by the cross-section of the wire: the larger the cross-section of the wire, the lower the loss. However, at the same time, non-ferrous metal costs and capital costs for the construction of the line increase. Deductions for depreciation, maintenance and servicing are increasing (as capital costs increase). For reasons of economic feasibility, capital costs and annual operating costs are compared for several line options (but not less than two) [5]. The sum of the indicated components of the annual costs (C, monetary units) will have a minimum at an economically feasible section of the wire S_{ec}, mm^2 (Figure 16).

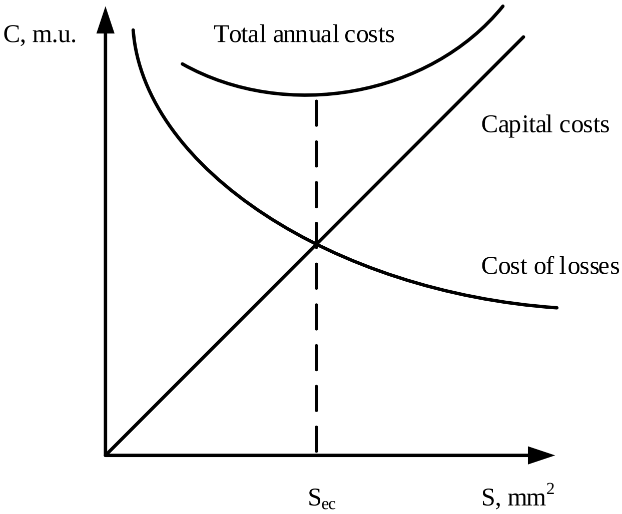


Figure 16 – Graph for determination the economic cross-section of conductors [5]

An economically feasible conductor cross section is determined by the rated current of the I_{calc} line and the economic current density J_{ec}:

$$S_{ec} = \frac{I_{calc}}{J_{ec}}, \tag{13}$$

where I_{calc} – calculated current, A;

J_{ec} - economic current density, A/mm^2.

The values of the economic current density J_{ec}, depend on the material, the design of the wire and the duration of use of the maximum load T_m.

It was found that in networks with voltages up to 1000 V, the cross-section selected by the economic current density is 2-3 times higher than the cross-section selected according to technical requirements (mechanical strength, heating, voltage loss).

Therefore, to eliminate this discrepancy, it is allowed:

1) to increase the economic current density for insulated wires with a cross section of more than 16 mm^2 by 40%;

2) do not check for economic density in:

- electrical networks at $T_m \leq$ 4000–5000 h;
- all branches to individual power consumers;
- lighting networks of industrial enterprises, residential and public buildings;
- networks of temporary structures with a service life of up to 5 years;
- busbars of switchgears and transformer substations.

Thus, in networks with voltages up to 1000 V, only workshop power networks (from transformers to distribution cabinets or buses) are selected in accordance with the economic current density.

3.4 Calculation of power supply transformers

The number of transformers and supply lines is determined depending on the reliability category of consumers. In the presence of a warehouse reserve or connections at a secondary voltage, reliable power supply to consumers of category II and III is provided by single-transformer substations [4].

If consumers of categories I and II prevail, then two-transformer substations are used.

When choosing the power of the transformers proceed:

- from the design load;
- from the number of hours of using the maximum load;
- from the perspective of enterprise development (load growth).

If one of the transformers or the line fails, according to the [22], the second can be overloaded by 40% for 5 days, 6 hours a day. If there is a load schedule, the power of the transformer is selected according to its overload capacity.

The rated power of the transformer is calculated by the expression:

$$S_{nom} = \frac{S_{calc}}{K_{allow.over.}}, \tag{14}$$

where $K_{allow.over.}$ – coefficient of allowed overload of transformer, dimensionless quantity. It depends on reliability category of power consumer; S_{nom}, S_{calc} – total powers, kVA.

By the value of S_{nom}, the nearest large standard power of the transformer $S_{nom.tr}$ is taken. If the load curve is not known, the transformer power is taken from the rated load. When designing a large enterprise with a large number of workshop transformers, the choice of the number and power of these transformers can be made according to the specific load density of the workshops.

The specific load density is determined by the expression:

$$\sigma = \frac{\sum S_{calc}}{\sum F_{workshop}}, \tag{15}$$

where $F_{workshop}$ - area of each workshop of enterprise, m^2;

S_{calc} – calculated total power, kVA;

σ - specific load density, kVA/m^2.

Recommended nominal power of transformers for different load densities are given in Table 7.

Table 7 – Recommended nominal power of transformers [5]

Specific load density, kVA/m^2	Recommended nominal power transformers, kVA
0.05-0.1	630
0.15	1000
<0.2	1600
<0.3-0.35	2500

The minimum number of transformers is determined by the formula:

$$N = \frac{\sum S_{rated}}{\beta_t \cdot S_{nom.tr}}, \tag{16}$$

where β_t - load coefficient of transformers in nominal work mode, dimensionless quantity;

S_{rated} – rated total power, kW;

N – number of transformers, units;

$S_{nom.tr}$ – selected rated power of transformer, kVA.

The calculated value is rounded to the nearest larger integer value N.

3.5 Summary

The mathematical model of PBA is based on probability theory. It is well-developed and tested over the years. The database for the calculations was collected from the middle of the last century. The results of PBA can be considered reliable at the beginning of the 21st century. However, PBA does not take into account changes in the power consumers themselves and the growth of computing abilities. Power consumers have changed significantly. The share of semiconductor devices has grown; the world economy is aimed at saving resources, more and more energy consumers are striving to reduce energy consumption, to be highly energy efficient. Moreover, we can say that the electrification of the world is almost complete. The growth of loads, which was laid in the basis of PBA, has become much less and somewhere it has completely opposite situation. In turn, computing abilities have developed greatly. This allows you to automate the calculation process and reduce the number of assumptions.

The mentioned factors and opportunities have become the reason for the appearance of CBA.

4. Computer based approach

The growth of computing power has made it possible to make a large number of complex calculations accurately and quickly. Certainly, this gave a step in the development of PBA, too. Now it is possible to compute all PBA algorithms and quickly fill out tables with the calculation of electrical load. However, the improvement of the mathematical model and the rejection of probability theory brought new ways to solve both the Load Flow problem and the design of the power supply system as a whole. In this chapter, mathematical methods of the CBA will be considered. Most of these methods are based on the Newton method, which is used in programs such as MatLab, ETAP, RastrWin, etc. [18]

4.1 Overview of computer based approach

Load flow study also known as power flow study, is an important tool involving numerical analysis applied to a power system. A power-flow study usually uses simplified notation such as a one-line diagram and per-unit system, and focuses on various forms of AC power (i.e.: voltages, voltage angles, real power and reactive power). Load flow studies are performed to determine the steady-state operation of an electric power system. It calculates the voltage drop on each feeder, the voltage at each bus, and the power flow in all branch and feeder circuits. Determine whether system voltages remain within specified limits under various contingency conditions, and whether equipment such as transformers and conductors are overloaded. It is used to identify the need for additional generation, capacitive, or inductive support, or the placement of capacitors and/or reactors to maintain system voltages within specified limits. Losses in each branch and total system power losses are also calculated. It is necessary for planning, economic scheduling, and control of an existing system as well as planning its future expansion.

There are two popular numerical methods for solving the power flow equations. These are the Gauss-Seidel and the Newton-Raphson methods. [18]

4.2 Load calculation methods

This chapter discusses methods for calculating the load and finding all the parameters of the system in steady state. These methods are used in the ETAP software that I used for modeling.

4.2.1 Load flow problem

The goal of a power flow study is to obtain complete voltage angle and magnitude information for each bus in a power system for specified load and generator real power and voltage conditions. Once this information is known, real and reactive power flow on each branch as well as generator reactive power output can be analytically determined.

The solution to the load flow problem begins with identifying the known and unknown variables in the system. The known and unknown variables are dependent on the type of bus. A bus without any generators connected to it is called a Load Bus. A bus with at least one generator connected to it is called a Generator Bus. The exception is one arbitrarily-selected bus that has a generator. This bus is referred to as the slack bus.

In the power flow problem, if the real power and reactive power at each Load Bus are known. For this reason, Load Buses are also known as PQ Buses. For Generator Buses, it is assumed that the real power generated P_G and the voltage magnitude V is known. For the Slack Bus, it is assumed that the voltage magnitude $|V|$ and voltage phase Θ are known. Therefore, for each Load Bus, the voltage magnitude and angle are unknown and must be solved for; for each Generator Bus, the voltage angle must be solved for; there are no variables that must be solved for the Slack Bus. [18]

4.2.2 Gauss-Seidel method

Gauss-Seidel method is the modification of Jacobi iteration method. In this chapter basics of the Jacobi iteration method and Gauss-Seidel method are considered. This chapter based on [23]

Jacobi iteration method

Consider the following system of linear equations,

$$\begin{aligned} &a_{11}x_1 + a_{11}x_2 + \ldots + a_{1n}x_n = b_1; \\ &a_{21}x_1 + a_{22}x_2 + \ldots + a_{2n}x_n = b_2; \\ &\qquad\qquad . \\ &\qquad\qquad . \\ &\qquad\qquad . \\ &a_{n1}x_1 + a_{n2}x_2 + \ldots + a_{nn}x_n = b_n. \end{aligned} \tag{17}$$

These Equations 17 can be rewritten, by solving the *i*th equation for the unknown x_i (i=1, 2, …, n), as follows:

$$\begin{aligned} &x_1 = \frac{1}{a_{11}}\left[b_1 - a_{12}x_2 - \ldots - a_{1n}x_n\right]; \\ &x_2 = \frac{1}{a_{22}}\left[b_2 - a_{21}x_1 - \ldots - a_{2n}x_n\right]; \\ &\qquad\qquad . \\ &\qquad\qquad . \\ &\qquad\qquad . \\ &x_n = \frac{1}{a_{nn}}\left[b_n - a_{n1}x_n - \ldots - a_{n,n-1}x_{n-1}\right]. \end{aligned} \tag{18}$$

It could be expressed in a compact form as

$$x_i = \frac{1}{a_{ii}}\left[b_i - \sum_{j=1,\ j\neq i}^{n} a_{ij}x_j\right];\ i = 1, 2, \ldots, n. \tag{19}$$

In the Jacobi iteration method, we start with a set of initial (approximate) values $x_1^{(1)}, x_2^{(1)}, \ldots, x_n^{(1)}$ for $x_1, x_2, \ldots, x_n$, respectively. If no better initial estimate is available, we can assume each component to be zero. The assumed solution $x_i^{(1)}$ is substituted into the right-hand side of Equation 18 or 19 to generate a new solution as

$$x_i^{(2)} = \frac{1}{a_{ii}}\left[b_i - \sum_{j=1,\ j\neq i}^{n} a_{ij}x_j^{(1)}\right];\ i = 1, 2, \ldots, n. \tag{20}$$

These values, $x_i^{(2)}$, obtained after the first iteration, are substituted into the right-hand side of Equation 19 or 20 to generate the next set of values, $x_i^{(3)}$. This iterative process can be expressed as

$$x_i^{(k+1)} = \frac{1}{a_{ii}}\left[b_i - \sum_{j=1,\ j\neq i}^{n} a_{ij}x_j^{(k)}\right];\ i = 1, 2, \ldots, n;\ k = 1, 2, \ldots. \tag{21}$$

The iterative process is continued until the values of $x_i^{(k)}$ determined in two successive iterations are sufficiently close to one another. Thus, the convergence criterion for stopping the iterative process can be assumed as

$$\left|x_i^{(k+1)} - x_i^{(k)}\right| \leq \varepsilon;\ i = 1, 2, \ldots, n, \tag{22}$$

or

$$\left|\frac{x_i^{(k+1)} - x_i^{(k)}}{x_i^{(k)}}\right| \leq \varepsilon;\ i = 1, 2, \ldots, n, \tag{23}$$

where ε is a small number. It has been found that a sufficient condition for the convergence of Jacobi method is

$$\left|a_{ii}\right| > \sum_{j=1,\ j\neq i}^{n} \left|a_{ij}\right|, \tag{24}$$

Thus, the values $x_i^{(k)}$ will converge to the correct solution irrespective of the initial values $x_i^{(1)}$ used when the condition of Equation 24 is satisfied. Note that the condition of Equation 24 implies that the equations are diagonally dominant; that is, the coefficient on the diagonal in any row is larger than the sum of the absolute values of the other coefficients in the same row.

Gauss-Seidel iteration method

Gauss-Seidel iteration method is modification of Jacobi method. The main idea of the modification is that the new values $x_i^{(k)}$ are used here immediately as they are received, while they are not used in the Jacobi method until the next iteration.

In Jacobi iteration method, all the variables $x_i^{(k+1)}$ are computed using the values of the previous iteration $x_i^{(k)}$. This implies that both the present, as well as the previous set of values, are to be stored. The storage requirement and the rate of convergence can be improved using the Gauss-Seidel method. The main idea is that the values of $x_1^{(k+1)}$, $x_2^{(k+1)}$, …, $x_i^{(k+1)}$ computed in the current iteration, along with values of $x_{i+2}^{(k)}$, $x_{i+3}^{(k)}$, …, $x_n^{(k+1)}$, are used in finding the value $x_{i+1}^{(k+1)}$. This implies that always the most recent approximations to the variables are used during the computations. The iterative process can be expressed as follows:

$$x_i^{(k+1)} = \frac{1}{a_{ii}}\left[b_i - \sum_{j=1}^{i-1} a_{ij}x_j^{(k+1)} - \sum_{j=i+1}^{n} a_{ij}x_j^{(k)}\right];\ i=1,2,...,n;\ k=1,2,.... \tag{25}$$

The convergence criterion can be found as in Jacobi iteration method. [23]

The Gauss-Seidel method is simple to program and implement. An accurate solution can be expected even when the number of equations is very large. The main criterion to imply this method is diagonally dominant (sparse) matrix. In the case of the Load Flow problem, the matrix is mainly diagonally dominant. Since the conductivity of own power consumer conductor will be quite large, while the parallel conductivity of other conductors will be small.

4.2.3 Newton-Raphson method

The theoretical explanation of this method is based on [23].

The Newton-Raphson method, or simply the Newton's method, is a well-known and most powerful method used for finding the root of the equation $f(x)=0$. The Newton's method can be derived to considering the Taylor's series expansion of the function $f(x)$ about an arbitrary point x_0 as

$$f(x) = f(x_0) + (x - x_0)f'(x_0) + \frac{1}{2!}(x - x_0)^2 f''(x_0) + ..., \tag{26}$$

where the function, f, and its derivatives, f', f'', ... on the right-hand side are evaluated at x_0. By considering only the first two terms in Equation 26, we have

$$f(x) \approx f(x_0) + (x - x_0) f'(x_0). \tag{27}$$

In order to find the root of *f(x)=0*, we set *f(x)* equal to zero to obtain:

$$f(x_0) + (x - x_0) f'(x_0) = 0. \tag{28}$$

Since the higher order derivative terms were neglected in the approximation of *f(x)*, the solution of yields in the next approximation to the root (instead of exact root) as

$$x = x_1 = x_0 - \frac{f(x_0)}{f'(x_0)}, \tag{29}$$

where x_1 denotes an improved approximation to the root. To further improve the root, method uses x_1 in place of x_0 on the right-hand side of Equation 29 to obtain x_2. This iterative procedure can be generalized as

$$x_{i+1} = x_i - \frac{f(x_i)}{f'(x_i)} : i = 1, 2, ... \tag{30}$$

The procedure is shown graphically in Figure 17 assuming a real root for the equation *f(x)=0*.

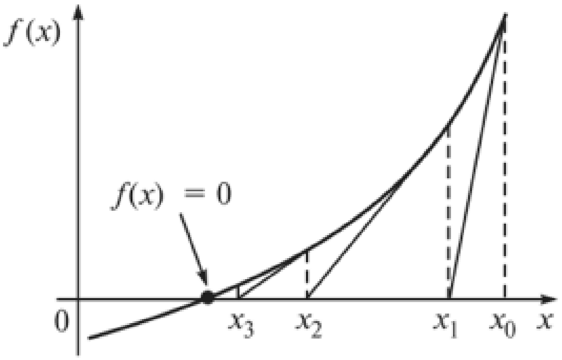


Figure 17 – Newton-Raphson method [23]

If x_0 is the initial guess for the root of *f(x)=0,* the point of intersection the tangent to the curve at x_0 with the *x* axis gives the next approximation to the root, x_1. The convergence of the procedure to the exact root can also be seen in Figure 17. [23]

The disadvantage of this method is its high sensitivity to the choice of the initial approximation (x_0). This disadvantage is almost neglected in case of a Load Flow problem because the unknown variable is voltage. In this case, the nominal value of the voltage of the device, bus, node can be used as an initial assumption. This ensures high accuracy of this calculation method. In addition, one of the main advantages of this method is the convergence rate.

The Newton Raphson method is used in ETAP software to calculate the steady state conditions. The Newton-Raphson method formulates and solves iteratively the following load flow equation [24]:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \tag{31}$$

where ΔP and ΔQ are bus real power and reactive power mismatch vectors between specified value and calculated value, respectively; ΔV and $\Delta\delta$ represents bus voltage magnitude and angle vectors in an incremental form; and J_1 through J_4 are Jacobian matrices of current. We use this method for CBA and to evaluate PBA calculations. [24]

4.3 Calculation of power supply lines

Power supply lines should be already known to use Newton-Raphson method. Therefore, using the methods, the selected lines are checked for voltage, losses and other parameters. The decision on the choice of lines, one way or another, is made by the engineer. Simulation data in various programs only help him make this choice. Therefore, in this chapter, we consider the calculation of the parameters of already selected power lines. Modeling capabilities allow you to simulate several options and choose the best.

4.3.1 Selection of the cross-section of wires, cables and busbars

Cross-section of wires, cables and busbars are input data for program like ETAP, MATLAB, RastrWin and etc. A typical cable cross-section determines its electrical parameters: positive-sequence cable resistance, positive-sequence cable reactance, positive-sequence cable charging susceptance and the same parameters for zero-sequence.

The insulation of the conductor, armor and type of conductor are important for calculation. These parameters are determined by cable type (as presented in Chapter 2.2). Also, the type of cable determines ampacity of cable in different conditions. The last but not least determining factor is installation parameters. Depending on what and where the cable connects, its length and base temperature varies.

4.3.2 Calculations of losses in cables

Losses are calculated based on the calculation of the Load Flow problem. The approach to finding the value is as follows. The power value at the end of the line and at the beginning is known. The difference between these two values gives a loss of power on the line. A similar situation with voltage losses.

In fact, the calculation of losses has not changed, but its accuracy has increased significantly due to a more accurate calculation of the steady state.

4.4 Calculation of power supply transformers

The situation with transformers is the same as the situation with cables. It is necessary to know the parameters of the transformer before we carry out the calculation using the CBA. To calculate the transformer, its following technical parameters are needed:

- Voltage rating – primary and secondary winding;
- Rated power;
- Impedance base;
- Type of cooling;
- Installation information – room temperature.

The more input parameters, the more accurate the calculation is. Mandatory parameters are the rated power and voltage of the transformer.

4.5 Summary

CBA is very effective in calculating electrical load data. The accuracy of the calculation of the load is significantly better than PBA. This is due to the use of strong mathematical methods – the Newton-Raphson method and others. However, the CBA has difficulties with the selection of equipment. In order to make this selection, there must be an extensive database of equipment, as well as algorithms that consider many parameters. Such algorithms exist and they are applied. However, they are difficult to learn and require the entering of a lot of information into the database. Therefore, it is much more efficient to simulate several models of the selected equipment yourself. Modeling allows you to quickly change the transformer to a higher or lower power, cable to a larger or smaller one, and evaluate the results of these changes.

Summing up, the CBA will be used to evaluate the results obtained by the PBA method. In the case that these results are unsatisfactory, the equipment should be improved to obtain satisfactory results.

5. Calculating by paper based approach

We will calculate the power supply system of the metallurgical plant. Initial data on workshop loads and location are presented in Table A.1 and Figure B.1. For all workshops, data on the nominal load are available. The data of the mechanical repair workshop are presented from the level of end-use power consumers.

The calculation of the power supply system begins to calculate the electrical load of the electrical receivers. Then, according to the calculated electrical load, supply lines and transformers will be selected.

5.1 Calculating of electrical load

Mechanical repair workshop

Calculation of electrical loads of power receivers with voltage up to 1 kV is performed according to form F636-92 and is performed for each power supply unit, as well as for the workshop and the building as a whole. [1, 19]

Initial data for mechanical repair workshop presented in Table A.2. First of all, all consumers should be divided into groups by location. Such groups will be powered from a single distribution box. This distribution is presented in Figure B.2. Explanations for the calculations are presented below. Table with the calculations is presented in Table A.3.

Columns 1–4 are filled out on the basis of the initial data, columns 5–7 according to the reference materials. If there is an interval value of K_u in the reference materials, the highest value should be taken for calculation. Each line indicates power consumers of the same power. At the same time, reserve consumers are not taken into account in the calculation, and the rated power of electric motors with intermittent operation is not reduced to continuous operation.

Further, for each group of power consumers in columns 8 and 9, respectively, values are written row by row, and the sum of these quantities is determined in the final line:

$$\sum K_u \cdot P_{nom} \text{ and } \sum K_u \cdot P_{nom} \cdot \tan\varphi, \tag{32}$$

There are values of active and reactive power, where K_u – utilization rate, relation between average and nominal power, P_{nom} – nominal power of power consumer, $\tan\varphi$ – relation between reactive and active components of the load. All this data is given.

Weighted average (group) utilization rate for a given power unit:

$$K_{u.group} = \frac{\sum K_{usage} \cdot P_{nom}}{P_{nom}} \tag{33}$$

This value written in column 5 of the total line. The effective number of power consumers is determined by the formula:

$$n_{eff} = \frac{\left(\sum P_{nom}\right)^2}{\sum P_{nom}{}^2 \cdot n}, \tag{34}$$

where n – number of power consumer connected through one distribution box. The number of effective consumers found by the formula is rounded to the nearest lower integer. The rated active power connected to one distribution box (column 12) is determined by the formula:

$$P_{rated} = K_{rated} \cdot \sum K_u \cdot P_{nom}\,[W], \tag{35}$$

where K_{rated} is rated coefficient of active power (more information presented at Chapter 3.2.2.)

The rated reactive power connected to one distribution box (column 12) is determined by the next formulas:

- if $n_{eff} \le 10$, $Q_{rated} = 1.1 \cdot \sum K_u \cdot P_{nom} \cdot \tan\varphi\,[Var]$, (36)
- if $n_{eff} > 10$, $Q_{rated} = \sum K_u \cdot P_{nom} \cdot \tan\varphi\,[Var]$. (37)

The total rated power (column 14) is determined by the formula:

$$S_{rated} = \sqrt{P_{rated}{}^2 + Q_{rated}{}^2}\,[VA], \tag{38}$$

where P and Q is rated active and reactive power respectively. You also could find value of current for the workshop. Total load of mechanical workshop is 338.15 kVA. Now, we should recalculate loads of all workshops. The calculation is done. Now we can proceed to consider the load of the entire enterprise.

Entire enterprise. The rated power of the enterprise is determined by the rated active and reactive loads of the workshops (up to and above 1000 V), taking into account the design load of the lighting of the workshops and the territory of the enterprise, the power losses in the transformers of the workshop substations and main power stations and losses in high-voltage lines.

The electrical load of the plant is calculated using the demand coefficient method [1]. The goal of the calculation is to determine the rated power that the company needs to work. Therefore, this power should take into account losses (MSDS, workshop transformers, high-voltage lines) and lighting (workshops and enterprise area).

The calculation of power load and lighting load is carried out according to the following formulas

$$\begin{aligned} P_{rated} &= K_d \cdot P_{nom}\,[W], \\ Q_{rated} &= \tan\varphi \cdot P_{rated}\,[Var], \end{aligned} \tag{40}$$

where P_{nom} is total installed capacity of all receivers in the workshop; K_d is the demand coefficient, taken according to the table data [4]; tanφ is found according to the corresponding value of the power factor for this workshop.

To determine the total loads in the workshop, transformer or substation as a whole, we add to the power loads the lighting load from lighting, determined by the formula:

$$P_{ratedL} = K_{dL} \cdot P_{nomL} \ [W], \tag{41}$$

where K_{dL} is the demand coefficient for lighting, $P_{nomL} = F_{ws} \cdot P_{spec}$ is nominal lighting load for workshop, P_{spec} is the specific density of the lighting loads, $W/\,m^2$ taken as reference data [4], F - workshop area, m^2.

The total rated load of the workshop is determined by the expression:

$$S_{rated} = \sqrt{\left(P_{rated} + P_{ratedL}\right)^2 + Q_{rated}} \ [VA], \tag{42}$$

Calculation of all workshops by this algorithm are presented in Table A.4. Total demand of power for enterprise presented in Table 8.

Table 8 – Total demand of power for metallurgical plant

Total area of workshops, F, m^2	37 100
Total nominal power, P_{nom}, kW	16 548
Total rated active power, P_{rated}, kW	7 848
Total rated reactive power, Q_{rated}, kVar	6 878
Total rated power, S_{rated}, kVA	10 485

This demand of power is distributed between the workshop substations. All data on the rated power are known, we can proceed to the selection of equipment.

5.2 Selection of supply transformers

In order to select workshop transformers, we should find specific load density as mentioned in Chapter 3.4:

$$\sigma = \frac{\sum S_{rated}}{\sum F_{workshop}} = \frac{10485}{37100} = 0.28\,\text{kVA/m}^2 \tag{43}$$

where $F_{workshop}$ - area of each workshop of enterprise, m^2. According to Table 7 (Chapter 3.4) recommended nominal power of transformers with σ<0.3-0.35 is 2500 kVA. However, the load on the workshops is unevenly distributed and I will also use transformers with a power of 1600 kVA in order to manage transformers load more precisely.

The reliability category of all workshops is I or II (Table A.1). It means that load coefficient of transformers should be less or equal to 0.7 [4]. In addition, two transformers must be installed at each workshop substation to satisfy the reliability category. Also, the location of the workshops is a factor in choosing the number of transformers. Since the number of workshops is quite large (15) and the load varies greatly, it is impractical to install a workshop substation in each workshop. Therefore, we will preliminarily distribute the workshops among the workshop substations. The study guide [4] recommends that you install the number of transformers almost half as many as the number of workshops in this category of reliability. In this way we get eight transformers, two at each workshop substation. A total number of workshop substations is four.

Workshop substations and workshops connected to them and their rated power are presented in Table 9.

Table 9 – Workshop substations

No. of substation	Connected workshops	Total rated power, kVA
WS 1	Workshops 5, 11	3 163
WS 2	Workshops 6, 8, 9, 10	3 101
WS 3	Workshops 12, 13, 14	1 651
WS 4	Workshops 1-4, 7, 15	2 571

The total power of workshop substations WS 1 and WS 2 are higher than 3 000 kVA, so I decided to use transformers with nominal power 2 500 kVA for them. Now I can calculate the number of required workshop transformers.

$$N_{2500} = \frac{S_{ratedWS1} + S_{ratedWS2}}{\beta_t \cdot S_{nom.tr}} = \frac{3163 + 3101}{0.7 \cdot 2500} = 3.58 \approx 4, \tag{44}$$

$$N_{1600} = \frac{S_{ratedWS3} + S_{ratedWS4}}{\beta_t \cdot S_{nom.tr}} = \frac{1651 + 2571}{0.7 \cdot 1600} = 3.73 \approx 4, \tag{45}$$

As mentioned in Chapter 3.4 calculated value is rounded to the nearest larger integer value *N*. The final results of transformer's selection presented in Table 10.

Table 10 – Selected transformers

No. of substation	Connected workshops	Model and number of transformer
WS 1	Workshops 5, 11	2x TS-2500/10/0.4
WS 2	Workshops 6, *8*, 9, 10	2x TS-2500/10/0.4
WS 3	Workshops 12, 13, 14	2x TS-1600/10/0.4
WS 4	Workshops 1-4, 7, 15	2x TS-1600/10/0.4

I selected dry transformers with air blast cooling TS-2500/10/0.4 and TS-1600/10/0.4 by SVEL [25]. It is experienced company with leading positions on Russian transformers market. All products comply with state standards, international and European standards.

Figure 18 – Dry transformer SVEL TS-2500/10/0.4 [25]

SVEL transformers shows high efficiency and quality of work. These transformers are widely used in the metallurgical, drilling, oil, gas, and other industries of Russia [25]. Selected transformers will be evaluated by load coefficient and voltage loss. The selection of transformers is completed, now we can proceed to the selection of cable lines.

5.3 Selection of cable lines

The distribution network above 1000 V in the territory of the plant is carried out by cable lines laid in trenches. We select cable lines with aluminum core and paper insulation for 10 kV distribution network according to study guide [4]. The selection of cable cross-section is carried out using the economic current density (Chapter 3.3.2). Consider the choice of cable for workshop substation 1. Calculations for all cables presented in Table 11.

First, we should find current which is determined by the nominal power of the transformer.

$$I_{WS1} = \frac{n_{tr} \cdot S_{nom.tr}}{n_{cables} \cdot \sqrt{3} \cdot U_{nom.tr}} = \frac{2 \cdot 2500}{2 \cdot \sqrt{3} \cdot 10} = 144.34 \text{ A}, \tag{46}$$

where $U_{nom.tr.}$=10 kV, nominal voltage of high voltage side of transformer. Next step is to determine economically feasible cable cross-section:

$$S_{ec} = \frac{I_{WS1}}{J_{ec}} = \frac{144.34}{1.2} = 120.28 \text{ mm}^2, \tag{47}$$

where J_{ec}=1.2 – economic current density for 10 kV cable line, A/mm^2 [16]. We round the resulting cross-section to the nearest standard value and accept a cable with a cross-section of 120 mm^2. Then check this cross-section.

In the conditions of a two-transformer substation and several cables of one line, the conductor cross-section (selected for heating by continuous current) is checked by heating with current after the emergency mode:

$$I_{adm} \geq \frac{I_{a.emergency}}{K_1 \cdot K_2 \cdot K_{overload}} = \frac{2 \cdot 144.34}{1 \cdot 0.92 \cdot 1.2} \tag{48}$$

$$240\text{ A} \geq 261\text{ A}$$

The requirements are not met. We increase the cable section by one size. We accept a cable with a cross-section of 150 mm^2. This algorithm has been applied to all cable lines.

Table 11 – Selected cables

Connection	Current per one cable, A	S_{ec}, mm^2	I_{adm}, A	After emergency checking, A	Final cross-section, mm^2
MSDS – WS 1	144.34	120.28	240	261	150
MSDS – WS 2	144.34	120.28	240	261	150
MSDS – WS 3	92.38	76.98	165	167	95
MSDS – WS 4	92.38	76.98	165	167	95

Selected cable lines will also be evaluated by load and voltage loss. All the main parameters of the power supply system are selected.

5.4 Supply system overview

In Chapter 5, the calculation of the electrical load is made and all the necessary equipment for the transmission and distribution of energy is selected. At this point, the results of PBA seem to be reliable and satisfying the needs of the plant. All the selected parameters presented in Table 12.

Table 12 – Results of PBA

Method	PBA			
Workshop substation	1	2	3	4
Nominal power of transformers, kVA	2500	2500	1600	1600
Cable, mm^2	150	150	95	95

Evaluation of technical effectiveness can also be done by PBA. However, modeling using ETAP software will show more accurate results and allow us to evaluate PBA and CBA equally. Therefore, the results of the PBA simulation presented in Chapter 7.

6. Computing by computer based approach

The nominal data on the electrical load of the workshops are the initial data for the calculation. Based on the features of the CBA (Chapters 4.3, 4.4), the initial equipment for the calculation will be the equipment selected by the PBA. After modeling the results of the PBA, a conclusion will be made about further changes in the parameters of the power supply system.

6.1 Modeling a power supply system using computer based approach

According to the results of calculations of the power supply system of the metallurgical plant by the PBA (represented at Chapter 5), we obtained data on all the necessary parameters: cables, transformers and loads. Transformers and cables parameters presented in Table 13 and Table 14, respectively.

Table 13 – Parameters of transformers [25]

Substation	Model of transformer	Nominal power S, kVA	U_h, kV	U_d, kV	ΔP_{idle}, kW	ΔP_{sc}, kW	U_{sc}, %	I_{idle}, %
WS 1/2	TS-2500/10/0.4	2500	10	0.4	4	20.5	6	0.65
WS 3/4	TS-1600/10/0.4	1600	10	0.4	4.2	16	5.5	1.5

Table 14 – Parameters of cable lines [26]

Cross-section, mm^2	Unit active resistance, r_0, Ohm/km	Unit reactive resistance, x_0, Ohm/km	I_{adm}, A
150	0.206	0.079	240
95	0.32	0.083	165

We have all information to simulate power supply system in ETAP. We will evaluate the following parameters: loading of cable lines and workshop transformers, workshops voltages. These parameters are selected as fundamental for technical analysis. We will present 15 workshops of the enterprise in the form of a distributed load and we will present the mechanical repair workshop as a separate subsystem. External power generation system presented as infinite power buses. Simulated power supply system presented at Figure 19.

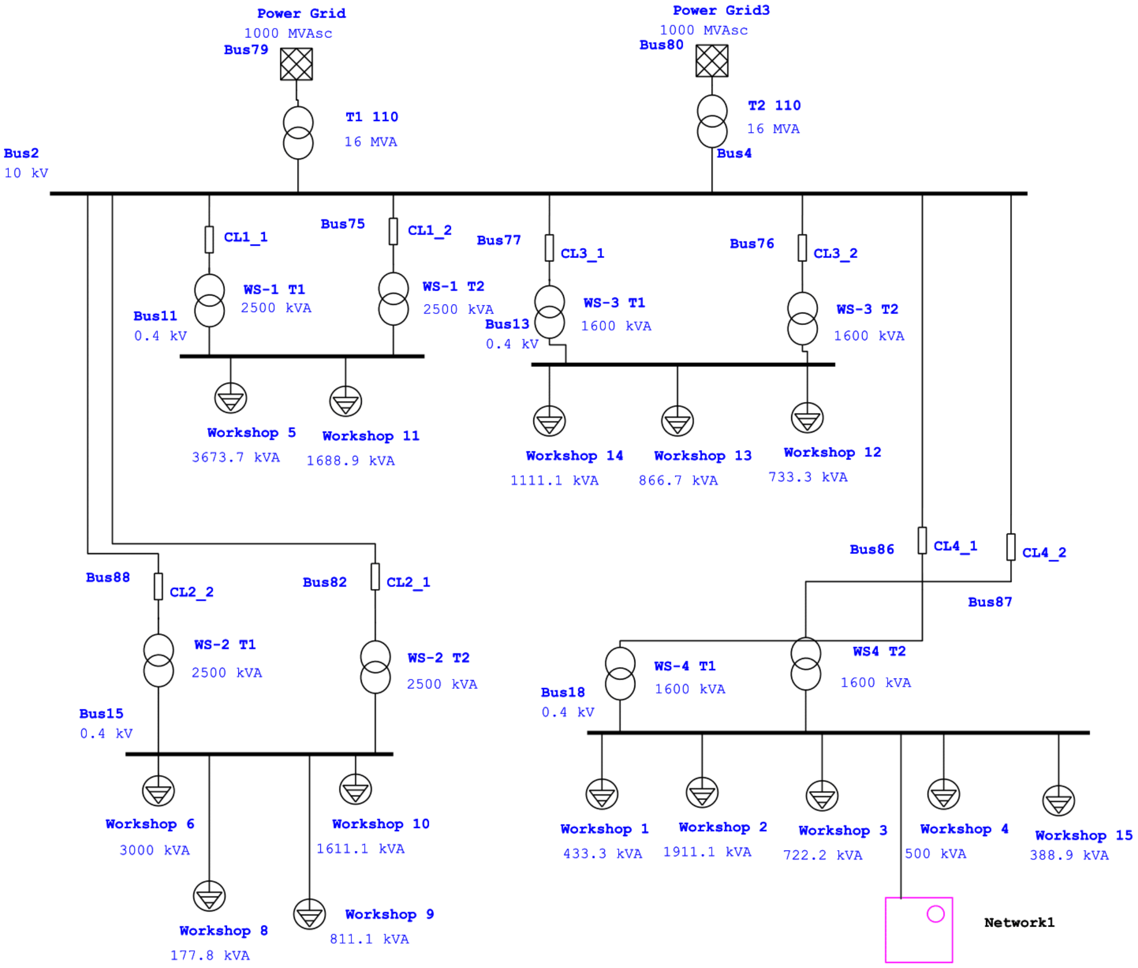


Figure 19 – Power supply system by PBA

After modeling, we obtain the following results. The first parameter to compare is the loading of transformers and cable lines. Two transformers in one substation operate in parallel. Therefore, the data given for one transformer at substation, the data for the second are identical. The same statement is true for cable lines. Transformer loading is presented in Table 15.

Table 15 – Results for transformer loading

Substation	Nominal power of one transformer *S*, kVA	Total load of one transformer , kVA	Loading, %
WS1	2 500	2 533	101.3
WS2	2 500	2 550	102
WS3	1 600	1 190	74.8
WS4	1 600	2 585	161.1

The load coefficient of transformers should be less or equal to 70% [4]. This condition is not met for any substation. All transformers are overloaded. Next step is to estimate loading of cable lines. Loading of cable lines is presented in Table 16.

Table 16 – Results for cable lines loading

Cable line	Current after simulation, A	Admissible current, A	Loading, %
CL1	161.45	240	67.27
CL2	162.71	240	67.37
CL3	75.43	165	45.72
CL4	108.95	165	66.05

The load coefficient of cable lines should be less than 1 [4]. This condition is met for all cable lines. However, CL3 shows a low load. This cable can be replaced by reducing one section. This replacement can make the project more cost effective.

The second parameter to compare is the voltage of workshops. Rated voltage must be within the standards of GOST. This means that it should be within range 380V ± 5% [8]. Workshop's voltage and tolerance bounds are shown on Figure 20.

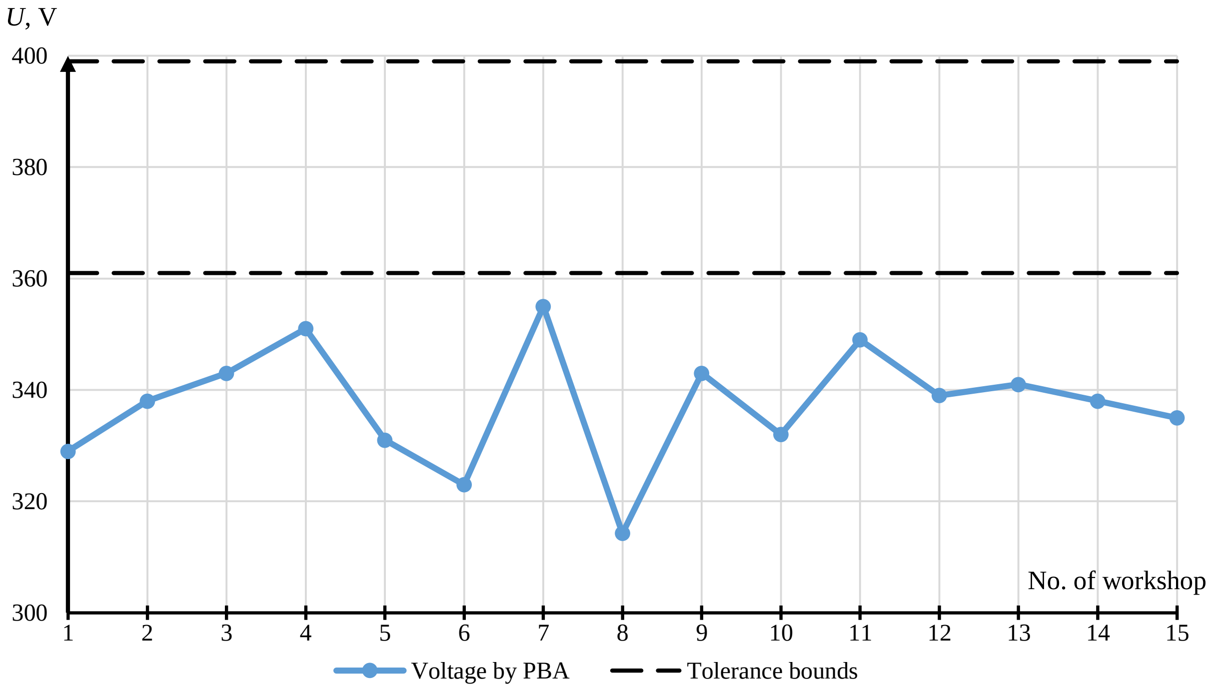


Figure 20 – Voltage of workshops according to PBA results

The voltage of all workshops lies below the tolerance bounds. A discussion on the reliability and quality of such a power system is presented in Chapter 7. At the moment, we can say that the results of PBA modeling are unsuccessful. Therefore, the parameters of the power system should be adjusted. Adjustment carried out to a satisfactory voltage of the shops and loading lines and transformers.

The main reason for this difference in the expected voltage and load lies at the root of the difference between the PBA and the CBA. This is the difference in calculating the electrical load described in Chapters 3 and 4. With the same input data, various results were obtained using the PBA and CBA simulation.

6.2 Adjusting power supply system by computer based approach

The PBA model for the power supply system showed unsatisfactory results. Overloaded transformers negatively affect the voltage of the workshops. Therefore, it is necessary to replace transformers with more powerful ones. Also compare the new loading of transformers with the previous ones. Results after simulation with new transformers are presented in Table 17.

Table 17 – New transformers and loading comparison

Substation	PBA transformers *S*, kVA	Loading for PBA, %	CBA transformers *S*, kVA	Loading for CBA, %
WS1	2 500	101.3	4 000	66.1
WS2	2 500	102	4 000	67.0
WS3	1 600	74.8	1 600	74.8
WS4	1 600	161.1	3 150	71.5

The simulation results show that the loading of the transformers has decreased significantly. Now it satisfies or is very close to the requirements of a design study guide [4]. An increase in power in the case of the third and fourth substation will lead to underloading of transformers. This makes it irrational to use high power transformers both technically and economically.

The next step is to replace the cable line. Cable line CL3 with cross-section 90 mm^2 from Table 16 is replaced by cable line with cross-section 50 mm^2. This replacement increased the cable load to 64%. This value is acceptable for cable lines [4]. Also, we reduce the cost of this cable.

The next step is to compare voltage of workshops. Let us evaluate voltage level in the workshops changes and whether it satisfies the norms now.

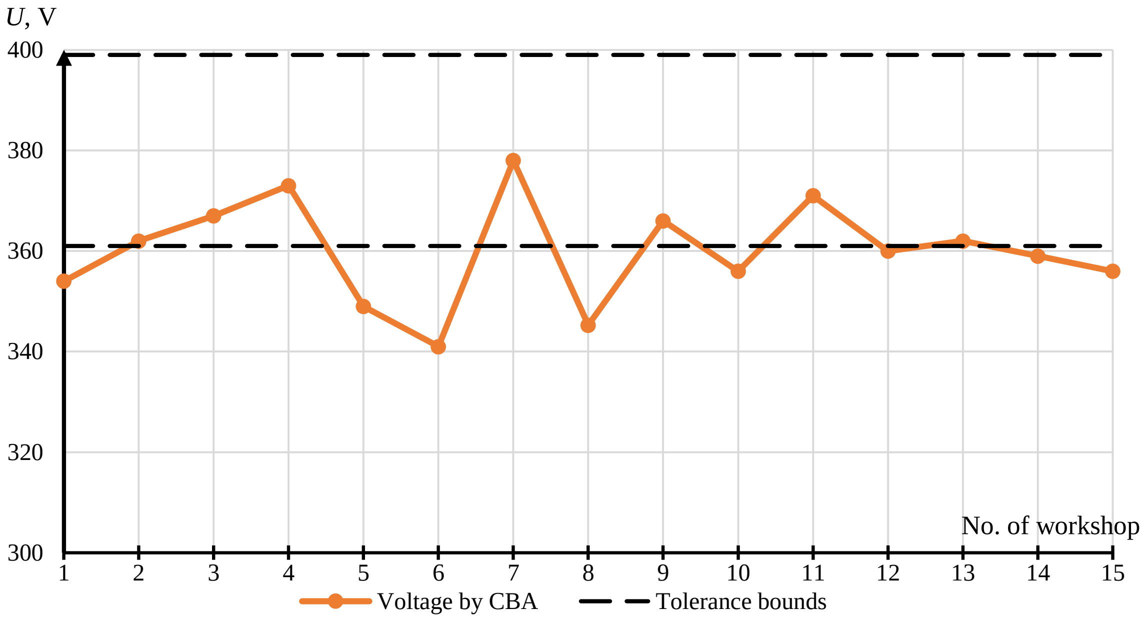


Figure 21 – Voltage of workshops according to CBA results

The voltage level of half of workshops corresponds with tolerance bounds. Voltage of other workshops could be adjusted by different ways. Certainly, voltage regulation can also be carried out in the case of PBA with on-load tap changer of transformer or capacitor banks. However, such an adjustment cannot be unlimited. The lower the voltage drop, the better power consumers will work.

6.3 Results

In this chapter, the PBA has adjusted using the CBA. New transformers and cable lines are selected. CBA results are more satisfactory than PBA results. Of course, the voltage of several workshops is still beyond the tolerance bounds. However, the loading of transformers has become normal.

The installation of more powerful transformers leads to a significant improvement in the technical component of the project. However, this also affects the economic efficiency of the system. In addition, an important technical and economic parameters are not considered - electricity losses. These parameters are discussed in Chapters 7 and 8.

7. Technical comparative analysis of results obtained by PBA and CBA

The output data of methods are presented in Table 18.

Table 18 – Output data of PBA/CBA method

	PBA/CBA			
Substation	1	2	3	4
Nominal power of transformers, kVA	2 500/ 4 000	2 500/ 4 000	1 600/ 1600	1 600/ 3 150
Cross-section of cable, mm^2	150/150	150/150	95/50	95/95

First, we should compare technical characteristics of the system. In this chapter, we consider the level of voltage, energy loss and the possibilities that the selected parameters provide for the expansion of the enterprise.

7.1 Analysis of voltage level

An important parameter of the quality of electricity is voltage. A proper parameter for comparing voltage is voltage drop (Chapter 2.1.5). To analyze stability of system we compare average voltage deviation of 380 kV buses of enterprise. Figure 22 shows the voltage deviations at enterprise workshops.

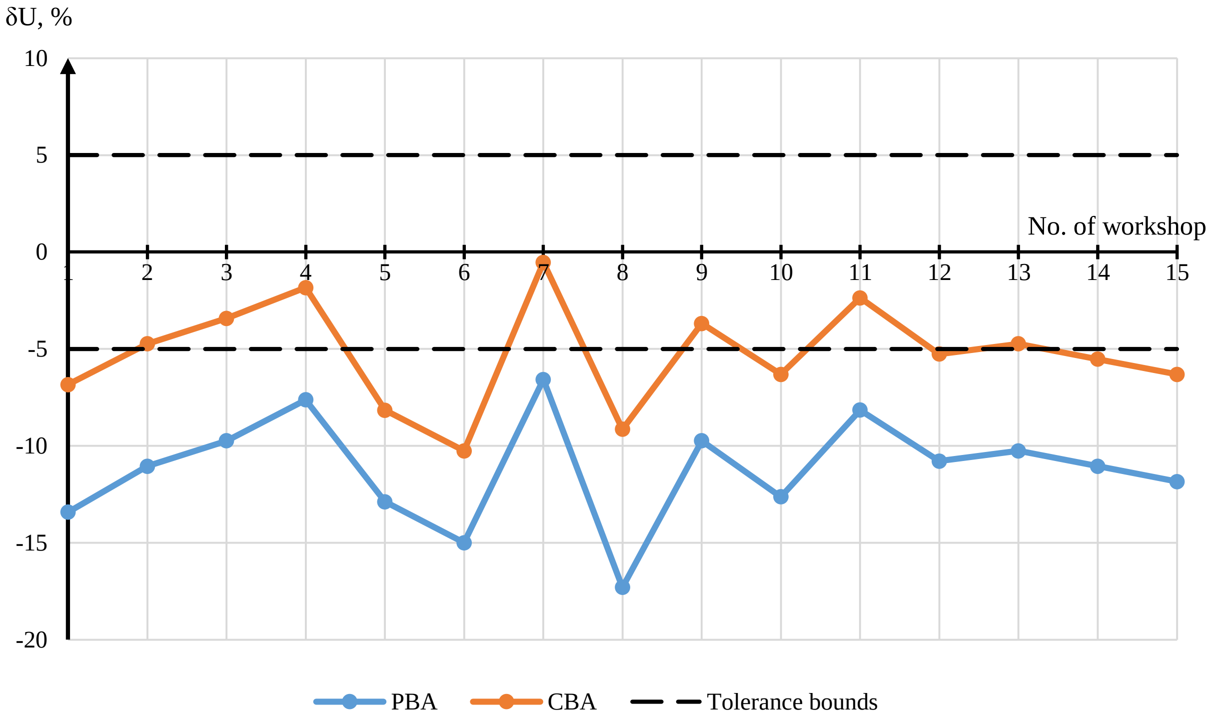


Figure 22 – Voltage deviation at workshops

Voltage deviation should be in ±5% range to satisfy standards [8]. Figure 22 shows that the voltage of most workshops for CBA meets the requirements. According to the PBA calculation, not a single workshop meets the requirements. Both options do not fully meet the requirements. However, it is possible to adjust the voltage by ±10% with the methods described in Chapter 6.2. Definitely, the CBA shows the best results for this technical indicator.

7.2 Analysis of power losses

Comparison of power losses allow us to evaluate the energy efficiency of the power supply system and move on to economic calculation.

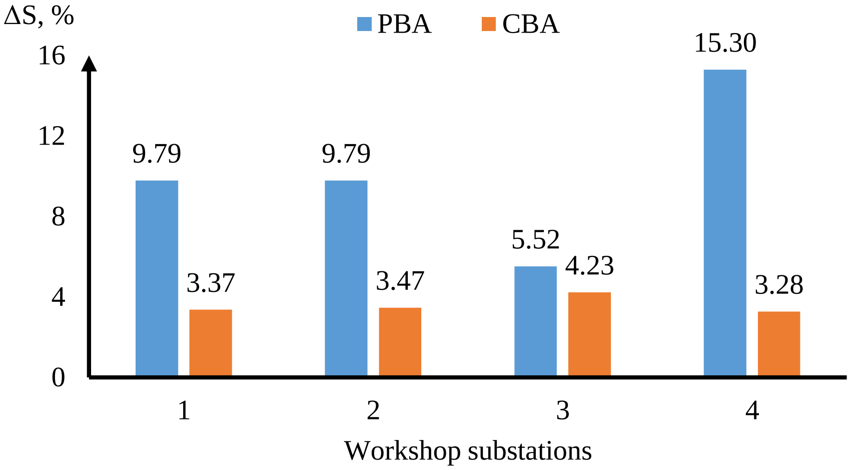


Figure 23 – Total power losses by PBA and CBA

Figure 23 shows that total power losses decrease almost in three times by using CBA. But the most important are active losses, which are taken into account by active energy meters and for which the enterprise must pay. We compare them separately in Figure 24.

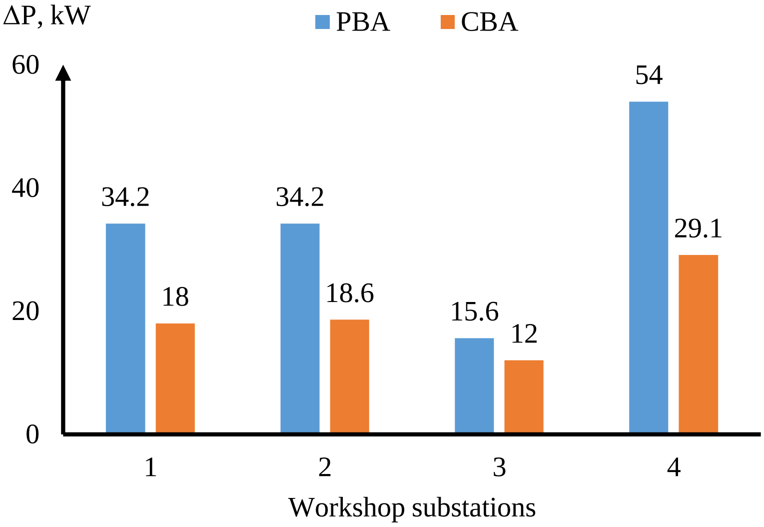


Figure 24 – Active power losses by PBA and CBA

Active power losses decrease significantly after applying the CBA (in total by about 40%). One of the main goals of an energy-efficient enterprise is to reduce active energy losses. Reducing active energy losses reduces the temperature of cable lines and transformers, and also directly affects annual energy losses. Annual energy losses are included in the electricity bill.

Now we can find the energy loss and move on to an economic comparison of approaches. Annual energy losses can be found by the following formula:

$$\Delta W_{year} = \Delta P \cdot 8760\,[\mathrm{MWh}], \tag{49}$$

where 8760 is number of hours in one year.

Table 19 – Energy losses by PBA and CBA

Approach	Total active power losses, kW	Annual energy losses, MWh
PBA	138	1 209
CBA	77.7	681
Difference	60.3	528

Thus, when using CBA, we can reduce the number of annual losses from 1 209 to 681 MWh (i.e. 44%). We estimate power losses impact on the economic component of the project.

7.3 Summary

In this chapter technical comparison of PBA and CBA is done. The first parameter to compare is the voltage level on the buses of the enterprise's workshops. Chapter 7.1 shows that CBA is totally better than PBA in this aspect.

The second parameter is power and energy losses. CBA active losses are 44% less than in PBA. This is very important both technically and economically. So, in terms of technical parameters, the system calculated by the CBA turned out to be better. Chapter 8 shows an economic comparison of PBA and CBA.

8. Economic comparison of results obtained by PBA and CBA

To assess the effectiveness of PBA and CBA, you need to know both technical and economic indicators. In this chapter economic analysis of PBA and CBA power supply systems is conducted.

8.1 Economic parameters

Depreciation will be considered by the declining-balance method. The depreciation rate is determined by the formula:

$$K = \frac{2}{n} \cdot 100\% \tag{50}$$

where n is the asset lifetime in years. In addition, when the residual value of a fixed asset reaches 20% of the initial value, the residual value is used as a base value for additional calculations of depreciation of a fixed asset [27]. Fixed asset is CBA equipment price with lifetime 20 years [25]. So, for instance, depreciation for first eight years is:

$$Depreciation = \frac{2}{20} \cdot P_{\mathrm{T}}^{\mathrm{CBA}} \tag{51}$$

Calculations of depreciation presented in NPV calculation table (Table A.5).

CAPM theory

To calculate *discount rate* the formula from the capital asset pricing model (CAPM) is used. The capital asset pricing theory is the best-known model of risk and return. It is plausible and widely used. [28]

$$r = R_f + \beta \cdot ERP = 6.50 + 1.31 \cdot 10.04 = 19.65\,\% \tag{52}$$

The following data for Russia is used: R_f as Russian Government Bond Zero Coupon Yield [29] is 6.50%, β is 1.31 [30] for metal industry, market risk premium ERP for Russia is 10.14% [30].

Income tax is 20% for enterprises according to Russian tax code. [27]

Escalation rate of electricity price

The dynamics of growth in electricity prices over inflation in Russia for last ten years is presented in the Table 20.

Table 20 – Growth of electricity prices [31]

Year	Growth, %
2010	13.82
2011	5.09
2012	6.97
2013	8.07
2014	4.54
2015	9.33
2016	5.12
2017	5.91
2018	6.13
2019	6

Average level of electricity price escalation is found by geometric mean:

$$g = \left(\prod_{t=2010}^{2019} g_t \right)^{\frac{1}{n}} = 6.72\,\% \tag{53}$$

where g_t is annual growth of electricity price, %; n is 10 years, sampling period. So, the price of electricity will increase every year by an average of 6.72%. [32, 33]

8.2 Definition of economic model and investments

We consider the economic side of the project as the difference between the CBA and the PBA. This is due to the fact that we do not know the other income of the enterprise. A positive cash flow in this case is a decrease in annual electricity losses. Reducing annual losses is our annual profit.

For economic calculation, we need initial data - prices of transformers and cables. The total purchase price of this equipment is the initial *investment* of the project.

Table 21 – Price of transformers for PBA

Nominal power of transformers, kVA	2 500	1 600
Number of transformers	4	4
Price, RUB (ths.) [25]	1 470	854
Total price, RUB (ths.)	9 296	

Table 22 – Price of transformers for CBA

Nominal power of transformers, kVA	4 000	3 150	1 600
Number of transformers	4	2	2
Price, RUB (ths.) [25]	2 050	1 748	854
Total price, RUB (ths.)	13 404		

The price for a cable line is calculated using the following formula:

$$P_{CL} = p \cdot L\,[\text{RUB}] \tag{54}$$

where *p* - price per meter of cable, RUB; *L* - cable length, m. Lengths of cable lines are taken from initial data of metallurgical plant.

Table 23 – Price of cable lines for PBA

Substation no.	1	2	3	4
Cross-section, mm^2	150	150	95	95
Cable length, m	100	175	225	175
Price per meter, RUB/m [26]	650	650	490	490
Price of cable line, RUB (ths.)	130	227.5	220.50	171.5
Total price, RUB (ths.)	749.5			

Table 24 – Price of cable lines for CBA

Substation no.	1	2	3	4
Cross-section, mm^2	150	150	50	95
Cable length, m	100	175	225	175
Price per meter, RUB/m [26]	650	650	363	490
Price of cable line, RUB (ths.)	130	227.5	163.4	171.5
Total price, RUB (ths.)	692.4			

Total price of cable lines for PBA is 749.5 ths. RUB., for CBA 692.4 ths. RUB.

The prices of cables and transformers are initial data to calculate investments. Since we are considering project differences, we should find the price difference for all equipment.

Difference in equipment price:

$$P_{\Sigma} = (P_T^{CBA} + P_{CL}^{CBA}) - (P_T^{PBA} + P_{CL}^{PBA}) = 4\,108\ \text{ths. RUB} \tag{55}$$

For initial investment we should take into account price of installation – 20% of equipment price [34]:

$$INV_0 = P_{\Sigma} \cdot 1.2 = 4\,930\ \text{ths. RUB} \tag{56}$$

We consider the maintenance of the power supply system as 3% of the CBA equipment price [34]:

$$M = (P_T^{CBA} + P_{CL}^{CBA}) \cdot 3\% = 402\ \text{ths. RUB} \tag{57}$$

The annual cash flow consists of depreciation, maintenance, decreasing of annual losses as revenue, taxes.

Electricity tariff

According to [35] electricity tariff for industrial enterprises with capacity over 10 MW is 2 450 RUB/MWh. However, in previous calculation I used all power in kW and kWh. Therefore, I recalculate the tariff for the price per kWh.

$$tariff_1 = 2450\ \text{RUB/MWh} = 2.45\ \text{RUB/kWh} \tag{58}$$

Certainly, enterprises pay a fixed rate for electricity under an energy supply agreement [32]. However, the fiscal payment is not taken into account in the calculations since it is paid in the case of both PBA and CBA. The fixed payment is the same in both cases since the installed capacity of the enterprise is the same.

8.3 Calculation of economic model

Net Present Value

Revenue is difference in annual energy losses (Table 19) multiplied by tariff of electricity for enterprise. The assumption for the analysis of the economic model is the constancy of energy losses every year. Certainly, this number will change every year in real conditions, but it will be close to the calculated average value. However, the electricity tariff will increase each year by an average of *g* as presented in Chapter 8.1. Revenue for *t*-th year:

$$Revenue_t = tariff_i \cdot \Delta W = tariff_1 \cdot (1+g)^t \cdot \Delta W \tag{59}$$

I use depreciation to reduce tax payments. Tax rate is 20%. Tax payment is calculated as:

$$Tax\ payment_t = 0.2 \cdot (Revenue_t - M - Depreciation_t) \tag{60}$$

Cash flow per year is calculated as:

$$CF_t = Revenue_t - Tax_t \tag{61}$$

All parameters for Net Present Value (NPV) are known. Net present value is the difference between the present value of cash inflows and the present value of cash outflows over a period of time. NPV is used in capital budgeting and investment planning to analyze the profitability of a projected investment or project [28]. NPV is calculated as:

$$NPV = \sum_{t=1}^{20} \frac{CF_t}{(1+r)^t} - INV_0 = 7.20\ \text{mln. RUB} \tag{62}$$

Detailed NPV calculation presented in Table A.5.

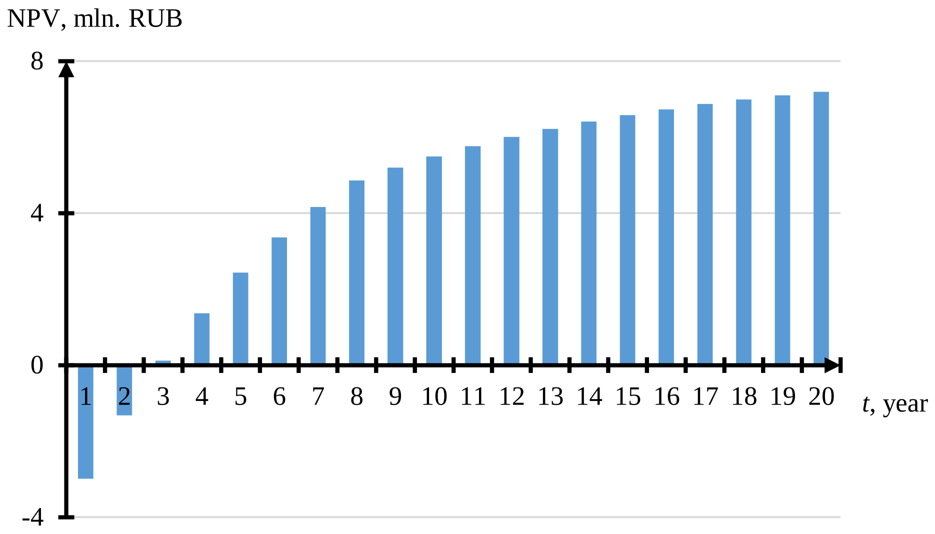


Figure 25 – Cumulated NPV

Figure 25 shows that payback period of our project is less than three years. NPV of project is positive. This means that the use of CBA is more cost-effective than PBA. Initial costs are 4.93 million rubles is greater for CBA than PBA, but reducing annual energy losses saves more money. The next step is to evaluate the other economic parameters of the project.

Payback Period

First, we find the exact value of the payback period (PP) by next formula [28]:

$$PP = t^* - 1 + \frac{\left|NPV_{t^*-1}\right|}{\dfrac{CF_{t^*}}{(1+r)^{t^*}}} = 2.79 \text{ years} \tag{63}$$

The project pays off for the third year out of 20. This is an important indicator of the economic efficiency of the project.

Internal Rate of Return

The internal rate of return on an investment or project is the "annualized effective compounded return rate" or rate of return that sets the net present value of all cash flows (both positive and negative) from the investment equal to zero. The IRR could be found from next equation [28]:

$$\sum_{t=0}^{T} \frac{CF_t}{(1+IRR)^t} = 0 \tag{64}$$

I used Excel formula IRR to obtain result. IRR=49.29%. This is quite a large value, which indicates a high profitability of the project.

Profitability Index

Profitability Index (PI) is an indicator of the net present value method, which is calculated as the ratio of the amount of discounted cash flows to the initial investments. The PI could be found by next formula [28]:

$$PI = \frac{\sum_{t=1}^{T} \frac{CF_t}{(1+r)^t}}{INV_0} = \frac{12.12}{4.93} = 2.46 \qquad (65)$$

Profitability index greater than 1 indicates that the present value of future cash flows greater than initial investments. This is another confirmation of the success of the project.

Return on Investments

Return on Investments (ROI) is a financial ratio illustrating the level of profitability or loss-making of a project, taking into account the amount of investments made in this project. The ROI could be found by next formula [28]:

$$ROI = \frac{\frac{\sum_{t=0}^{T} CF_t}{T}}{|CF_0|} = \frac{\frac{45.89}{20}}{|-4.93|} = 0.47 = 47\% \qquad (66)$$

The ROI means that we can generate 47% of our investment from this project. This is quite large value for projects, which also mean that the project is successful.

All calculated economic parameters in this chapter indicate the reliability and success of the CBA project. The next step is to consider and evaluate the sensitivity of the project to the economic situation.

8.4 Sensitivity analysis

First of all, I consider the impact of the discount rate on the project. The graph of the dependence of the NPV on the discount rate (r) is presented on Figure 26.

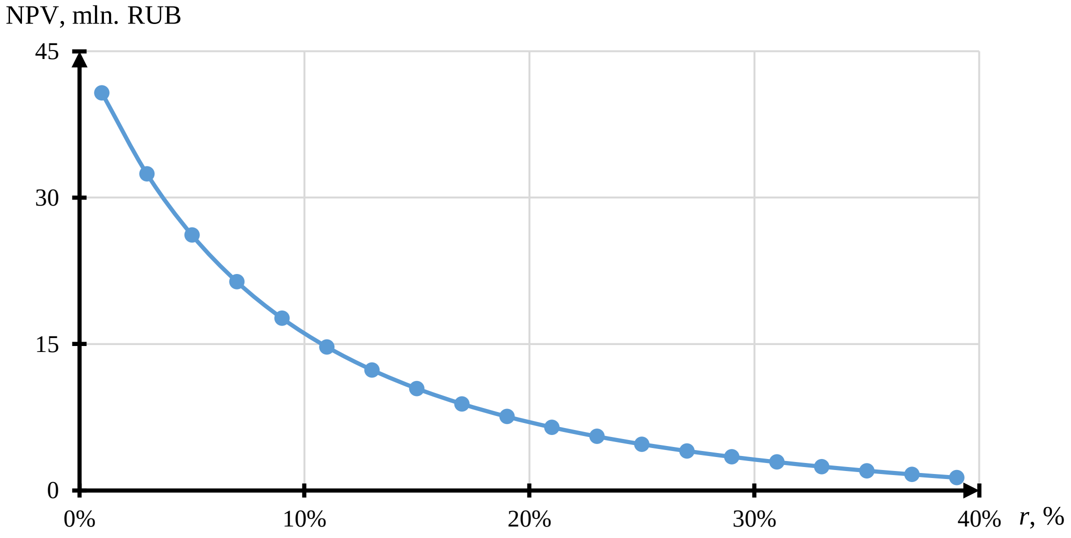


Figure 26 – Dependence of NPV on discount rate (r)

Figure 26 shows that NPV positive in expected range of discount rate. This indicates a high reliability of the project.

Secondly, need to know how the change in electricity tariff affects the NPV of the project. The graph of the dependence of the NPV on the growth of electricity tariff (*g*) is presented on Figure 27.

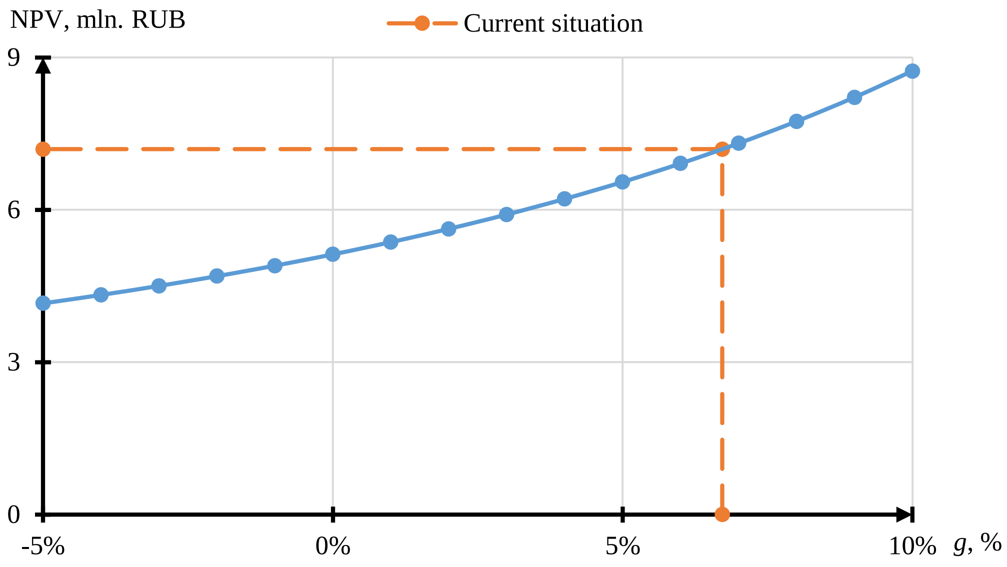


Figure 27 – Dependence of NPV on the growth of electricity tariff (*g*)

Figure 27 shows that even if electricity prices fall (which is highly unlikely for Russia), the project's NPV will still remain positive. The current forecasting for growth of electricity prices presented by orange dotted line.

Thirdly, we should consider changes in initial parameters such as initial investments, amount of energy losses, and maintenance costs. Changing the values of input parameters leads to a change in project results. Influence of different parameters can be presented by the Tornado diagram.

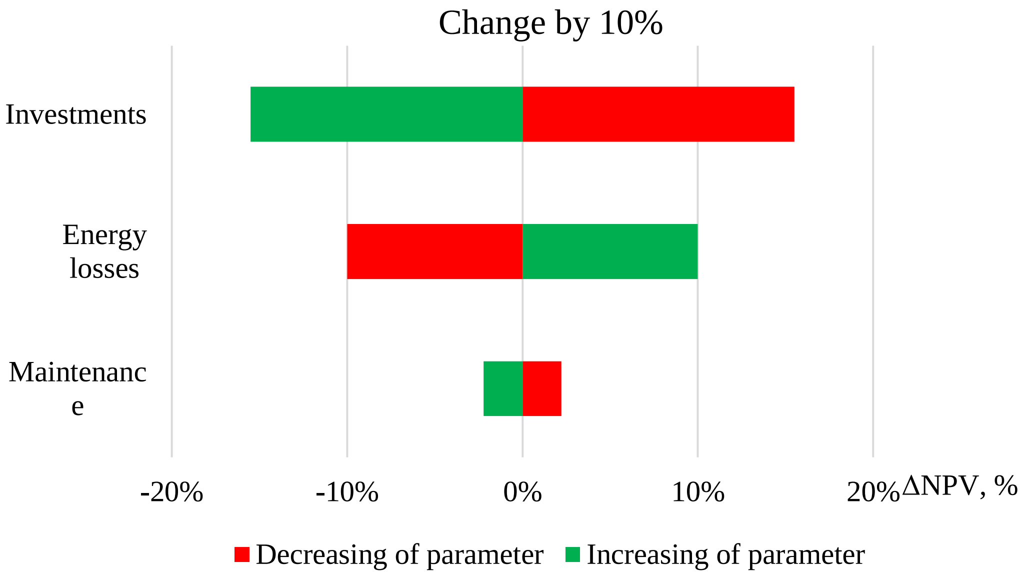


Figure 28 – Tornado diagram for NPV

If the amount of energy losses (e.g., as a result of increasing the capacity of the enterprise) increases NPV also increases. It is marked in green. If we increase investments NPV decreases. It is marked in red. The amount of investment is the most important parameter of NPV, maintenance is the least important parameter of NPV.

Finally, we can say that the project pays off despite the change in various parameters. Rising of electricity prices may even increase the project's NPV [33].

8.5 Summary

Comparison of methods shows that the CBA method is more effective. In terms of energy quality, it provides a higher voltage, which will ensure more stable operation of power consumers. In economic terms, CBA calculations significantly reduce annual energy bill. The difference between the results for CBA and PBA can be estimated as a project with an NPV of 7.20 mln. RUB.

9. Discussion of results

There are two major reasons for comparing PBA and CBA. First reason is assumptions in calculation of electrical load. The analysis of the mathematical model of PBA and CBA shows that there are significant differences in the models for calculating the electrical load. Certainly, it is impossible to achieve a perfectly accurate mathematical model even for a steady state power system. However, it is necessary to minimize the number of assumptions at this design stage. The calculation results by different methods differ significantly.

The load calculation results determine the choice of equipment for the power system. At this design stage, we can say that the assumptions of the PBA led to unsatisfactory consequences. Equipment selected from PBA showed inappropriate technical simulation results. The average voltage level according to the PBA results below the nominal by 10-15% and out of tolerance bounds. The second reason is choosing equipment according to outdated PBA algorithms. It leads to difference in choice of PBA and CBA equipment. The simulation results show that this choice should be checked by modeling and adjusted.

We compare PBA and CBA from a technical and economic point of view. From a technical point of view, the results of PBA do not pass the test on the level of voltage. This indicates a low energy quality and a significant decrease in the efficiency of power consumers. This deterioration in the operation of power consumers will have an effect on the company's products, reduce its quality, increase the cost of operating equipment, and may require the installation of additional equipment. All these consequences will also affect the economic structure of the enterprise. Ineffectively operating equipment quickly fails, poor-quality products cannot be sold expensively, the purchase and installation of additional equipment reduces annual revenue.

However, the most important parameter affecting the economic component is the energy losses. Transformers and cable lines selected by PBA cannot cope with the load. This leads to significant energy losses on these elements of the power system. Computation by CBA showed a 44% (more than 500 MWh) decrease in annual energy losses compared to PBA. Loss of electricity is useless energy, but it is also included in the electricity bill. Certainly, transformers and cable lines selected by PBA are 4 mln. RUB cheaper than those selected in the CBA. However, the calculation of the economic model showed that the CBA is more profitable. Net present value of project difference is over 6 mln. RUB. The profitability index of project is 2.46, the return on investments is 46.5%.

Investments under CBA turned out to be larger, but for the entire time of the project showed the best result. Reducing the electricity bill is always beneficial since electricity prices in Russia are growing every year [31]. Having spent more at the beginning of the project, we will ensure the stable operation of the enterprise and also reduce annual energy costs. The overpaid difference will pay off already in the 4th year.

In addition, more powerful equipment of CBA leaves horizons open to increase the capacity of the enterprise and its expansion. Thus, CBA proved to be a more efficient method for computing than PBA. PBA can be used as an auxiliary method for CBA. The results of the PBA can be taken as the initial data for the PBA. However, the possibility of using only PBA without a CBA is doubtful.

In order to improve PBA new databases should be compiled on the applicable equipment and their parameters. Some algorithms need to be revised due to the introduction of more energy efficient equipment. It is also necessary to take into account the possibilities of computer calculation since the technologies and capabilities of software and hardware have significantly increased.

Conclusion

In this thesis two methods for calculating parameters of a power supply system was compared. The first method is *paper based approach* (PBA), combination of various historical and statistical methods. The second method is a *computer based approach* (CBA). The basis of CBA calculation is the Newton-Raphson method. These two methods were used to calculate the equipment and select the parameters of the power supply system.

The main parameters of the power supply system were determined. These are cable lines, transformers and power consumers. The main technical indicators of their work are voltage and power loss. They became the basis for the technical comparison of the PBA and CBA. This comparison was carried out by simulating steady-state power supply systems in the ETAP software. The results of the simulation showed that the results of the PBA are unsatisfactory. The voltage level does not meet the standards; energy losses are significant. CBA technical results showed a satisfactory voltage level for most of the metallurgical plant. Energy losses reduced by almost half. The selection of transformers using PBA was unsuccessful. However, most of the selected cable lines are reliable and there is no need to change them.

The difference in the technical part of the PBA and CBA appears due to the difference in the mathematical approaches of electrical load evaluation. This is discussed in details in Chapters 3 and 4. The growth of computing power allows for many complex calculations and fewer assumptions. This makes the CBA method more accurate.

An economic analysis of PBA and CBA was also carried out. The following parameters were calculated: net present value, profitability index, payback period and others. The project was considered as the difference in annual energy losses between PBA and CBA. The calculation results showed that the project pays off in three years and generates profit. Large investments at the beginning of the project were covered by a significant reduction in electricity bills. This means that the CBA project is better than the PBA in terms of technical and economic parameters.

PBA should not be used without the use of a CBA. PBA results should be simulated and adjusted. Some calculation algorithms should also be fixed, especially regarding the selection of transformers. The selection of cable lines for PBA are acceptable.

The aim of the PBA in the direction of a potential increase of load should also be reviewed [36]. In the 21st century, more and more companies are focused on energy efficiency and reducing energy consumption. Therefore, the power supply system should not be developed in order to potentially increase the load of the enterprise, but rather to reduce it.

This paper shows unsatisfactory results of PBA in technical and economic terms. CBA turned out to be better in all aspects. The power supply system calculated only by the PBA is inefficient. Results by CBA shows a reliable power supply system with satisfactory economic performance.

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Appendices

Appendix A – Tables

Table A.1 – Initial data for enterprise's workshops [16]

No.	Workshop name	P_{nom}, kW	Reliability category
1	Dumping machine	390	II
2	Coal preparation workshop	1720	I
3	Preparation workshop 1	650	I
4	Coal warehouse	450	II
5	Metallurgical workshop 2	3310	I
6	Metallurgical workshop 1	2700	I
7	Mechanical repair workshop	-	II
8	Concentrate bunker	160	I
9	Flotation concentrate bunker	730	I
10	Mixing compartment 1	1450	I
11	Mixing compartment 2	1520	I
12	Coal-storage tower 1	660	I
13	Coal-storage tower 2	780	I
14	Coal-storage tower 3	1000	II
15	Preparation workshop 2	350	II

Table A.2 – Initial data for mechanical repair workshop [16]

Name	Plan number	P_{nom}, kW
Overhead crane DF=25%	1,2	14
Plate bending machine	3	50
Universal milling machine	6,7	13
Turn-milling machine	10,11	3
Screw-cutting lathe	4,5	2
Bench drilling machine	13-16,26,27	10
Thread-cutting semiautomatic device	17-20	8
Sharpening machine	8,9	25
CNC milling machine	44	50
Grinding machine	21-25	23
Radial drilling machine	28,29	55
Universal tool grinder	30-33	19
Surface grinding machine	12	2
Polishing machine	40,41	10
Welding machine DF=25%	42,43	6
Welding cabin DF=40%	34-39	1,5
Drill press machine	45,46	14

Table A.3 – Calculation of mechanical repair workshop

Power consumer	***n***	**Nominal power**		**K$_u$**	**Reactive power coefficient**		$K_{usage}\cdot P_{nom}$	$K_{usage}\cdot P_{nom}\cdot\tan\varphi$	$P^2\cdot n$	**Effective number of consumers,** n_{eff}	K_{rated}	**Rated power**		
		For each, kW	**Total,** $P_{nom}\cdot n$**, kW**		$\cos\varphi$	$\tan\varphi$						P_r**, kW**	Q_r**, kVar**	S_r**, kVA**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
DB 1														
Bench drilling machine	2	10	20	0.14	0.50	1.73	2.80	4.85	200					
Grinding machine	5	23	115	0.14	0.50	1.73	16.10	27.89	2645					
Total:	7		135	0.14			18.90	32.74	2845	6.41	2.10	39.61	36.01	53.53
										6				
DB 2														
Bench drilling machine	2	10	20	0.14	0.50	1.73	2.80	4.85	200					
Screw-cutting lathe	2	2	4	0.14	0.50	1.73	0.56	0.97	8					
Turn-milling machine	2	3	6	0.14	0.50	1.73	0.84	1.45	18					
Radial drilling machine	2	55	110	0.16	0.50	1.73	17.60	30.48	6050					
CNC milling machine	1	50	50	0.16	0.50	1.73	8.00	13.86	2500					
Total:	9		190	0.16			29.80	51.62	8776	4.11	2.26	67.41	56.78	88.13
										4				
DB 3														
Universal tool grinder	4	19	76	0.14	0.50	1.73	10.64	18.43	1444					
Surface grinding machine	1	2	2	0.14	0.50	1.73	0.28	0.48	4					
Overhead crane DF=25%	1	14	14	0.05	0.45	1.98	0.70	1.39	196					
Universal milling machine	1	13	13	0.14	0.50	1.73	1.82	3.15	169					
Drill press machine	2	14	28	0.14	0.50	1.73	3.92	6.79	392					
Total:	9		133	0.13			17.36	30.25	2205	8.02	2.02	35.00	33.27	48.29
										8				

Table A.3 continuing

Power consumer	***n***	**Nominal power**		**K$_u$**	**Reactive power coefficient**		$K_{usage}\cdot P_{nom}$	$K_{usage}\cdot P_{nom}\cdot\tan\varphi$	$P^2\cdot n$	**Effective number of consumers, n_{eff}**	K_{rated}	**Rated power**		
		For each, kW	**Total, $P_{nom}\cdot n$, kW**		$\cos\varphi$	$\tan\varphi$						**P_r, kW**	**Q_r, kVar**	**S_r, kVA**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
DB 4														
Polishing machine	2	10	20	0.14	0.50	1.73	2.80	4.85	200					
Universal milling machine	1	13	13	0.14	0.50	1.73	1.82	3.15	169					
Plate bending machine	1	50	50	0.16	0.50	1.73	8.00	13.86	2500					
Overhead crane DF=25%	1	14	14	0.05	0.45	1.98	0.70	1.39	196					
Total:	5		97	0.14			13.32	23.25	3065	3.07	3.12	50.00	86.50	99.91
										3				
Busbar														
Bench drilling machine	2	10	20	0.14	0.50	1.73	2.80	4.85	200					
Thread-cutting semiautomatic device	4	8	32	0.14	0.50	1.73	4.48	7.76	256					
Sharpening machine	2	25	50	0.14	0.50	1.73	7.00	12.12	1250					
Welding cabin DF=40%	6	1.5	9	0.30	0.65	1.17	2.70	3.16	14					
Welding machine DF=25%	2	6	12	0.30	0.65	1.17	3.60	4.21	72					
Total:	16		123	0.17			20.58	32.10	1792	8.44	1.60	32.93	35.31	48.28
										8				
Workshop total	92	353	1356				200	340	37365	59	11	**224.95**	**247.86**	**338.15**

Table A.4 – Calculation of all workshops

No.	**Workshop name**	**P_{nom}, kW**	**Area**	**P_{spec} [Kab]**	**K_{dL} [Kab]**	**P_{nomL}**	**P_{ratedL}**	**K_d [Kab]**	**$\cos\phi$**	**$\tan\phi$**	**P_{rated}**	**Q_{rated}**	**P_{total}**	**S_{rated}**
			m^2	W/m^2		kW	kW				kW	kVar	kW	kVA
1.	Dumping machine	390	1800	17	0.95	30.6	29.07	0.40	0.80	0.75	156	117	185.07	218.95
2.	Coal preparation workshop	1720	1500	15	0.95	22.5	21.38	0.50	0.70	1.02	860	877	881.38	1243.63
3.	Preparation workshop 1	650	750	17	0.95	12.75	12.11	0.40	0.80	0.75	260	195	272.11	334.77
4.	Coal warehouse	450	7000	17	0.6	119	71.40	0.20	0.50	1.73	90	156	161.40	224.39
5.	Metallurgical workshop 2	3310	1750	17	0.95	29.75	28.26	0.50	0.70	1.02	1655	1688	1683.26	2384.15
6.	Metallurgical workshop 1	2700	3750	17	0.95	63.75	60.56	0.50	0.70	1.02	1350	1377	1410.56	1971.44
7.	Mechanical repair workshop	678	1750	16	0.95	28	26.60				225	248	251.55	353.15
8.	Concentrate bunker	160	1500	17	0.95	25.5	24.23	0.20	0.50	1.73	32	55	56.23	78.95
9.	Flotation concentrate bunker	730	1500	17	0.95	25.5	24.23	0.20	0.50	1.73	146	253	170.23	304.84
10.	Mixing compartment 1	1450	1800	15	0.95	27	25.65	0.40	0.80	0.75	580	435	605.65	745.68
11.	Mixing compartment 2	1520	1600	15	0.95	24	22.80	0.40	0.80	0.75	608	456	630.80	778.36
12.	Coal-storage tower 1	660	3600	15	0.95	54	51.30	0.50	0.80	0.75	330	248	381.30	454.58
13.	Coal-storage tower 2	780	3600	15	0.95	54	51.30	0.50	0.80	0.75	390	293	441.30	529.44
14.	Coal-storage tower 3	1000	3600	15	0.95	54	51.30	0.50	0.80	0.75	500	375	551.30	666.75
15.	Preparation workshop 2	350	1600	17	0.95	27.2	25.84	0.40	0.80	0.75	140	105	165.84	196.29

Table A.5 – Calculation of NPV

Year	0	1	2	3	4	5	6	7	8	9	10
Investments, mln. RUB	-4.93										
Depreciation, mln. RUB		1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	0.22	0.22
Maintenance, mln. RUB		-0.40	-0.40	-0.40	-0.40	-0.40	-0.40	-0.40	-0.40	-0.40	-0.40
Revenue, mln. RUB		1.29	1.38	1.47	1.57	1.68	1.79	1.91	2.04	2.18	2.32
Tax base, mln. RUB		-0.45	-0.36	-0.27	-0.17	-0.06	0.05	0.17	0.30	1.55	1.70
Tax payment, mln. RUB		-0.09	-0.07	-0.05	-0.03	-0.01	0.01	0.03	0.06	0.31	0.34
CF, mln. RUB	-4.93	2.32	2.39	2.47	2.55	2.63	2.72	2.82	2.92	1.69	1.81
DCF, mln. RUB		1.94	1.67	1.44	1.24	1.07	0.93	0.80	0.69	0.34	0.30
Cumulated NPV, mln. RUB		-2.99	-1.32	0.12	1.36	2.44	3.36	4.16	4.86	5.19	5.50

Table A.5 Continuation

Year	11	12	13	14	15	16	17	18	19	20
Investments, mln. RUB										
Depreciation, mln. RUB	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Maintenance, mln. RUB	-0.40	-0.40	-0.40	-0.40	-0.40	-0.40	-0.40	-0.40	-0.40	-0.40
Revenue, mln. RUB	2.48	2.65	2.82	3.01	3.22	3.43	3.66	3.91	4.17	4.45
Tax base, mln. RUB	1.85	2.02	2.20	2.39	2.59	2.81	3.04	3.28	3.55	3.83
Tax payment, mln. RUB	0.37	0.40	0.44	0.48	0.52	0.56	0.61	0.66	0.71	0.77
CF, mln. RUB	1.93	2.06	2.21	2.36	2.52	2.69	2.88	3.07	3.28	3.51
DCF, mln. RUB	0.27	0.24	0.21	0.19	0.17	0.15	0.14	0.12	0.11	0.10
Cumulated NPV, mln. RUB	5.76	6.00	6.22	6.41	6.58	6.73	6.87	6.99	7.10	7.20

Appendix B – Figures

WS – Workshop Substation
MSDS – Main Step-Down Substation

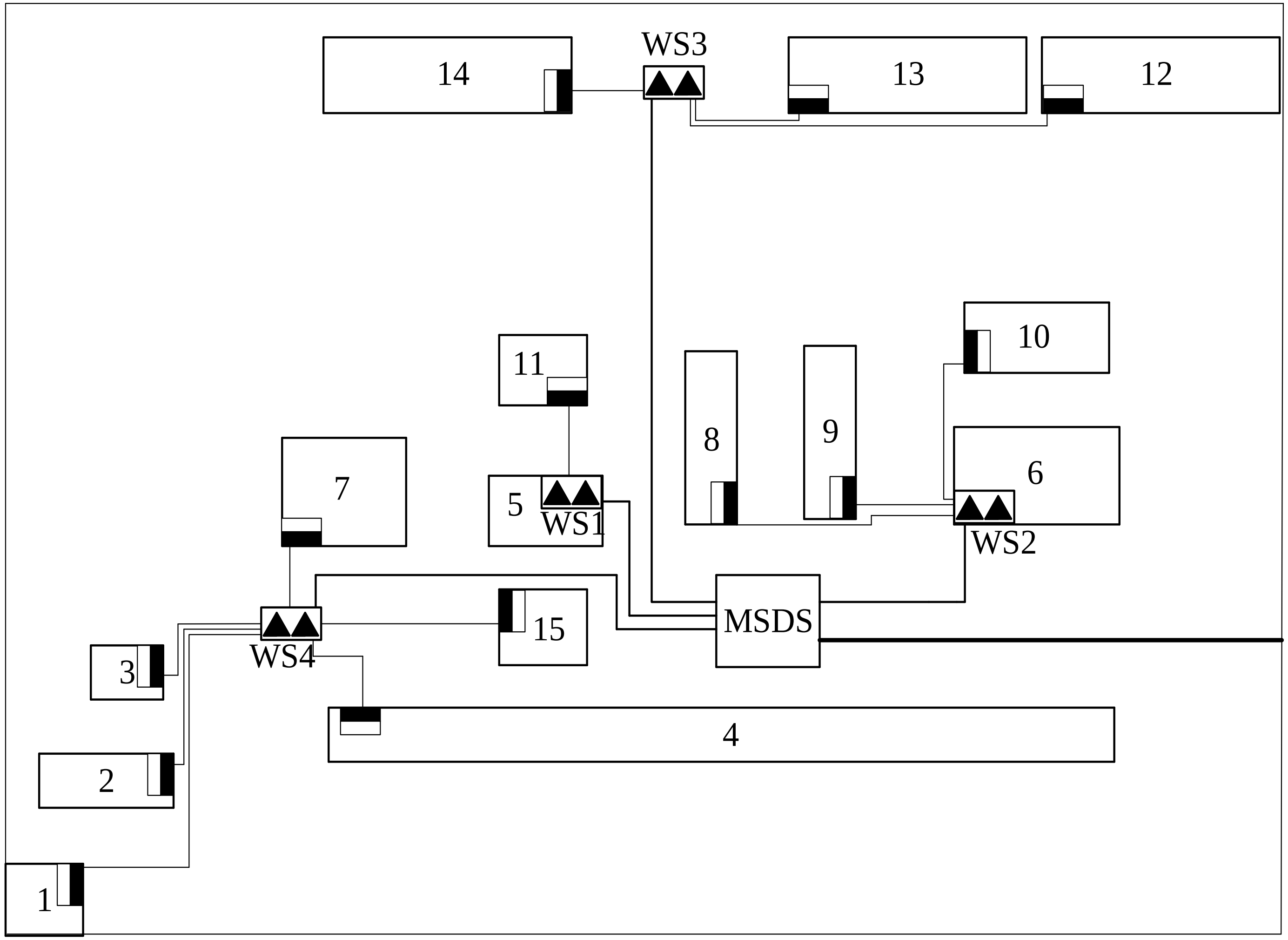

Figure B.1 – The territory of the metallurgical plant [16]

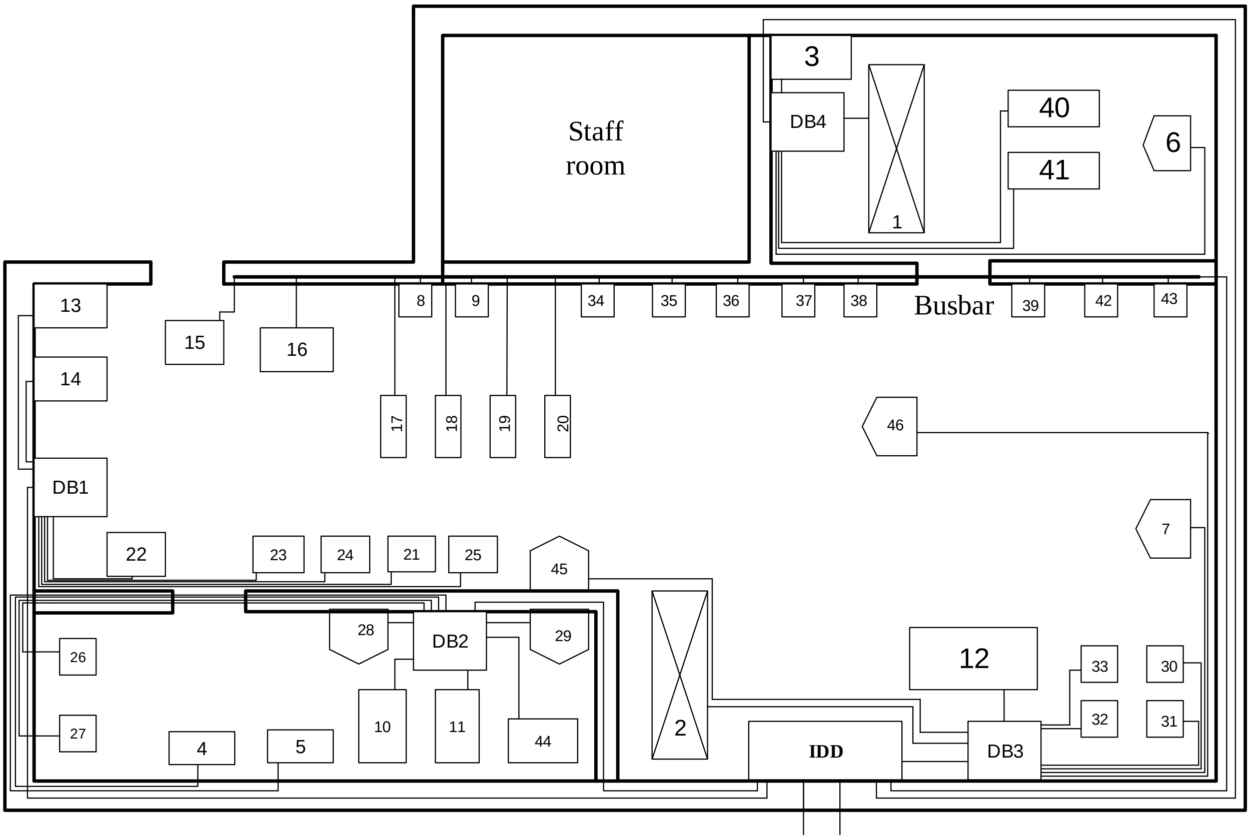

Figure B.2 – Mechanical repair workshop scheme [16]