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Faculty of Electrical Engineering

Department of Economics, Management and Humanities

Voltage Regulation in The Lighting Nodes of the Electrical Workshop

Master's Thesis

Study Program: Electrical Engineering, Power Engineering and Management

Branch of study: Management of Power Engineering and Electrotechnics

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2. Identify necessary technical information from the enterprise;
3. Evaluate economic efficiency of proposed technical improvements;
4. Perform technical and economic analyses for the result.

Bibliography / sources:

1. Volkov N. G. Kachestvo elektroenergii v sistemakh elektrosnabzheniya; National Research Tomsk Polytechnic University. - Tomsk, 2010. - 152 p.
2. BREALEY, R., MYERS, S., ALLEN, F. Principles of Corporate Finance, 12th ed. McGraw-Hill, 2016. ISBN:9781259253331

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III. Assignment receipt

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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

The object of study is the Novosibirsk Concrete Products Plant. This plant is characterized by a large plant area and the huge distance between the workshops, which results in a significant voltage drop in the low-voltage distribution network, especially in the lighting systems. For a more detailed voltage quality analysis, one of the most remote workshop was chosen.

The purpose of the work is to determine the effects of voltage deviation on the performance of lighting sources and to consider existing solutions for eliminating the negative consequences of deviation, as well as the design of natural and artificial lighting systems. This paper considers the effect of voltage drop on parameters such as electrical energy consumption and changes in illumination level. In order to design the lighting system, I have done a feasibility analysis for all considered types of luminaries and voltage stabilizing devices, after I have selected several options with the optimum performance. Once the artificial light sources had been selected, I proceeded to design the lighting system. After I have analyzed the designed system on changes in energy consumption and illumination level in the working place during each month. Further local voltage regulation in lighting networks was considered. It was followed by a technical and economic analysis of the implementation of these technologies, after the optimum lighting configuration meeting all conditions was selected.

All calculations are based on the plant load data, daily load diagrams for minimum and maximum operation modes, as well as on existing researches in the field of voltage deviations effects on the operation of electrical equipment. In this paper, the technical part consists of calculations of the window dimensions for natural lighting, selection of the luminaires amount for artificial lighting, calculation of the voltage deviation and the illumination level changes. The economical part consists of the calculation of net present value, equivalent annual payments, and sensitivity analysis of these indicators.

Keywords: illumination system, lighting system, power quality, voltage deviation, voltage variation, voltage quality.

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List of abbreviations

Abbreviation	**Russian**	**English**
CAPM		Capital asset pricing model
CF		Cash flow
CFL		Compact florescent lamp
DC		Direct current
DDB		Double-declining balance
EAA		Equivalent annual annuity
EMF		Electromotive force
GOST	Gosudarstvennyy standart	Russian technical standard
LDP		Lightning distribution panel
LV		Low voltage
MSDS		Main step-down substation
MV		Medium voltage
NPV		Net present value
SG		Switchgear
SP	Svod pravil	Rosstandart technical rules
TS		Transformer station
VDB		Variable-declining balance

Introduction

All people need light to do most of their work. Low illumination level leads to lower quality of work, higher rates of rejection, causes worker fatigue and reduces productivity [1]. The task is to design optimum lighting conditions for work in the electrical workshop of a reinforced concrete products plant.

Comfortable conditions in the workplace are achieved by observing the minimum illumination level for a particular production area. When designing artificial lighting, the fact that the level of supply voltage changes the characteristics of the lighting system must be taken into account. Thus, the considered plant has a large area and a huge distance between the workshops which leads to a voltage drop in the distribution network. In lighting systems voltage deviation leads to change parameters such as electrical energy consumption, illumination level and service life [1]. Voltage deviation analysis must be undertaken when designing a lighting system as this helps to identify and eliminate increased electrical energy consumption, lighting variations below minimum levels, and accelerated ageing of equipment.

The goal of this paper is to design natural and artificial lighting in an industrial building, analyze the effects of voltage deviation on the characteristics of lighting sources and implement a local voltage regulation method.

The following tasks are solved in the process of work implementation:

1. Feasibility study on the choice of lighting sources;
2. Feasibility study on the choice of voltage regulation devices;
3. Lighting system design;
4. Analysis of changes in lamps performance;
5. Application of voltage regulation device in the illumination system;
6. Selection of lighting system configuration based on economical evaluation.

Only local voltage regulation sources are considered in this thesis. This is due to the fact that individual power consumers have different distances from transformer substations and different load schedules resulting in inconsistent requirements for overall voltage regulation. Also, this paper does not examine the effect of voltage deviation on equipment service life because at the moment this information is not available.

Chapter 1. Voltage quality problem for lighting systems

Electrical energy is a special type of product that has certain characteristics that allow determining its suitability in various production processes. The set of characteristics at which the electrical equipment is able to perform the intended functions are united by the general concept of electricity quality. The quality of electricity is assessed according to technical and economic indicators, which take into account [1]:

- Technological damage. It leads to decreasing of product quality, loss of labor productivity, and disruption of the technological process.
- Electromagnetic damage. It leads to damage of electrical equipment, increasing power losses, and disruption of communication devices [2].

To avoid all of the consequences described above, standards have been developed to regulate the characteristics of electrical energy. In Russia, the power quality is regulated by GOST 32145-2013 [7], which I will often use in this project.

As part of the thesis, I will look at one of the most important indicators of power quality - voltage deviation.

Voltage deviation is the difference between the actual (steady-state) voltage value and the nominal voltage value. The voltage deviation can be calculated in volts or percentages, but in the standards the permissible deviation values are taken as a percentage [1].

$$\delta U = U_{act} - U_{nom}\,, (V) \quad (1.1)$$

$$\delta U = \frac{U_{act} - U_{nom}}{U_{nom}} \cdot 100\ \%, (\%) \quad (1.2)$$

Where:

δU – Voltage deviation (% or V),

U_{act} – Actual or steady-state voltage value (V),

U_{nom} - Nominal voltage value of the electrical system (V).

According to GOST 32144-2013 “normally permissible steady-state voltage deviation at the terminals of working lights installed in industrial and public buildings, where considerable visual tension is required, are allowed to vary from -10% to +10%” [7]. It means that a large voltage deviation is unacceptable. However, these deviations can be reduced. In chapter 4 these values will be reduced in accordance with the Rosstandart rule for illumination level of comfortable working environment.

The main factors for voltage deviations in power systems are changes in the operating modes of electrical consumers and power sources, as well as irrational connection of single-phase loads to elements of the electricity supply system. Deviation of power quality indicators from the normative values manifests in the form of economic damage to consumers. Lighting sources have only the electromagnetic damage, which is determined by additional electricity losses and reduced service life of electrical equipment due to accelerated insulation aging [2].

An important characteristic of light sources is the dependence of the luminous efficiency on the steady-state voltage and the corresponding power consumption. In [1] graphs show the dependence of energy and lighting characteristics of lamps on the voltage value. Based on this, I can conclude that with an increase in voltage level, power consumption increases too and the service life is reduced. A reduction of steady-state voltage leads to decrease of luminous flux, which leads to darkening of a room. More detailed information on effect of voltage deviation on the lamps will be presented in the second chapter of the thesis.

The electrical lighting system feed from a common power system for lighting and power loads, where the voltage level equals to 220/380V. Predominantly electric lighting is powered from 220 V or lower. Electric lighting networks are characterized by a large ramification and length [5].

In order to make rational use of electricity for lighting purposes and to reduce operating costs, it is necessary to effectively stabilize the voltage at the terminals of lighting sources. Naturally, there are many ways to regulate voltage, both at common nodes and at local points. There are some assumptions in this thesis that allow us to consider only local voltage regulation methods. The assumptions include that I do not consider the power quality at the equipment installed in the electrical department. On assignment, it is assumed that it is located within acceptable limits.

Methods and techniques for local regulation in illumination systems will be discussed in chapter 3.

Chapter 2. Types of luminaries used for industrial lightning

2.1. Types of luminaries

Artificial light sources are technical devices of various designs that convert electrical energy into light emission. Light sources use mainly electricity, but sometimes chemical energy and other methods of generating light are used (e.g. triboluminescence, radioluminescence, bioluminescence, etc.) [2].

Main characteristics of light sources [5]:

- Nominal supply voltage, (V);
- Electrical power consumption, (W);
- Luminous flux, (lm);

- Light efficiency (ratio of the luminous flux of lamp to its power) (lm/W);
- Service life, (h).

In this paper, only the power consumption, luminous flux level and service life will be considered for choosing of lighting sources. The value of nominal voltage does not influence on the choice of equipment because it will be connected to the same input voltage level.

The following types of lamps are used to illuminate industrial and public areas [2]:

- Incandescent lamps;
- Halogen incandescent lamps;
- Fluorescent lamps;
- Compact fluorescent lamps;
- Led lamps.

In the following, the principles of each light source will be described, as well as the main advantages and disadvantages. At the end of the chapter, summary tables will present the main characteristics of the lamps and the relationship between these characteristics and voltage deviation.

An incandescent lamp is a light source where the conversion of electrical energy into light occurs as a result of the incandescence of a refractory conductor (tungsten filament) by an electric current. Refractory conductor located in a vacuum flask. The efficiency of incandescent lamps is equal about 5-10%, this part of the consumed electricity is converted into visible light and other part of it is converted into heat. Each incandescent lamp consists of the same basic elements. But their size, shape and positioning can vary greatly, so different designs are not similar to each other and have different characteristics [1].

Figure 1 – An incandescent lamp [8]

These lamps are very sensitive to the magnitude of the input voltage. The input voltage has a significant effect on the light output and lamp service life. Also, during voltage fluctuations, flickering will occur, which can lead to irritation up to health problems such as headaches and in extreme cases cramps [5].

Halogen lamps are the same as incandescent bulbs, the difference between them is in adding a buffer gas. This made it possible to increase the luminous efficiency and service life. By filling the lamp with halogen compounds soot formation on the inside of the glass lamp can be avoided so that the lamp emits constant light energy throughout its service life [1].

Figure 2 – Halogen incandescent lamp [8]

These lamps like incandescent have a very huge sensitivity to the magnitude of the input voltage.

Fluorescent lamps are low-pressure discharge lamps that have a cylindrical tube with electrodes where mercury vapor is injected. From all types of lamps, fluorescent lamps have the highest luminous efficiency. Their main application is in industrial areas (workshops, offices, factory halls, etc.). The electric field between the electrodes of the lamp causes the mercury vapor to emit invisible ultraviolet radiation and the phosphor converts this radiation into visible light [1].

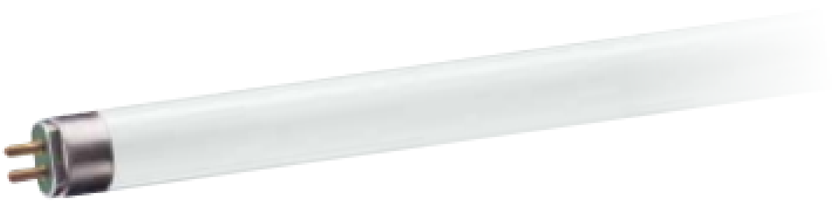


Figure 3 – Fluorescent lamp [8]

The performance of fluorescent lighting can be affected by the magnitude of the input voltage. If the supply voltage is too low, it will be difficult for the lamp to start, especially in high humidity. This condition can cause the lamp to flash off and on without starting, which can lead to the slow destruction of the lamp electrodes. When the supply voltage is too high, preheat or quick start lamps sometimes operate as instant start lamps. As a result, the cathode coating of the lamp will deteriorate due to high voltage pulses applied to the cathode. The maintenance of the lumen will also suffer [5].

Compact fluorescent lamps consist of a bulb filled with mercury, argon pores and a ballast. The inside surface of the bulb is covered by a special substance called phosphor. The phosphor is a substance which allowed emits visible light under expose of ultraviolet light. When compact fluorescent lamp is turned on under the action of electromagnetic radiation, the pores of mercury contained in the lamp begin to create ultraviolet radiation. Ultraviolet radiation is converted into visible light through passing the phosphor coated on the lamp surface [2].

Compact fluorescent lamps are available in different wattages. The power range varies from 3 to 90 W. The compact fluorescent lamp has a very high efficiency and a light output that is approximately 5 times that of a conventional incandescent lamp [3].

Figure 4 – Compact florescent lamp [8]

The ballast for all florescent lamps provides a certain immunity to changes in luminous flux caused by the supply voltage. Higher supply voltages increase the luminance of the lamp while the opposite is true at lower supply voltages. It is known that electronic ballast components, especially the DC bus capacitor, are sensitive to the supply voltage and that high supply voltage levels lead to shortened lamp life especially if the lamp is frequently switched on and off. Voltage sags and rapid voltage changes can affect the light output of a lamp. Minor changes in voltage will show up in the form of a momentary reduction in the brightness of the lamp. Deeper changes in voltage can cause the lamp to extinguish [5].

All fluorescent lamps need starting devices which is called ballasts. The current in the gas discharge increases in an avalanche-like manner that leads to a sharp drop in resistance. To prevent the electrodes of a fluorescent lamp being damaged by overheating, an additional load is added in series to limit the current. This additional load is ballast [2].

Two types of ballast are used: electromagnetic and electronic. The electromagnetic ballast has a classic transformer-type configuration: copper wire, metal plates. Electronic ballasts use electronic components, such as diodes, diode-controllers, transistors and micro-circuits. Nowadays, electronic ballasts are mainly used because they are compact, lightweight, free of flicker and noise from vibration, and have lower heat losses [2].

As the cost of *LED lighting* technology has decreased over time, LED lighting has become more popular. Nowdays, LED lighting is the most energy efficient mass produced lighting technology. LED lighting has advantages over CFL lighting in terms of service life, color and starting performance. An LED is a semiconductor device that converts electrical current into light radiation. Specially grown crystals give minimum power consumption. The excellent performance of LEDs (light output up to 120 Lm/W, service life up to 100 thousand hours) has already ensured leadership in illumination systems [2].

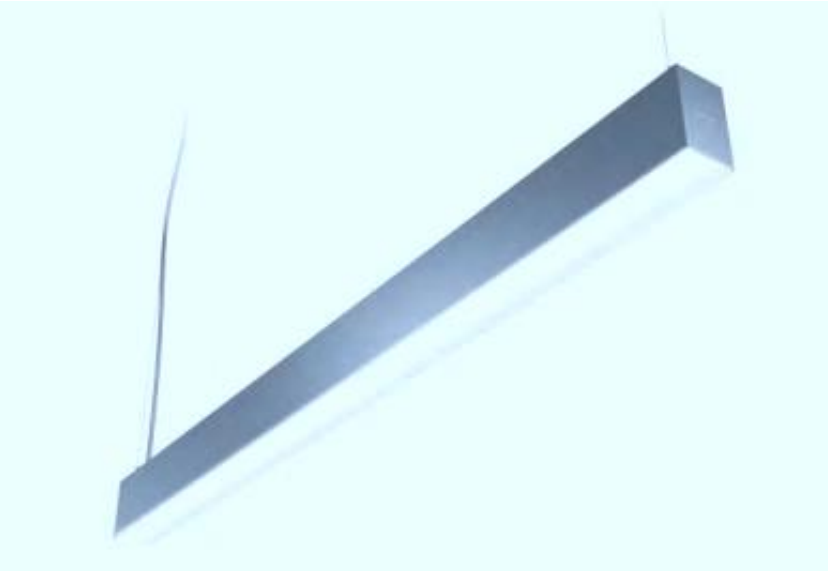


Figure 5 – Led lamp [9]

All LED lamps require an AC to DC conversion to operate. This conversion is usually carried out by an electronic circuit. As with compact fluorescent lamps, the components of these electronic circuits are sensitive to the magnitude of the supply voltage. Excessively high voltage levels can lead to a reduction in the service life of the electronics associated with an LED lighting system. Voltage dips and rapid voltage changes can change the light output of LED lighting systems. For other supply voltage variations (e.g. changes in steady-state voltage), the susceptibility of LED lighting systems depends on the design of the electronic driver [4]. In general, LED lighting systems contain electronic power supplies and operate at low voltages, they are less sensitive to changes in the input voltage than traditional incandescent lamps. In other words, the same change in input voltage will result in a much greater change in illumination flux in a traditional incandescent lamp than in an LED lighting system. As with any electronic equipment, if the voltage drops to a sufficiently low level for a sufficiently long period of time, the LED lamps will extinguish [5].

2.2. Comparative luminary characteristics

As it can be seen from the description above, each type of lamp has its own characteristics and different parameters. Table No. 1 shows the main characteristics and parameters from [8,9,10,11,12,13,14] that I will use in chapter 4 to identify all necessary data for calculations. Due to the fact that all lamps from different suppliers have different characteristics, I have decided to use only one supplier Phillips as an example. This manufacturer is also one of the leaders in the luminaire industry. There are a lot of lamps with different characteristics in the catalogue, so I have selected and tabulated the lamps with the highest luminous flux. Also, according initial technical data the luminous flux should be approximately 6000 lm., so for Fluorescent and LED lamps I limited parameters only to this value.

Table 1. Lamps characteristics (data from [8], [9], [10], [11], [12], [13], [14], [15], [16])

	Incandescent lamp [8]	Halogen incandescent lamp [8]	Fluorescent Lamp [8] with electronic ballast [15]	Compact fluorescent lamp [8] with electronic ballast [16]	LED lamp [9]
Lamp name	Philips A55	Philips PAR38	Philips Master TL5 HO	Philips Master PL-L4	Philips T5M HO
Nominal voltage, V	220	220	220	220	220
Electrical power consumption, W	75	175	75	55	45
Luminous flux, lm	930	2200	6050	4800	6000
Service life, h	1000	5000	24000	20000	50000
Power factor	0.99	0.99	0.92	0.92	0.95
Price for 1 u., RUB	36.9 [10]	733.2 [11]	1433.6 [12,15]	1024 [13,16]	1860 [14]
Price for 1 u., EUR*	0.45	8.95	17.5	12.5	22.7

*Note: The price was found in RUB on 29.10.2021 and converted by the actual exchange rate of 1 EUR to 81.92 RUB on the same day.

According to current researches [1,2,3,4,6], Table No. 2 shows the results of the effect of voltage deviation on the main parameters of artificial light sources.

Table 2. Changing lamp parameters due to voltage deviation (data from [1], [2], [3], [4], [6])

Parameters	Voltage deviation, %				
	-10	-5	0	+5	+10
Electrical power consumption, $\frac{P}{P_{nom}} / \frac{Q}{Q_{nom}}$					
Incandescent lamp [1]	0.8/0.95	0.9/0.98	1/1	1.08/1.02	1.20/1.05
Halogen incandescent lamp [3]	0.85/0.95	0.93/0.98	1/1	1.07/1.02	1.15/1.05
Fluorescent Lamp with Electronic Ballast [3]	1.005/0.5	1.002/0.75	1/1	1/1.3	1.002/1.6
Compact fluorescent lamp with Electronic Ballast [3]	0.9/0.98	0.96/0.99	1/1	1.04/1.02	1.08/1.04
LED lamp [3]	0.96/0.9	0.98/0.95	1/1	1.02/1.06	1.05/1.1
Luminous flux, $\frac{\lambda}{\lambda_{nom}}$					
Incandescent lamp [1]	0.75	0.88	1	1.18	1.4
Halogen incandescent lamp [1]	0.78	0.87	1	1.2	1.37
Fluorescent Lamp with Electronic Ballast [2]	0.86	0.92	1	1.06	1.15
Compact fluorescent lamp with Electronic Ballast [6]	0.9	0.95	1	1.05	1.1
LED lamp [4]	0.95	0.98	1	1.01	1.04

This table clearly shows how the active power, reactive power and luminous flux changes with voltage deviation. For example, for an incandescent lamp, if the voltage is increased by 10 %, the active power consumption will increase by 20 %, the reactive power consumption by 5 % percent and the luminous flux will increase by 40 %.

Unfortunately, there is currently no research on the dependence of service life of equipment from voltage variation. Therefore, the economic justification for the choice of equipment will be based on the nominal values of service life.

Chapter 3. Voltage regulation methods for lighting systems

The main factors influencing the voltage deviation in power supply systems are the reactive power balance in the load nodes, optimum voltage regulation in the main step-down substation, application of local voltage regulation, and rational distribution of phase loads [1].

One of the main conditions for reducing power losses and improving power quality is to increase the nominal voltage level. As a rule, excessive voltage deviations above permissible values indicate about an irrational voltage level at a given stage of power supply [1].

As mentioned above, only local voltage regulation sources will be considered in this thesis. This is due to the fact that individual power consumers have different distances from transformer substations and different load schedules, resulting in inconsistent requirements for overall voltage regulation. Therefore, individual voltage regulation is used in individual networks or directly at consumer nodes. Voltage limiters and voltage adding devices such as voltage regulators are used for this purpose [18].

3.1. Types of local voltage regulators

The main advantages of voltage regulators and voltage limiters are that it helps to prevent voltage surges in the system and consumes a small amount of electricity. In addition, it helps to protect artificial lighting from premature failure and maintain stable flicker-free lighting, thus reducing eye strain [17]. In this paper the following devices will be considered:

- Triac voltage stabilizers;
- Relay voltage stabilizers;
- Servo voltage stabilizers;
- Booster transformers;
- Thyristor voltage limiters.

Triac voltage stabilizers are equipped with a microcontroller to monitor all processes. After the input voltage is measured, the voltage is redistributed between the autotransformer windings by means of triacs (semiconductors). The operational principle of this unit is that the incoming voltage is measured by the controller using a special sensor. Further, based on the measurements the controller makes a decision on adjusting the voltage. The controller sends an appropriate signal to the input triacs. This signal is used to supply a voltage aligned to a certain value, the voltage is stabilized by an autotransformer [19].

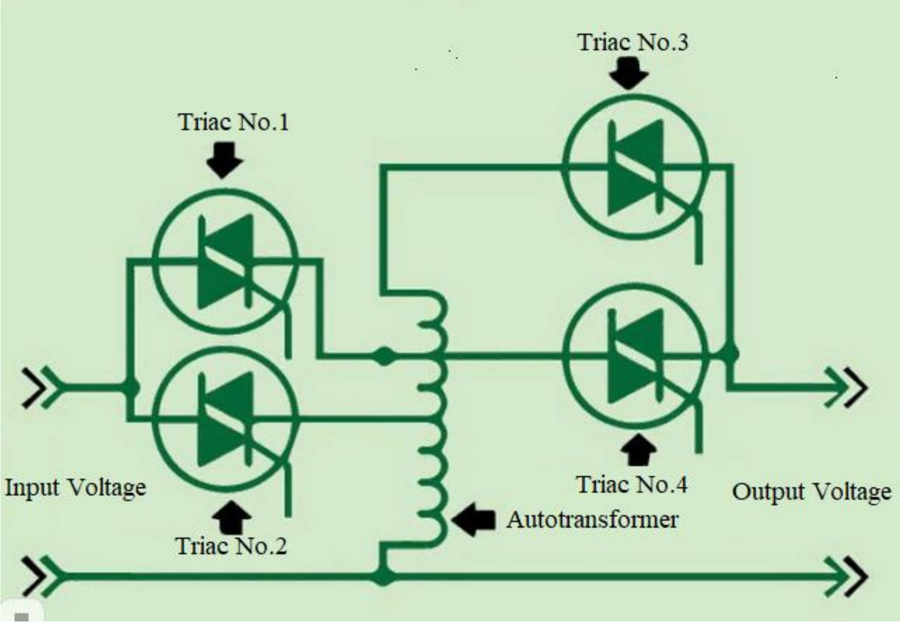


Figure 6 – The simplest scheme of triac voltage stabilizer [20]

The advantages of triac stabilizer are [20]:

- High speed operation - due to high-speed switching triacs;
- Wide range of input voltage - stabilizers are able to operate at input voltage values from 95 to 275 V (for single-phase models), from 260 to 470 V (for three-phase stabilizers);
- High stabilization accuracy - fluctuations within 1,5% of nominal voltage;
- High efficiency - due to the use of triac, the value of this indicator in most models reaches 95-97%;
- Noiselessness - the absence of relay switches and mobile contacts allows the device to be nearly quite;
- Small size;
- Long service life - most modern models can normally operate for 10 years or more.

Disadvantage of triac stabilizers device [20]:

- High cost relative to other stabilizers.

In *relay voltage stabilizers* voltage regulation is accomplished by switching the relays to connect one of a number of tapings of the transformer to the load. The principle of relay stabilizer operation is that the input voltage passes through a surge suppression filter and is measured electronically. After, the voltage level is compared with the nominal value which should be at the output. In case of an unacceptable voltage deviation in the network the electronic circuit generates a signal to activate certain relay contacts which are switched to achieve the required transformation ratio. These actions provide an output voltage value close to the nominal voltage [19].

Also, the electronic circuit is able to stop the stabilizer operation in case of short circuits, current overloads, long pulses or mismatch between the actual voltage in the network and the working range of the stabilizer input voltage [19].

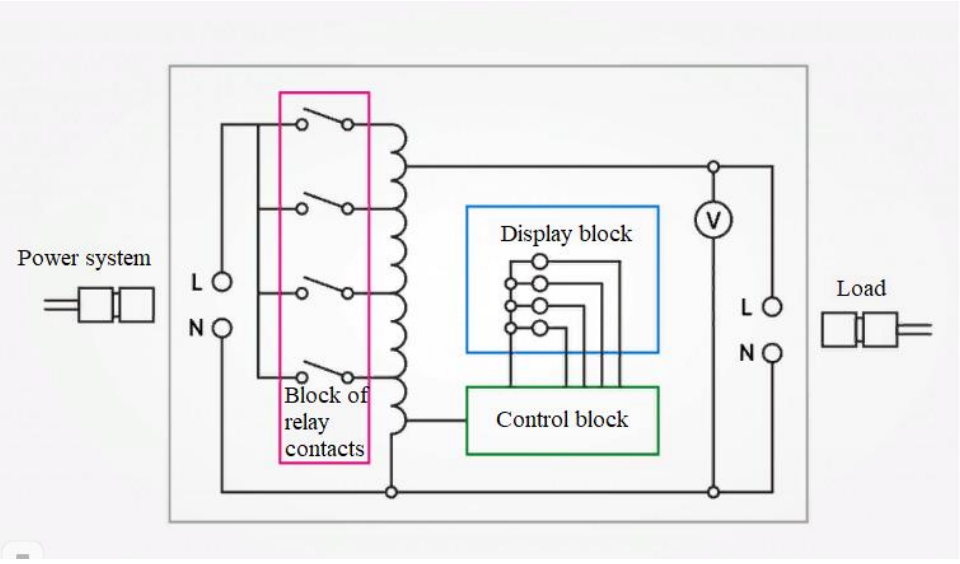


Figure 7 – The simplest scheme of relay voltage stabilizer [21]

The advantages of this relay stabilizer [21]:

- Compact design;
- No special maintenance required;
- High resistance to overload;
- No special cooling required;
- Wide ambient operating temperature range;
- Possibility of operation with no-load;
- The low cost.

Disadvantages of this device [21]:

- Stepwise non-smooth voltage correction;
- Slow response to sudden changes in voltage (10-20 ms);
- Low accuracy of stabilization (5-10%);
- Noise in operation. The characteristic clicks from the relays operation are serious limitation in the placement of devices in residential premises;

- The presence of mechanical parts, which negatively affects the service life.

Servo voltage stabilizers work on servomechanism which also known as negative feedback and the name suggests it uses a servo motor to enable the voltage correction. A servo drive controls the movement of the slider along the transformer windings ensuring a stable voltage level. These are mainly used for high output voltage accuracy, typically ± 1 percent [18].

The operation of the servo voltage stabilizer is that the electric current flows from the network to the control board where a voltmeter measures the voltage level. Depending on the results, a signal is given to the servo drive which move a contact across the winding that leads to changing the ratio of the autotransformer up to nominal value. In another words, the number of turns of the primary winding is changed while the secondary winding remains unchanged [18].

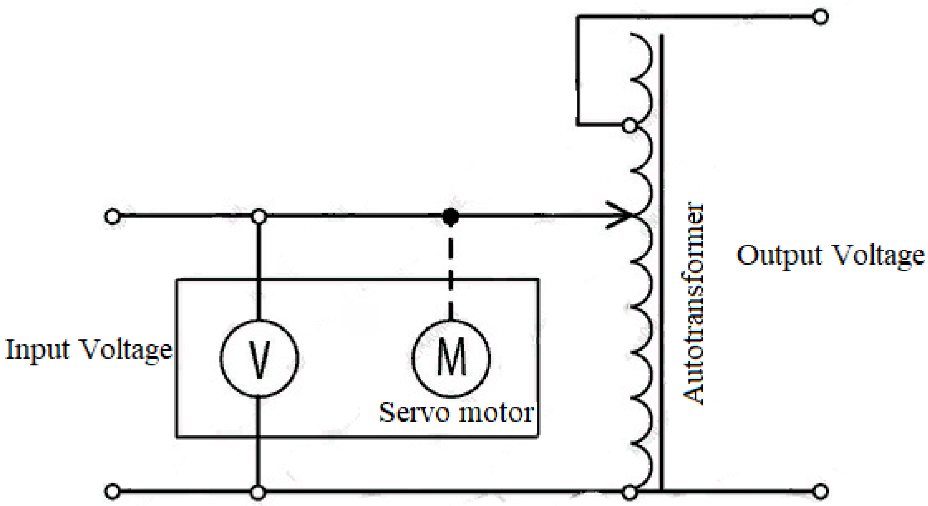


Figure 8 – The simplest scheme of servo voltage stabilizer [22]

Advantages of this device are [22]:

- Low cost;
- High stabilization accuracy as the mechanical stabilizer has no fixed taps from the autotransformer, but can form the required number of winding turns itself;
- Smooth stabilization;
- Resistant to short-term overloads;
- Resistant to voltage, frequency and current waveform disturbances;
- Compact size;
- High efficiency;

Disadvantages of this device [22]:

- Existence of moving parts;
- Needs regular maintenance;
- Noise;
- Slow response speed;
- Limited operating temperature range.

A booster (step-up) transformer can be used instead of voltage stabilizers. This device is a conventional single-phase or three-phase transformer with a transformation ratio equal to 220/12 V or 220/24 V [1].

The booster transformer allows creating an additional electromotive force which is added to the main network voltage vector. Such a transformer has two windings: a secondary winding in series with the load where the voltage is regulated, and a primary winding connected to the power supply system. The additional EMF generated by the transformer depends on the supply voltage of the primary winding and the transformation ratio. The magnitude of the additional voltage can be changed by [1]:

- The transformer ratio;

- The voltage supplied to the transformer's primary windings by means of an auxiliary regulation of transformer or autotransformer.

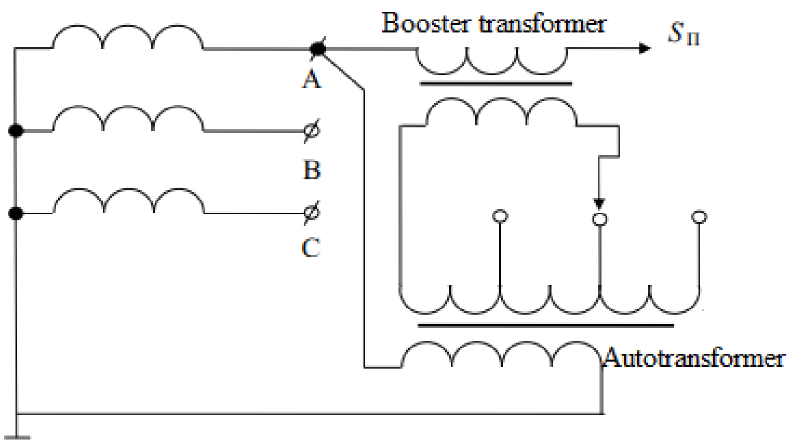


Figure 9 – Scheme of connection booster transformer through autotransformer [1]

Typically, the power consumption of this device is 10-15% of the load capacity. The installation of a voltage step-up transformer can equalize the voltage in the power grid, eliminate voltage unbalance in a particular circuit and reduce the dangerous effects of a zero conductor burnout [1].

Thyristor voltage limiters are used to maintain the required voltage on the artificial light sources. Voltage limiters ensure that the consumer's voltage is maintained only when the input voltage level is exceeded the nominal value. This device usually is designed for 380/220V voltage level and has output voltage regulation in the range of 0.9-1.05 from nominal voltage and provides an accurate voltage at a given set of - 1.5 % from the nominal value. The voltage limiters cannot be used in lighting installations where there are restrictions on the permissible level of radio interference. The limiters should be installed preferably in front of group lighting panels [1].

3.2. Comparative local regulator characteristics

As it seen from the description above, all stabilizers and voltage limiters have different features and characteristics. For example, all stabilizers consist of an autotransformer and differ only in the approach of windings switching. Table 3 shows the main technical characteristics and costs of the electrical equipment.

Table 3. Voltage regulator's characteristics (data from [23], [24], [25], [26])

	Triac voltage stabilizer [23]	Relay voltage stabilizer [24]	Servo voltage stabilizer [25]	Booster transformer [26]	Thyristor voltage limiter [26]
Input voltage range, V	100-295	176-264	135-275	198-242	198-242
Nominal power	1.9 kW (2.2 kVA)	1.8 kW (2 kVA)	1.3 kW (1.5 kVA)	9 kW	5 kW
Regulation step, %	±3.5	±5	±3	±1	-1.5
Efficiency, %	98.5	98	95	95	96
Service life, year	10	8	8	10	10
Price for 1 u., RUB	13 583.2	2 170	6 771	23 892	28 729.3
Price for 1 u., EUR*	165.81	26.48	82.65	291.65	350.7

*Note: The price was found in RUB and converted by the exchange rate of 1 EUR to 81.92 RUB on 29.10.2021.

Only single-phase voltage stabilizers are considered in this thesis because a three-phase stabilizers are only required for the system with three-phase load, such as machines and other similar industrial equipment. If all connected devices are single-phase, it is more convenient to use single-phase stabilizers for each individual equipment or group of equipment. One-phase stabilizers are simpler in construction, cheaper and remain operable in the event of a phase failure [23].

Chapter 4. Lightning system of the electrical department

4.1. Preliminary front end engineering design

According to task, I need to regulate the voltage level on the lighting sources of the electrical department in a reinforced concrete products factory which is located in Novosibirsk.

Voltage regulation is an important issue because correct lighting projection in production facilities has a positive effect on the performance and health of the workforce. Lack of light leads to fatigue and irritability. In addition, prolonged exposure to inadequate lighting causes visual acuity to suffer from excessive strain on the eyes. Excessively bright light can cause photo burns to the eyes, overstimulation of the nervous system, and other nuisances [19].

There are mainly three types of lighting used in production facilities [19]:

- Natural (where the source of light is the sun);
- Artificial (where only artificial light sources are used);
- Combined or mixed lighting (characterized by a simultaneous combination of natural and artificial light).

Typically, combined lighting is used where only natural lighting cannot provide the necessary conditions for production operations [19].

In this thesis I have considered combined lighting, where natural and artificial lighting are using. Artificial lighting in a combined system can be operated continuously (in areas with insufficient natural light) or switched on at evening.

Within this chapter I will demonstrate the results of the calculations for natural and artificial lighting. The calculation of natural lighting comes down to determining the minimum area of the openings and their location. The area of light openings depends on the geographical location of the facility, its orientation and the internal dustiness of the building. Calculation of artificial lighting comes down to determining the minimum number of luminaires, their distance from each other and from the walls, as well as the distance from the luminaires to the working surface [1].

From the [28] for the calculation of lighting I was given the following initial data:

- Site location – Novosibirsk;

- Building size 600 m^2 (Length 40 m., width 15 m.);
- Ceiling height 5 m;
- Facility is bright, slightly dusty;
- The nature of the visual work is medium precision, workers need lighting that allows them to work with elements from 0.5 to 1 mm. Operations with such details possible at night time;
- Distance from the switchgear to the transformer station is 130 m;
- Distance from transformer station to MSDS 310 m;
- Data about load.

According to the [27] for the nature of precision work, a luminous flux must be not less than 300 lm that will allow to carry out operations with small parts in the absence of daylight.

In accordance with [30] the average daylight hours in Novosibirsk are shown in the figure 10. The average value in hours for the year 2021 was used to create this diagram. This model uses idealistic values that are based on the interval between sunset and sunrise. The exact time when natural light reaches its maximum value and the duration of this interval are not shown.

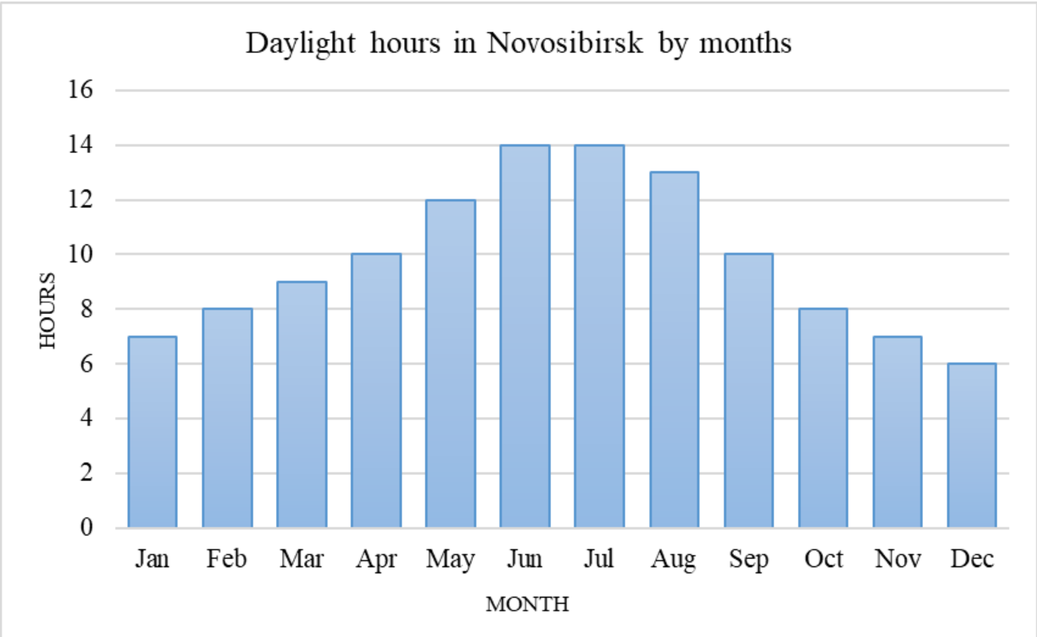


Figure 10 - Natural lightning duration in Novosibirsk (illustration based on data from [30])

Figure 10 shows an idealistic picture of the duration of daylight hours (excluding cloud cover and bad weather). Based on these figures, the approximate usage time of artificial light can be calculated using the formula below.

$$Artificial\ lightning\ duration = Day\ duration - Natural\ lightning\ duration;$$

Thus, for example, in the February the daylight period is 8 hours, which means that the time required to use the artificial lighting at full power is 16 hours. Based on the above, the minimum annual duration of artificial lighting is 5 167 hours.

In order to design the lighting system, I need to choose a certain type of lamp because all lamps have different luminous fluxes, which significantly effects on the number of installed luminaires. As an example and to give a better visual impression, I will take LED lamps for installation. Further calculations and schemes will be made for LED luminaires. After the final economic selection of the light source type in chapter 5.1, the model will be recalculated in chapter 6. At the end of the chapter I will recalculate and write the required number of lamps which have been selected in Table 1. Based on all the initial data, it was determined that 72 LED lamps with a rated illuminance of 6000 lm would be required for comfortable lighting. Part of the calculation below demonstrates this decision.

Calculation using the utilization factor method allows you to calculate the required luminous flux of each luminaire F [19]:

$$F = \frac{\mathrm{E} \cdot S_n \cdot K_z \cdot Z}{N_{lamp} \cdot \eta} = 5952.4\ (lm); \tag{4.1}$$

Where:

E = 300 lux - The standard illuminance [27];

S_n = 600 m^2 - Area of the building;

K_z= 1.5 - Safety factor which indicates the dustiness of the building. The minimum dust content in industrial plants is 1-5 mg/m^3 [27];

Z = 1 for LED lamps (1.1 for florescent lamps, 1.15 for halogen lamps, 1.2 for incandescent lamps) - coefficient of irregularity of illumination [19];

N_{lamp} = 72 - Number of lamps;

ŋ = 63% (for bright area with window openings)- Coefficient of utilization of luminous flux [19].

The distance between the luminaires is [19]:

$$L = h \cdot Z = 2\ m; \tag{4.2}$$

Where:

h = 2 - The distance between the work surface and the luminaire.

The average height of the working surface is 1 m. The height of the electrical department is 5 m. It was decided to use an average value of 2 meters, which allows reduces the cost of using more powerful lamps and reduces the glare effect.

The total number of luminaires is calculated using the formula [19]:

$$N_{lamp} = \frac{A - L}{L + l} \cdot \frac{B - L}{L + lb} = 11.8 \cdot 5.9 = 70.2 \cong 72; \quad (4.3)$$

Where:

A = 40m – Length of building;

B = 15m – Width of building;

L = 2m – Distance between luminaries;

l = 1.2m – Length of lamp;

lb = 0.2m – Width of lamp.

From the calculations, the number of installed lamps equal to 70.2. But for rational load distribution in a three-phase system, the number of luminaires must be divided by three without a remainder. Therefore, it is necessary to round the amount of lamps up to 72. Also, it is impossible to round amount of luminaries down to 69, as it would violate the [27] requirement for minimum lighting.

Calculations for natural lightning comes down to determining the minimum area of the window openings, which is calculated using the following formula [19]:

$$S_0 = \frac{S_n \cdot e_N \cdot K_z \cdot \eta_0}{100 \cdot \tau_0 \cdot r_0} = 109.4\ m^2; \quad (4.4)$$

Where:

e_N = 1.4 – The normalized value of the natural illumination coefficient which depend on the location area of the facility and the kind of the work [27];

η_0 = 8 - The value of the light characteristic of side windows illumination, which depends on the height of the working surface (see Figure 10) [19];

τ_0 = 0.384 - The light transmission coefficient, which depends on the thickness of the glass [27];

r_0 = 2.4 - The sidelight coefficient, which depends on the illuminance of the building and its area [27].

After calculations, I decided to install eight window openings, with a standard window dimension of 4.2 x 3.4 m. Thus, the area of the window openings is greater than the minimum allowable area, which makes it possible to obtain the necessary illumination in the daytime for working with parts from 0.5 to 1 mm. Equation below demonstrates it [19]:

$$8 \cdot 4.2 \cdot 3.4 = 114.24\,m^2 > 109.4\,m^2; \tag{4.5}$$

Thus, an approximate location plan for LED luminaries and window openings in the electrical department is shown in Figure 11. To check my calculations for artificial lightning, I have used the DIALux software to calculate the facility illumination. The result is shown in figure 12.

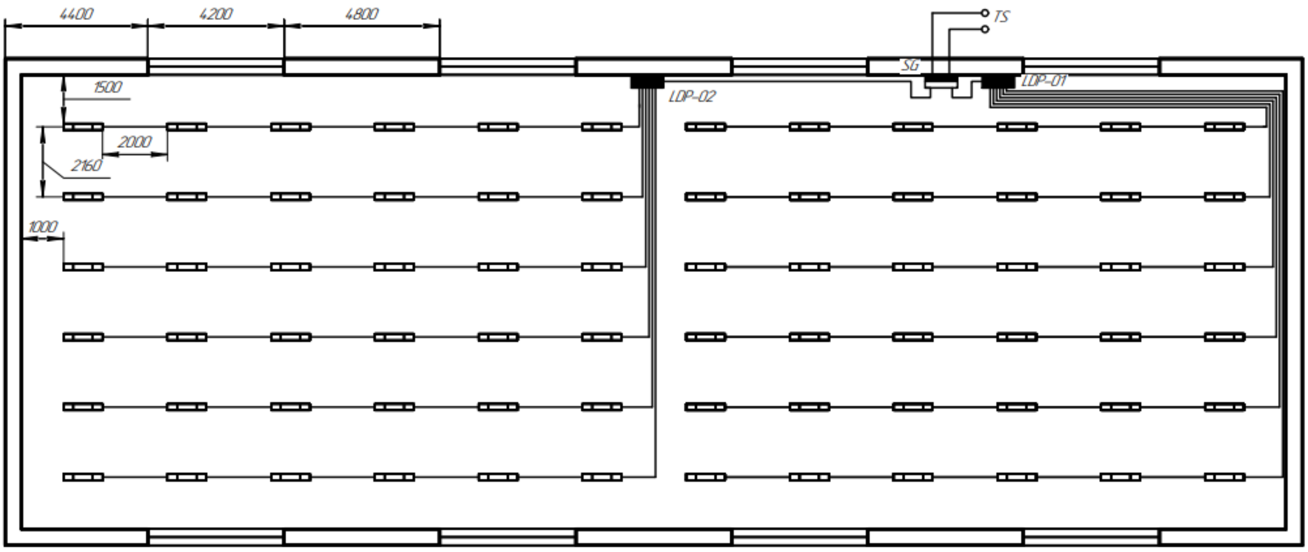


Figure 11 – Plan of electrical department (illustration based on data from [27], [28])

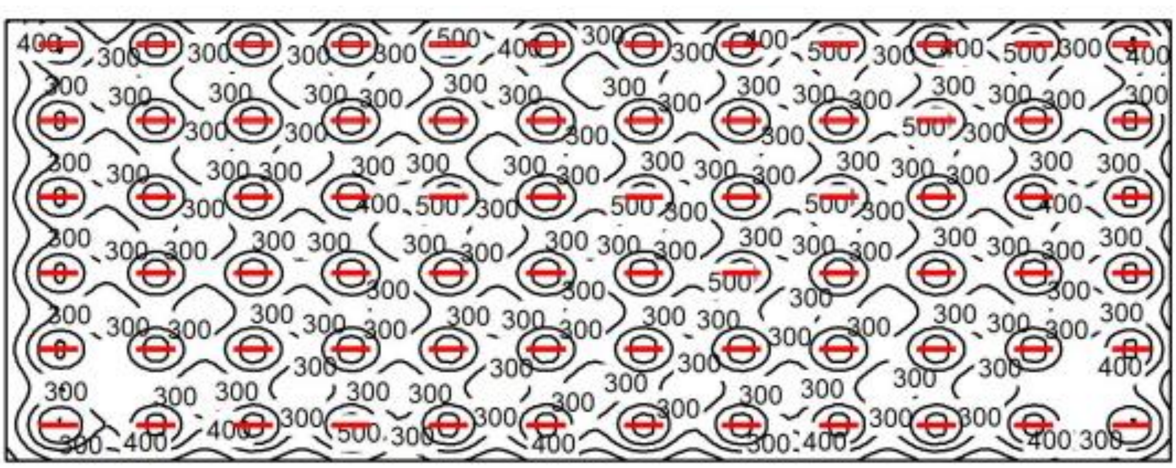


Figure 12 – Illuminance distribution in the building (illustration based on data from [27])

Figure 12 shows that illumination levels are unevenly distributed. Near the walls the level of light reaches 400-500 lux, it is due to the fact that the wall surface is bright and reflects the light flux.

4.2. Calculation of lightning characteristics for electrical department

For a more accurate economic calculation, the lamps for the electrical department must be recalculated according to the parameters and rules described above.

Due to the fact that formulas (4.1) and (4.3) have been rounded up, the illuminance must be recalculated. Also, using the formulas described above, it is necessary to determine the required number of all other luminaire types and the facility illuminance in each option.

Table 4. Comparison of light source characteristics (calculations based on data from [8], [9], [19])

Parameters	Incandescent lamp	Halogen incandescent lamp	Fluorescent Lamp	Compact fluorescent lamp	LED lamp
Required number of lamps	462	195	72	90	72
Power consumption, kWh	34.65	34.13	5.4	4.95	3.24
Illumination level, lux	300.76	300.3	304.92	302.4	302.4
Permissible flux deviation	0.98997	0.98999	0.98984	0.98992	0.98992
Permissible negative voltage deviation, %	-0.42	-0.39	-0.64	-1.01	-2.53

Table 4 shows how many lamps of each type are needed to illuminate the electrical department according to the set of rules [27]. Also, the table shows the electrical consumption, illuminance depending on the type of lamp and the permissible deviation of the luminous flux (see Table 2). According to the data in Table 2, it has been possible to calculate the permissible voltage deviation by interpolation method. For example, when using a LED lamp at nominal voltage level the luminous flux will be 302.4 lux. After voltage drop to 2.52% from nominal value the luminous flux will be 300 lux which is the minimum permissible value [27]. Therefore, reducing the voltage below this value is not permissible by SP, it must be regulated.

4.3. Calculation of voltage deviation for electrical workshop

Once all the necessary calculations have been made to determine the power consumption in each individual case, the number of luminaires and the permissible voltage deviation, the actual voltage deviation for the light sources can be calculated. The calculations will be made for 4 luminaires only. Two of which will be connected to LDP-01 and the other two to LDP-02. The calculation using formula (1.2) will be done for the closest and the furthest luminaire to show the deviation range. The voltage deviation for the other luminaires will be within this range. This type of calculation will simplify the model so that it is not necessary to perform calculations for e.g. 462 incandescent lamps. All final voltage deviation values will be shown in the table 5.

As an example, allow us to calculate the voltage deviation in the maximum operating mode for the first circuit section (see figure 12) using formula (1.2) and data from [28]. All necessary data from [28] are shown in figure 12.

First of all, it is necessary to calculate voltage drop or deviation on the element of supply system [1]:

$$\Delta U_{12,\%} = \frac{P_{12}R_{12} + Q_{12}X_{12}}{10{U_1}^2} = 0.145\ \%;$$

$$\Delta U_{12} = \frac{\Delta U_{12,\%} \cdot U_1}{100} = 0.015\ kV;$$

Where:

P_{12}, Q_{12} – Active and reactive power transmitted though the first cable line [28];

R_{12}, X_{12} – Active and reactive resistances of the first cable line [17];

$U_1 = 10.5\ kV$ – Voltage level at MSDS.

Active and reactive resistances can be found using follow formulas [17]:

$$R_{12} = \frac{r_{012} \cdot L_{12}}{n} = 0.048\ Ohm;$$

$$X_{12} = \frac{x_{012} \cdot L_{12}}{n} = 0.0989\ \ Ohm;$$

Where:

r_{012} – Specific resistance (Ohm/km) [17];

x_{012} - Specific reactance (Ohm/km) [17];

L_{12} – Length of the first cable line [28];

$n = 2$ – Number of parallel cable lines [28].

Level voltage in the end of first element:

$$U_2 = U_1 - \Delta U_{12} = 10.485\ kV;$$

Voltage deviation:

$$\delta U_2 = \frac{U_2 - U_{nom}}{U_{nom}} \cdot 100\% = 4.85\ \%;$$

Where:

$U_{nom} = 10\ kV$ – Nominal voltage level.

At maximum mode, it is necessary to increase the voltages at the transformer outputs by 5% in order to reduce the transport losses. In minimum load mode $U_1 = 10\ kV$. Maximum operation mode of the power system is achieved during the winter season, when the maximum load is connected. The minimum mode assumes the summer season, when only part of the load is connected. Similar calculation methodology for all other circuit elements.

The results of the voltage deviation calculations in the two power system modes for each luminaire type are shown in Table 5.

As can be seen from Table 5 voltage deviation in the two power system operating modes is existing. As can be seen from the minimum operating mode for all sources, the voltages need to be adjusted because the values fall below those shown in Table 4. This leads to insufficient lighting for the corresponding type of work in this building. In maximum mode, there is a positive voltage deviation, which increases the active power consumption (see table 2). With proper regulation, the power consumption can be reduced. Thus, Table 5 shows that in this case it is necessary to regulate the supply voltage in order to get rid of more power consumption and to maintain a comfortable working environment. The quality of these parameters directly depends on the type of regulator, as they all have different parameters.

Table 5 – Voltage deviation in percentages (calculations based on data from [8], [9], [17], [27], [28])

Operation mode	Place of connection		Incandescent lamp	Halogen incandescent lamp	Fluorescent lamp	Compact fluorescent lamp	LED lamp
Maximum mode	Luminaries connected to LDP-01	Near lamp	1.26	1.29	2.99	3.01	3.11
		Distant lamp	-1.64	-1.58	2.53	2.59	2.84
	Luminaries connected to LDP-02	Near lamp	-0.14	-0.09	2.77	2.81	2.98
		Distant lamp	-3.08	-3.01	2.31	2.39	2.71
Minimum mode	Luminaries connected to LDP-01	Near lamp	-6.94	-6.9	-5.07	-5.04	-4.93
		Distant lamp	-10.08	-10.01	-5.55	-5.49	-5.22
	Luminaries connected to LDP-02	Near lamp	-8.46	-8.4	-5.3	-5.25	-5.07
		Distant lamp	-11.66	-11.56	-5.79	-5.7	-5.36

Figure 13 shows the electrical circuit from the MSDS to the lighting sources in the electrical department, where the required power for each node is shown. For example, the load on the low voltage side of the transformer is 808 kVA and the load of the electrical department is 220 kVA. This means that the difference between these numbers equals the consumption of the other load shown in the picture and the losses. All the necessary data is shown in the figure.

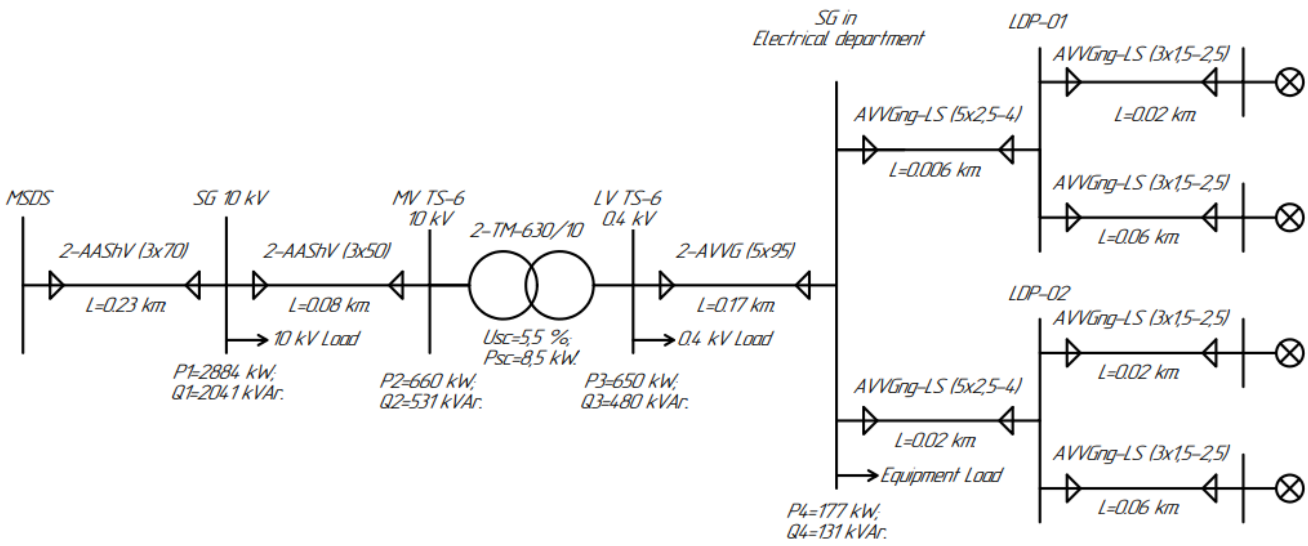


Figure 13 – Electrical circuit (illustration based on data from [28])

Where:

2-AAShV (3x70) – Two parallel cables, A - Aluminum conductive core, A - Aluminum shell, SHV - protective Hose from PVC plastic, 3 conductive cores, cross-section equal to 70 mm^2;

2-AAShV (3x50) – Two parallel cables, A - Aluminum conductive core, A - Aluminum shell, SHV - protective Hose from PVC plastic, 3 conductive cores, cross-section equal to 50 mm^2;

2-TM-630/10 – Two transformers, T - Transformer, M – oil, each capacity equal 630 kVA, primal voltage equal to 10 kV;

2-AVVG (5x95) - Two cables, A - Aluminum conductive core, V - PVC-insulated, V - PVC jacket, G - bare cable, 5 conductive cores, cross-section equal to 95 mm^2;

AVVGng-LS (5x2.5-4) – One cable, A - Aluminum conductive core, V - PVC-insulated, V - PVC jacket, G - Bare cable, ng - non-flam, LS - less smoke, 5 conductive cores, cross-section depend on type of luminaries;

AVVGng-LS (3x1.5-2.5) – One cable, A - Aluminum conductive core, V - PVC-insulated, V - PVC jacket, G - Bare cable, ng - non-flam, LS - less smoke, 3 conductive cores, cross-section depend on type of luminaries.

Chapter 5. Selection of electrical equipment

The step after primary front end engineering design of project, where I have checked the ability of project realization and designed a natural and artificial lighting system with one possible type of lighting system, is its economic evaluation. In this chapter I will estimate the volume of investments in each artificial system configuration and expenditures. After I will calculate the net present value and based on the average annual costs, I will select several lighting sources and stabilizers, then a technical and economic analysis of this solutions will be in chapters 6 and 7, which allows me to calculate the value of the money saved on electricity by voltage regulation.

In this chapter, I will face with the task of economic comparison of five options for artificial illuminating system and five options for local voltage stabilizers. Each of these considered options have different technical characteristics, therefore, each solution must be evaluated from an economic and technical point of view. Another feature of this solution is that I am going to consider these options from manager point of view. In this case, from the manager's point of view, it is necessary to get the maximum NPV value. It should be also understood that in this case, the lighting of the workplace cannot generate a profit, it only serves to create the necessary working condition. The only thing that can be done here is to save money through minimization of investments and reduce electricity consumption.

5.1. Methodology of economic evaluation

To implement the project, it is necessary to estimate the volume of investments and expected expenditures, as well as analyze the options with Net Present Value and Equivalent Annual Payments.

The Net Present Value (NPV) is the criterion that allows to decide whether it is reasonable to invest in a project. NPV estimate the difference between the present value of cash inflows and the present value of cash outflows. However, there are no cash flows in the current project, so the net present value for each measure will be estimated on the basis of electricity bills, taking into account annual inflation and the expected life of the project. Because the NPV calculation is purely cost-based, the NPV for all measures will be negative, and a closed to zero NPV would be more desirable [31].

The NPV is calculated according to following formula [31]:

$$NPV = C_0 + \sum_{t=0}^{T} \frac{C_t}{(1+r)^t}; \qquad (5.1)$$

Where [31]:

C_0 – Initial investment in the project (usually a negative number);

T – Service lifetime of the equipment;

t – Number of time periods;

C_t – Summary cash flow in the period t;

r – Discount rate.

The NPV approach properly considers the time value of money and adjusts for project's risk using the opportunity cost of capital as the discount rate. Thus, it clearly measures the increase in market value or wealth created by the project. NPV is the only metric that provides a theoretically correct measure of project cost [31].

Once the NPV has been calculated, the annual payments to operate must be calculated. The amount of the annuity payment with a given present or future value is calculated using the following formula [31]:

$$EAA = \frac{NPV}{T\ annuity\ factor}; \tag{5.2}$$

$$T\ annuity\ factor = \frac{1}{r} - \frac{1}{r \cdot (1+r)^T};$$

Where [31]:

EAA – Equivalent annual annuity;

$T\ annuity\ factor$ – Annuity factor for period T.

5.2. General economic parameters

For project implementation it is necessary to know the various economic parameters of the country where the project will be realized. In this sub-chapter I will evaluate some basic parameters, which will be the same for illumination system and regulators, such as inflation rate, corporate tax and discount rate.

1. Inflation

Inflation is an increase in the general price level of goods and services. In inflation, the price of identical goods increases over time. In effect, the purchasing power of money is reduced and money becomes worthless [32]. It is only possible to estimate the future rate of inflation by analyzing inflation in previous years. Therefore, for this project I have taken the average geometric inflation rate for the last 10 years. The data is presented in table 6.

Table 6 – Historic inflation in Russia [32]

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Inflation, %	6.58	6.45	11.36	12.91	5.38	2.52	4.27	3.05	4.91	8.39
Average inflation, %	6.53									

According to table 6, I have plotted a graphical chart to better representation of inflation level.

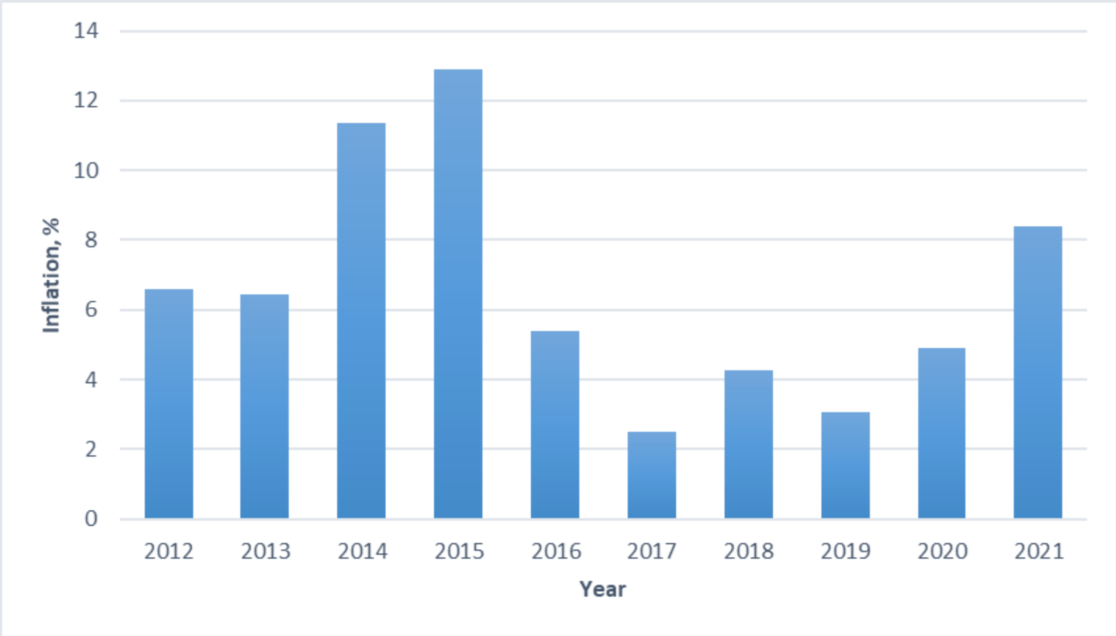


Figure 14 – Historic inflation in Russia (illustration based on data from [32])

According to [40] long-term target inflation is 4 %, but table 6 shows that desired inflation didn’t reach. Therefore, it was assumed to use historic-based inflation. In this thesis some economic parameters like maintenance and price of new equipment will rise every year on inflation rate.

2. Corporate tax

Corporate tax is a direct tax levied on the profits of an organization. Profit for the purposes of this tax is generally defined as income from a company's activities reduced by the amount of statutory deductions and exemptions [33].

According to the tax law of Russia, corporate tax rate is equal to 20% [33].

3. Discount rate

The discount rate is the ratio of return used to discount future cash flows to their present value. According to Capital Asset Pricing Model (CAPM), the discount rate can be calculated using followed formula [31]:

$$r = r_f + \beta \cdot (r_m - r_f) = 7.42 + 0.5 \cdot 8.1 = 11.47\ \%;$$

Where:

$r_f = 7.42$ % – Risk free rate equals to 10 years federal bond ratio [34];

$\beta = 0.5$ - The average volatility of stocks in this sector (construction and production of reinforced concrete) in Russia's market [35].

$r_m - r_f = 8.1$ % – Average risk premium rate on market for 10 years [36].

4. Escalation rate

Costs of goods every year increase or escalate. In this thesis energy consumption cost will increase on escalation rate which equal to average geometric electricity grows for the last 10 years [41]. Escalation rate for electricity equal to 3.3 %.

For another expenses such as maintenance and purchasing equipment escalation rate equals to inflation rate which is 6.53 %.

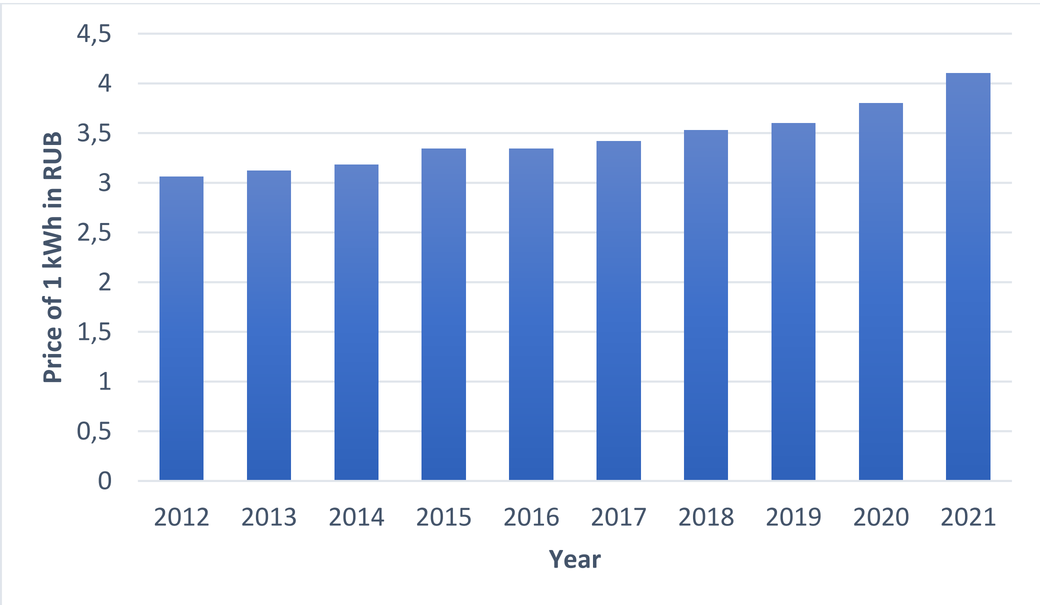


Figure 15 – Prices of 1 kWh in Russia (illustration based on data from [41])

5. Depreciation

Depreciation is the process of transferring the cost of fixed and tangible assets by instalments as they are technically or morally depreciated to the cost of products (works, services) produced [31]. According to Russian laws, the firm has a right to select the method for calculation of depreciation [33].

Accelerated depreciation has been adopted to reduce taxes faster as money is worth more now [31]. When calculating depreciation for tax reducing purposes, I used the variable declining balance method, the essence of which is to use two methods of calculating double-declining balance and straight-line depreciation. The point is that this VDB is better than the DDB method, as the second does not always achieve the full depreciation amount by the end of service life [39].

An example of a comparison between two types of accelerated depreciation is shown below in Table 7. As an example, the depreciation of fluorescent lamps is considered, the initial investment value is 103 219.2 RUB and the equipment service life is 7 years. See chapter 5.3.2 for more details about estimation of these values. All calculations have been done using functions in Excel.

As Table 7 shows, the final result of using double-declining balance depreciation does not cover the amount of initial investments in the project, so the variable-declining balance method will be used for further depreciation calculations.

Table 7 – Comparison of DDB and VDB methods (calculations based on data from [31], [39])

Year	1	2	3	4	5	6	7	Total amount, RUB
Double-declining balance method, RUB	29491.2	21065.1	15046.5	10747.5	7676.8	5483.4	3916.7	$\sum$ 93427.4
Variable-declining balance method, RUB	29491.2	21065.1	15046.5	10747.5	8956.3	8956.3	8956.3	$\sum$ 103219.2

According to [39] it is possible to derive a function of how variable-declining balance method is calculated. The first half of the lifetime is calculated using double-declining balance method [31] and the second half is calculated using straight-line depreciation [31] for the remaining non-depreciated value.

$$VDB = \begin{cases} \frac{2}{T} \cdot (Cost - Accumulated\ depreciation), & 0 < t \leq \frac{T}{2} \\ \frac{2}{T} \cdot Non\ depreciated\ value, & \frac{T}{2} < t \leq T \end{cases}$$

5.3. Selection of illumination system

According to tables 1 and 4, in this sub-chapter I will calculate NPV and estimate average yearly payments for five options of illumination system. In order to calculate all necessary costs, I will use some general economic indicators from chapter 5.2, as well as to specific economic indicators such as:

- Initial investment in the project;
- Energy consumption cost;
- Cost of maintenance;
- Purchasing new equipment.

5.3.1. Specific economic parameters

1. Initial investment in the project

According to tables 1 and 4, it is possible to obtain initial amount of money to realize a project. In order to determine the initial cost, the price of one luminaire must be multiplied by the recommended number of luminaires based on the calculations in chapter 4.2. The following formula is used:

$$C_0 = n \cdot C;$$

Where:

n – Required number of luminaries;

C – Price of one luminaire (data from table 1).

This formula does not take into account the inflation rate because the purchase is being made at the present time.

2. Energy consumption cost

According to calculations from chapter 4 and illumination load graph from chapter 6, the electricity consumption for each type of lighting installation can be determined using the following formula:

$$C_t^{en} = k_{max} \cdot n \cdot E \cdot (P \cdot h_1 + 0.2 \cdot P \cdot h_2) \cdot (1 + ESC)^t;$$

Where:

C_t^{en} – Cost of energy in the period t;

k_{max} - Coefficient of maximum increase in active power consumption from voltage deviation (data from Table 2);

$E = 4.1\ RUB\ per\ kW \cdot h$ - Cost of $kW\ per\ h$ in Novosibirsk, Russia [38];

P – Active power consumed by one luminaire, kW;

$h_1 = 2977\ h$ - Minimum annual operating time of artificial lighting in the daytime;

$h_2 = 2190\ h$ - Minimum annual operating time of artificial lighting in the night time;

$ESC = 3.3\ \%$ - Geometric average electricity price grows in Russia for 10 years' period.

In accordance with the typical load graphs for artificial lighting (see figure 16), it has been determined that at time from 22:00 to 04:00, the lighting consumption level in the building is 20% of the nominal power, for the convenience of the operating staff. The hours of artificial lighting operation during the day depend on the length of daylight hours (see figure 10) and vary from month to month but the annual duration equals 2977 h per year.

3. Cost of maintenance

Like all electrical equipment, lighting installations must also be maintained. The maintenance of lighting installations includes the initial installation of the equipment and the replacement of the equipment with a new one at the end of its service life.

For luminaires, the cost of maintenance consists of the staff wages. Thus, the average salary of an electrician in Novosibirsk is equal to 43 098 rubles [37] or 526 euros per month (the exchange rate is taken similar to all other calculations, the equivalent of 1 euro = 81.92 rubles). Knowing the worker's wage per month (160 hours), I am able to determine the rate per working hour. Based on safety rules, at least two workers are allowed to work with electrical equipment. In the cost of maintenance, I took into account the rate of two electricians for one working shift (8 hours) to replace or maintenance the lighting installations and stabilizers. Thus, one replacement of the equipment comes out at 4260 RUB, as well as taking into account the increase in maintenance by the inflation rate each year.

4. Purchasing new equipment

The investment for the replacement of equipment is calculated in the same way as the initial investment, but additionally inflation is taken into account. The equipment will be replaced after the end of the service life period, which is different for all lighting installations.

5.3.2. Economic model

In this sub-chapter I have created an economic model for each kind of lamp using parameters which I described above. A base period of 14 years was taken to calculate the NPV, which corresponds to the maximum lifetime of LED installation.

Also consider an example of calculating NPV for florescent lamps. At the end of the sub-chapter will be a general table with final calculations for all luminaire types.

Example of calculation for florescent lamps:

- Initial investments in the project

$$C_0 = n \cdot C = 72 \cdot 1433.6 = 103\ 219.2\ RUB;$$

The purchase is made at time t=0, so inflation rate is not taken into account.

- Energy consumption cost

$$C_{t=1}^{en} = k_{max} \cdot n \cdot E \cdot (P \cdot h_1 + 0.2 \cdot P \cdot h_2) \cdot (1 + ESC)^t$$
$$= 1.002 \cdot 72 \cdot 4.1 \cdot (0.075 \cdot 2977 + 0.2 \cdot 0.075 \cdot 2190) \cdot (1 + 0.033)^1 = 78\ 183\ RUB;$$

Thus, adjusted for escalation rate, the cost of electricity in second year would be 80 763.1 RUB, etc.

- Cost of maintenance

A maintenance fee will be charged at time t=1 for the initial installation of the equipment, as well as the replacement of the equipment after its service time. Service or lifetime of illumination equipment is calculated by following formula:

$$Service\ life\ in\ years = \frac{Service\ life\ in\ hours}{Minimum\ annual\ artificial\ light\ duraton} = \frac{Service\ life\ in\ hours}{2977 + 0.2 \cdot 2190}$$
$$= 7.03 \approx 7\ years.$$

This means that after the seventh year of use, the remaining running time of the lighting installation is:

$$Remaining\ time_{t=4} = 24000 - 7 \cdot (2977 + 0.2 \cdot 2190) = 95\ h;$$

As the remaining time is less than the minimum annual duration of artificial lighting, this means that in sixth year the fluorescent lamps will need to be replaced. Taking into account the inflation rate for year 7, the estimated cost of the maintenance would be 7065.9 RUB. The cost of initial installation of illumination system equals to 4538 RUB.

This model uses the general assumption that the 20% of lamps switched on at night will change, so that there is an equal and uniform reduction in the lifetime of all illumination equipment.

- Purchasing new equipment

As I have determined above, the replacement of lighting installations must be carried out at time t=5, then taking into account inflation, the purchase cost will be:

$$C_{t=8}^{reinv} = n \cdot C \cdot (1 + INF)^t = 72 \cdot 1\,433.6 \cdot (1 + 0.0653)^8 = 171\,212.7\ RUB.$$

- Depreciation

The depreciation method used for tax purposes does have monetary consequences that need to be taken into account when calculating NPV. Thus, accounting for depreciation will reduce the payment of taxes over the operating time of the equipment [31].

The VDB depreciation method and the depreciation values for fluorescent light bulbs are presented in Table 7.

- Tax saved

Since artificial lighting of the premises cannot inherently generate a profit, but only improves the working environment, this means that the project only generates expenditures from an economic point of view. If the project generates a loss, this loss can be used to reduce the tax on the rest of the company's business. In this case, the project generates a tax saving - the tax outflow is negative [31].

When calculating tax savings, only operating expenses are taken into account, the initial investment and further purchase of equipment are counted as a cash outflow.

$$Tax\ saved = Corp.tax \cdot Operational\ expenses;$$

So, for example, in the 1st year of use it was possible to save taxes by:

$$Tax\ saved_{t=1} = 0.2 \cdot (78\,183 + 4\,538 + 29\,491.2) = 22\,422.4\ RUB;$$

- Cash flow

To calculate cash flow for NPV, account for capital costs when they are incurred, not later when they show up as depreciation. To go from accounting income to cash flow, you need to add depreciation (which is not a cash outflow) and subtract expenses (which are cash outflows) [31].

So, in this case summary cash flow in the first year will be:

$$C_1 = -(78\ 183 + 4\ 538) + 22\ 422.4 = -60\ 278.6\ RUB;$$

Next, I calculated the discounted cash flow for each year using formula (5.1). After that, I summed all these values and got the total NPV for 14 years for this project. Then, using formula (5.2), I calculated the average annual cost for maintaining this project. Table 8 shows all the indicators needed to calculate NVP for a given type of lamp over a project period.

Table 8 – Economical model for fluorescent lamp, RUB

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Initial investment	103219														
Energy consumption cost		78183	80763	83428	86181	89025	91963	94998	98133	101371	104717	108172	111742	115429	119239
Maintenance		4538							7066						
Purchasing new equipment									171213						
Depreciation		29491	21065	15047	10748	8956	8956	8956	48918	34941	24958	17827	14856	14856	14856
Tax saved		22442	20366	19695	19386	19596	20184	20791	30823	27263	25935	25200	25320	26057	26819
Cash flow	-103219	-60279	-60397	-63733	-66796	-69429	-71779	-74207	-245588	-74109	-78782	-82972	-86422	-89372	-92420
Discounted CF	-103219	-55938	-52012	-50932	-49536	-47781	-45841	-43979	-135066	-37823	-37312	-36467	-35248	-33826	-32461

The NPV value of project equals to -797 440.26 RUB. The average annual payments (EAA) equals -95 382.86 RUB.

In accordance with the above described economic model, I have calculated the NPV and the average annual payments for each equipment. Tables showing the calculations for each lighting source for 14-year period are shown in appendix A. The final results with the NPV and EAA values for all configurations is given in Table 9.

Due to the fact that all lighting options have different lifetimes, and the calculation has been made for all lamps at 14 years, it is necessary to sell the lamps at a fair price at year 14 if their lifetimes have not yet expired in order to calculate correctly [42].

Table 9 – Calculation results for selection of illumination system

Type of luminaries	NPV, RUB	EAA, RUB
Incandescent lamps	-5 712 503.07	-683 279.86
Halogen incandescent lamps	-5 621 729.7	-672 422.34
Fluorescent lamps	-797 440.26	-95 382.86
Compact fluorescent lamps	-814 131.89	-97 379.37
LED lamps	-513 187.85	-61 383.06

As can be seen from table 9, LED lamps have the lowest total net present value and annual payments for considered 14-year period than all other types of lamps. Also, according to table 2, LED lamps are less sensitive to voltage variations, which significantly improves their performance from a technical point of view, as were demonstrated in chapter 4. Since LED lamps have the best technical performance and economic parameters, chapter 6 will present a technical analysis of the use of these lamps with the selected voltage regulators from chapter 5.4.

5.4. Selection of voltage regulation device

Similarly, to artificial light sources, the NPV and average annual costs of installing and purchasing local voltage stabilizers must be estimated. In order to calculate all necessary costs, I will use some general economic indicators from chapter 5.2, as well as to specific economic indicators such as:

- Initial investment in the project;
- Cost of power losses;
- Cost of maintenance;
- Purchasing new equipment.

5.4.1. Specific economic parameters

1. Initial investment in the project

The method of calculation for initial investment cost is identical to lighting installations. But for voltage stabilizers, three devices must be installed because it is a single-phase equipment. The choice of single phase equipment was based on the fact that this equipment is much cheaper than three phase equipment and has the possibility of independent voltage regulation on the different phases [23]. Booster transformer and thyristor voltage limiter are available only in three-phase configuration.

2. Cost of power losses

As can be seen from table 3, each device has a different efficiency, which means a different power loss for each device. Therefore, it is necessary to determine the value of the maximum possible active power losses when loading the voltage regulator devices at their rated power. This calculation is carried out according to the following formula [1]:

$$C_t^{loss} = n \cdot P \cdot h \cdot E \cdot (\frac{100 - \eta}{100}) \cdot (1 + ESC)^t;$$

Where:

C_t^{loss} – Cost of energy losses in the period t;
t - Number of time periods;
n – Number of installed devices;
P – Active power consumed by one device, kW;
$h = 5167\ h$ - Minimum annual artificial light duration;
$E = 4.1\ RUB\ per\ kW \cdot h$ - Cost of $kW\ per\ h$ in Novosibirsk, Russia [38];
η – Efficiency coefficient;
$ESC = 3.3$ % - Average electricity price grows in Russia for 10 years’ period.

3. Cost of maintenance

The cost of maintenance of regulator devices is calculated from the wages of workers for installation and replacement of equipment, similarly as in chapter 5.3.1. Also, for these devices the cost of replacement and repair of equipment is taken into account, which occurs 2 times during the service life and is equal to 30% of the equipment cost [1].

4. Purchasing new equipment

It is counted in the same way like in chapter 5.3.

5.4.2. Economic model

At this stage, I have created an economic model using the input parameters that were described above. Appendix B presents economic models for all options of voltage regulator devices. Similar with lamps, the NPV calculation was carried out for a 14-year time interval because it is the maximum service life of one of the considered equipment. The results of these calculations are shown in Table 10.

The situation here is the same as in the previous case of the sale of the equipment if it has not expired. This is done so that it is possible to compare NPV for projects with different life service [42].

Table 10 – Calculation results for selection of voltage regulation device

Device	NPV, RUB	EAA, RUB
Triac voltage stabilizer	-87 044.94	-12 778.27
Relay voltage stabilizer	-37 099.02	-5 446.17
Servo voltage stabilizer	-80 000.28	-11 744.11
Booster transformer	-110 602.56	-16 236.55
Thyristor voltage limiter	-84 014.25	-12 333.36

As shown in Table 10, the total costs of booster transformer exceed the costs of using other types of equipment. Therefore, this types of equipment will not be considered for usage. Exactly the same as thyristor voltage limiter, because this device is only capable of reducing the input voltage, but as can be seen from Table 5 the voltage at minimum operation exceeds the tolerance, which means that a higher voltage is needed. Therefore, only triac, relay and servo voltage stabilizers will be considered for installation.

In chapters 6 and 7, these three types of regulation devices will be considered, after which equipment that be able to accurately maintain the nominal mains voltage and reduce energy costs will be accepted for installation.

Chapter 6. Technical analysis

In this chapter, I will use the load graphs to determine the voltage level for one day in each month to determine the voltage deviation of the artificial light sources at each hour of their operation. This will allow me to calculate the total change in power consumption in each month using the data about voltage-power consumption dependence from Table 2. After that, I will simulate the installation of the three types of regulators and adjust the voltage level in the circuit, then calculate the amount of reduced power consumption.

According to [17], a typical electricity load schedule for the reinforced concrete industry is shown in the figure 16. The figure shows the graph as a percentage of the nominal power. This is done in order to understand the general concept, as my work does not consider the power supply for the whole plant, but only one branch, which affects the voltage level in the electrical workshop.

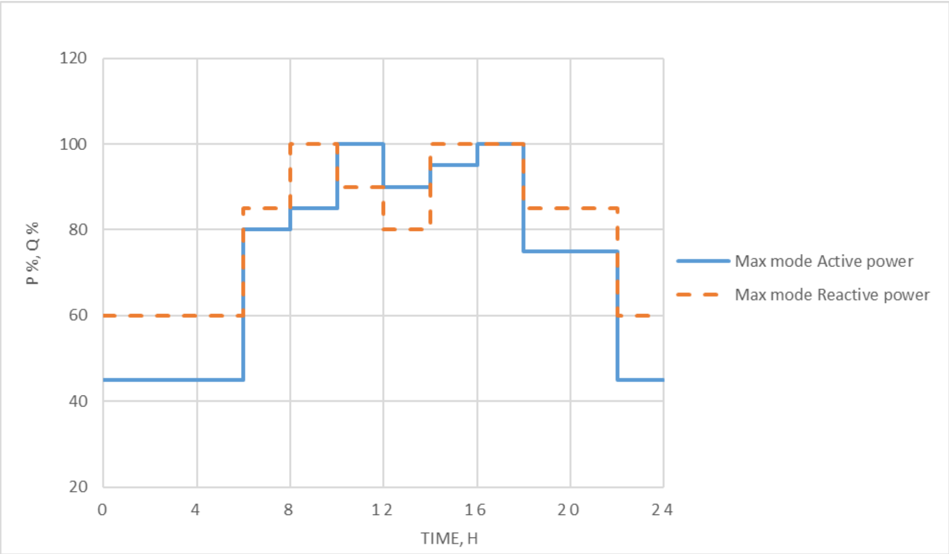
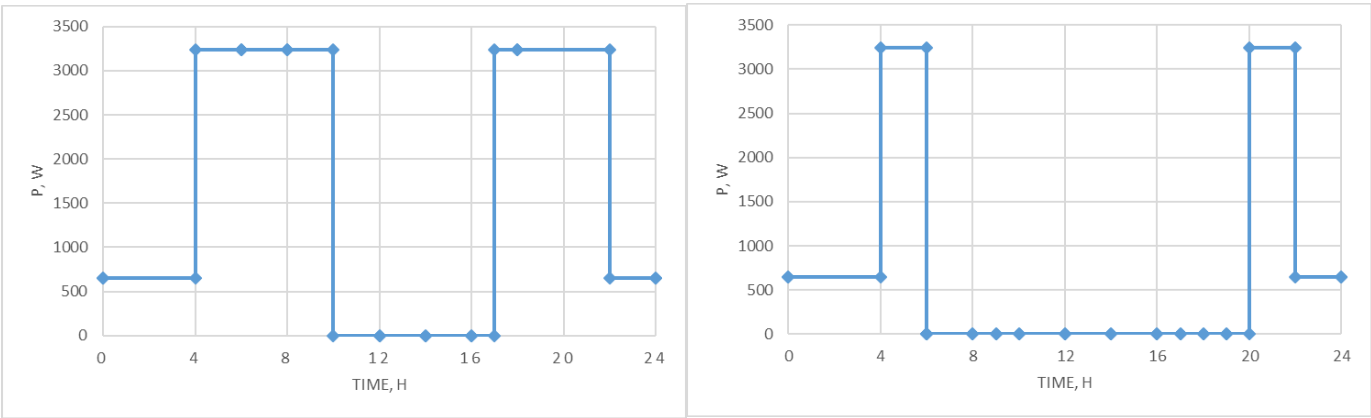


Figure 16 – Load graph for reinforce concrete product plant (illustration based on data from [17])

For the minimum mode of the electrical equipment operation, the active and reactive powers are 60% of the maximum mode [17], which is shown in Figure 16.

Based on the known load schedule for the plant, as well as the load schedule of power consumption for artificial lighting in a two-shift operation of the plant from [17] and the data presented in Figure 10, the duration of lighting and power consumption of LED lamps can be determined. For example, figure 17 shows the illumination load graphs for maximum and minimum modes.



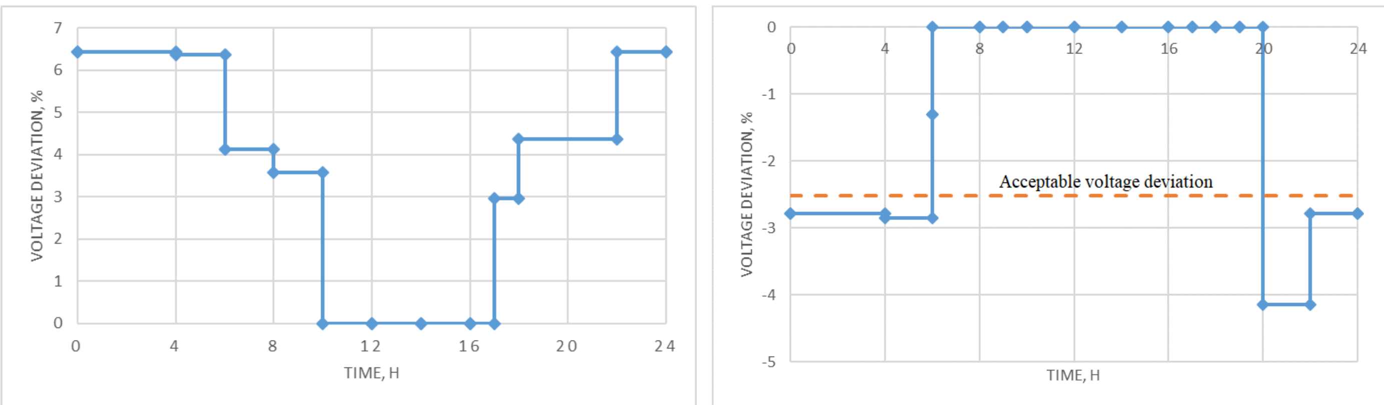
a) b)

Figure 17 – Load graph for illumination system (illustration based on data from [17])

(a – for January, b – for July)

According to knowledge of load schedules of considered plant and the lighting system, it is possible to calculate the voltage deviation for each hour of usage the electrical equipment for each month and find out by how much the electricity consumption has increased or decreased. Figure 18 shows two examples of voltage deviations for similar months as in Figure 17.

Figure 18 shows that the voltage deviation varies with the plant's load schedule, which is also confirmed by the calculations in chapter 4.3. Based on the given data about changing of power consumption with voltage deviation (see table 2) it is possible to determine the increase in power consumption in any period of time, so for example in January the power consumption due to voltage deviation has increased by 28.3 kWh from nominal value.



a) b)

Figure 18 – Voltage deviation during the day (illustration based on data from [17], [27])

(a – for January, b – for July)

Firstly, the load capacity of the stabilizers should be checked. To do this, the load factor for the autotransformers must be calculated. In our case, the β value should not exceed 1, this is because the considered stabilizers are single-phase and cannot serve as a reserve for another phase. This coefficient is calculated according to formula [17]:

$$\beta = \frac{S_{load}}{S_{autotr}} = \frac{\sqrt{k_p \cdot P_{load}^2 + k_q \cdot Q_{load}^2}}{S_{autotr}};$$

Where:

β – Load factor;

S_{load}, S_{autotr} – Apparent power of load and autotransformer;

$k_p = 1.05, k_q = 1.1$ – Active and reactive power increase factors from Table 2;

P_{load}, Q_{load} – Active and reactive load consumption.

An example calculation for relay voltage stabilizer is given below:

$$\beta_{relay} = \frac{\sqrt{1.05 \cdot 3.24^2 + 1.1 \cdot 1.06^2}}{3 \cdot 2} = 0.55;$$

As can be seen from the example, the relay stabilizer satisfies the load conditions and is suitable for installation. Also, by calculating the load factors for the other stabilizers I have obtained that this factor for triac voltage stabilize equals 0.5 and for servo voltage stabilizer equals 0.74. This means that all three types of stabilizers can be used to install.

Knowing the plant load diagram (Figure 16), the daylight duration for each month (Figure 10) and the lighting load diagram [17], the voltage deviation for each hour of operation can be calculated. Also, from table 2 using interpolation the actual power consumption after regulation can be determined. As an example, it will be better to consider 1 month of usage the lighting installations in January.

Work in the considered factory is done in two 8-hour shifts. The first shift starts at 6 a.m., the next at 2 p.m. During the night, lighting is maintained for the night shift by the operating staff, who monitor the operation of system [28]. Table 11 thus shows the change in voltage depending on the plant load and the percentage of lighting which is switched on.

Table 11 – Impact of voltage deviation on consumed power in one month (calculations based on data from [1], [7], [17], [28])

Time, h	Percentage of lightning used	Voltage deviation, %					Input voltage level, V	Nominal energy consumption, kWh	Actual energy consumption, kWh
		LDP-01-N	LDP-01-D	LDP-02-N	LDP-02-D	Average			
0-4	20	6.59	6.33	6.54	6.28	6.44	234.50	2.59	2.67
4-6	100	6.56	6.29	6.43	6.17	6.36	234.43	6.48	6.68
6-8	100	4.32	4.06	4.2	3.93	4.13	229.50	6.48	6.62
8-10	100	3.79	3.52	3.66	3.39	3.59	228.34	6.48	6.60
10-17	0						0	0	0
17-18	100	3.14	2.86	3.06	2.79	2.96	226.91	3.24	3.29
18-22	100	4.56	4.3	4.44	4.17	4.37	230.03	12.96	13.25
22-24	20	6.59	6.33	6.54	6.28	6.44	234.50	1.3	1.34
Total amount of energy consumed in January								1225.37	1253.67

Table 11 shows that the largest deviation in voltage occurs when the load on the facility is at its lowest values. At 9 am, for example, the voltage is 229.5 V, which increases the power consumption in 1.02 times (determined by interpolation using data from Table 2). All voltage deviation values for the four lamps were calculated similarly as the example in chapter 4.3. The nominal power values for each circuit section were used from Figure 13. Figure 13 shows the nominal power values that vary over time, as shown in Figure 16. Table 11 shows the values of voltage deviations and other parameters after voltage adjustment.

Table 12 shows that by adjusting the voltage level before lighting distribution panels, it was possible to reduce electricity consumption. For example, using triac voltage regulator for the January month allow to reduce electricity consumption by 28.3 kWh per January. Since each stabilizer has a different regulation step, the power consumption also varies.

Table 12 – Voltage regulation effect on power consumption in one month (calculations based on data from [23], [24], [25])

Time	Triac voltage stabilizer			Relay voltage stabilizer			Servo voltage stabilizer		
	Average deviation after regulation, %	Input voltage level, V	Actual energy consumption, kWh	Average deviation after regulation, %	Input voltage level, V	Actual energy consumption, kWh	Average deviation after regulation, %	Input voltage level, V	Actual energy consumption, kWh
0-4	-0.92	218.35	2.59	1.09	222.75	2.61	0.11	220.59	2.6
4-6	-0.98	218.28	6.47	1.02	222.66	6.53	0.05	220.53	6.50
6-8	0.46	221.45	6.51	-1.10	218.02	6.47	0.99	222.62	6.93
8-10	-0.05	220.33	6.5	-1.61	216.90	6.45	0.47	221.47	6.81
10-17									
17-18	-0.66	218.94	3.24	-2.19	215.53	3.22	-0.14	220.09	3.45
18-22	0.7	221.96	13.03	-0.34	218.53	12.97	-1.83	216.41	12.89
22-24	-0.92	218.35	1.29	1.09	222.75	1.31	0.11	220.59	1.4
Amount of energy consumed per month			1228.5	Amount of energy consumed per month		1226.04	Amount of energy consumed per month		1227.62

Table 13 contains all the summary information which shows the actual electricity consumption during each month before and after regulation by three considered stabilizers. Also the total annual energy consumption for all options is calculated.

Table 13 – Comparison of power consumption before and after regulation

Month	Nominal power, kW	Power consumption before regulation, kW	Energy consumption after regulation, kWh		
			Triac voltage stabilizer	Relay voltage stabilizer	Servo voltage stabilizer
January	1225.37	1253.67	1228.5	1226.04	1227.62
February	1016.06	1080.22	1028.94	1030.34	1050.03
March	1024.49	1100.36	1035.43	1040.36	1055.09
April	894.24	916.51	896.85	906.49	911.37
May	723.17	723.17	729.54	735.2	740.98
June	505.44	505.44	506.92	510.18	515.83
July	522.29	522.29	529.82	531.19	537.69
August	622.73	622.73	624.18	631.19	640.84
September	894.24	905.24	896.27	901.02	910.34
October	1124.93	1151.91	1141.34	1148.57	1151.23
November	1185.84	1213.23	1198.87	1201.49	1206.05
December	1283.04	1311.96	1290.04	1295.99	1298.4
Total per year	**11021.83**	**11304.73**	**11105.7**	**11158.06**	**11252.5**

As can be seen in Table 13, due to the voltage deviation on the LED lamps, the annual power consumption has increased by 282.9 kW from nominal value. By using three different voltage regulators, it was possible to reduce this value by a maximum of 199.03 kW power consumption when using a triac-voltage stabilizer. Each regulator has a different regulation step and different efficiency, which is why all the final values differ. Table 13 shows the power consumption after regulation taking into account the losses of electrical energy in the regulation devices.

In the next chapter, 3 lighting network configurations will be considered, after which the most economical option will be selected to installation. Because it can be seen that, from a technical point of view, all the regulators have fulfilled their main tasks, which are to keep the voltage within acceptable limits and reduce electricity consumption.

Chapter 7. Economic analysis

In chapters 5 and 6, I have prepared economic and technical analysis about the usage of equipment for lighting the industrial building and methods of local voltage regulation in the 220V lighting network.

After this analysis, it was determined that from a technical and economic point of view the best type of lighting is the installation of LED lamps, and among the voltage regulators are triac, relay and servo stabilizers.

Also, it can be noted that the previous calculations for selection of lighting technology are in line with the current market situation. The fact is that LED lamps are currently the most efficient technology for illumination, as it has more advanced features [4].

In this chapter I will calculate the economics of three equipment configurations that will use LED lamps with three different types of voltage regulator. The evaluation of the investment performance of each project will be assessed using NPV and EAA, similar to what was discussed in chapter 5. Once the final equipment configuration has been selected and the project cost and annual implementation costs have been calculated, a sensitivity analysis will be performed to show how the project costs will change when the various parameters are changed.

For NPV and EAA calculations, all of the specific parameters will add up to give an accurate picture of the investment in a particular option. For example, the amount of the initial investment in a project will be the sum of the purchase of the light bulbs and the regulator. Also the power consumption has been recalculated according to the data in Table 14, which makes the electricity costs different in each configuration. In addition, active power losses in the stabilizer are taken into account in cost of power consumption. Thus, appendix C shows the NPV calculations for all three lighting network configurations. Table 14 below shows the results of the calculations.

Table 14 – Calculation results for illumination system configuration

Configuration	Description	NPV, RUB	EAA, RUB
Configuration A	LED lamps, Triac voltage stabilizer	-497 277.1	-73 000.7
Configuration B	LED lamps, Relay voltage stabilizer	-449 363	-65 966.9
Configuration C	LED lamps, Servo voltage stabilizer	-475 170.5	-69 755.4

As Table 14 shows, the best solution is to install configuration B. The installation of LED luminaires and relay voltage stabilizer has the lowest cost. This is mainly due to the inherent price of the equipment.

Chapter 8. Sensitivity analysis

Project sensitivity analysis determines how different sources of uncertainty in a mathematical model contribute to the overall uncertainty of the economic model. In other words, sensitivity analysis examines the impact of input parameters such as investments, operating expenses, discount rate and so on final NPV result. Finally, it is possible to identify the impact of each parameter and each degree of influence on final result and make decision [31].

The first step is to identify the baseline parameters that can have the greatest possible impact on the project cost. After, I have made a change to each selected parameter and assess its impact. Results are represented on Figures 19 – 22.

Here is a list of parameters which will be used in sensitivity analysis of NPV:

- Electricity price
- Inflation rate
- Escalation rate for electricity price
- Discount rate

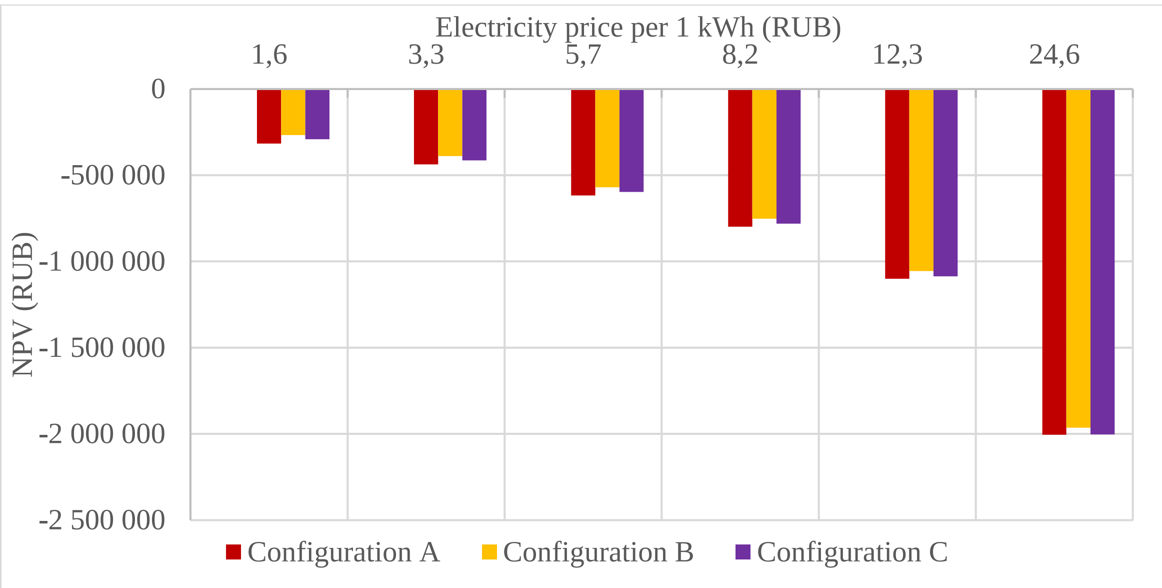


Figure 19 – Dependence of electricity price on NPV

I have used column chart to display the results better. When using a line diagram, the results are superimposed on each other and it is impossible to see the differences. The graph in figure 19 has exponential characteristic. From the graph it can be seen that when the cost of electricity increases, configuration B has better economic effect then others. Then electricity price riches a 138 RUB per 1 kWh, configuration A is the best option because it will have lower NPV than others.

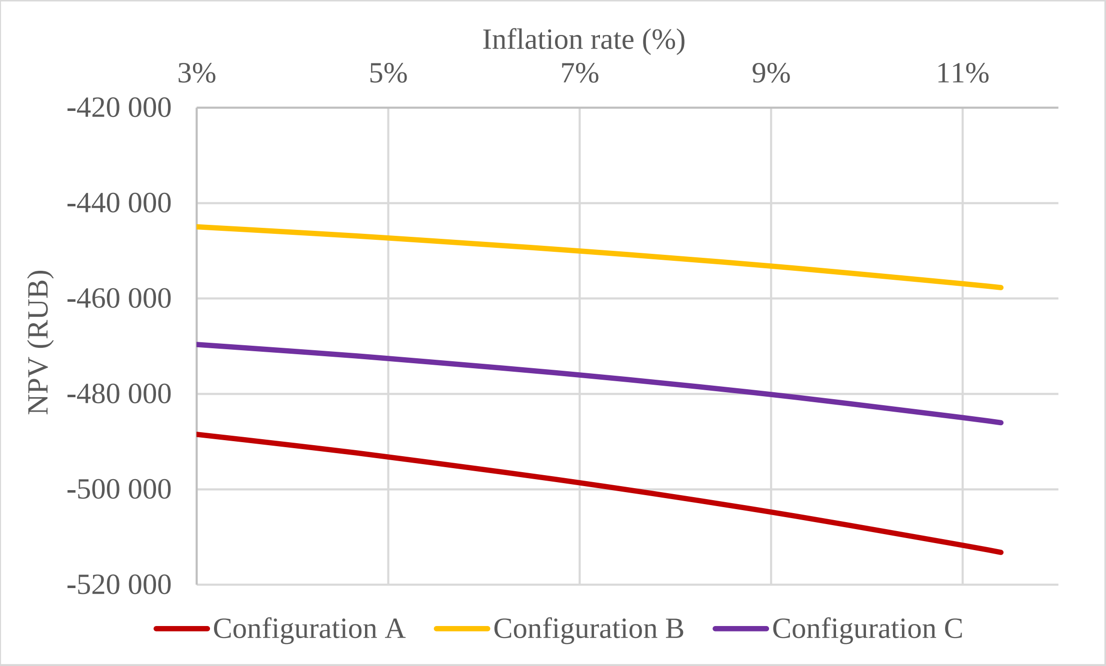


Figure 20 – Dependence of inflation rate on NPV

Figure 20 shows that as the inflation rate increases, the cost of project implementation also increases. Configuration B has the lowest NPV. These calculations are based on the assumption that inflation rate should be less than the calculated discount rate (11.47 %).

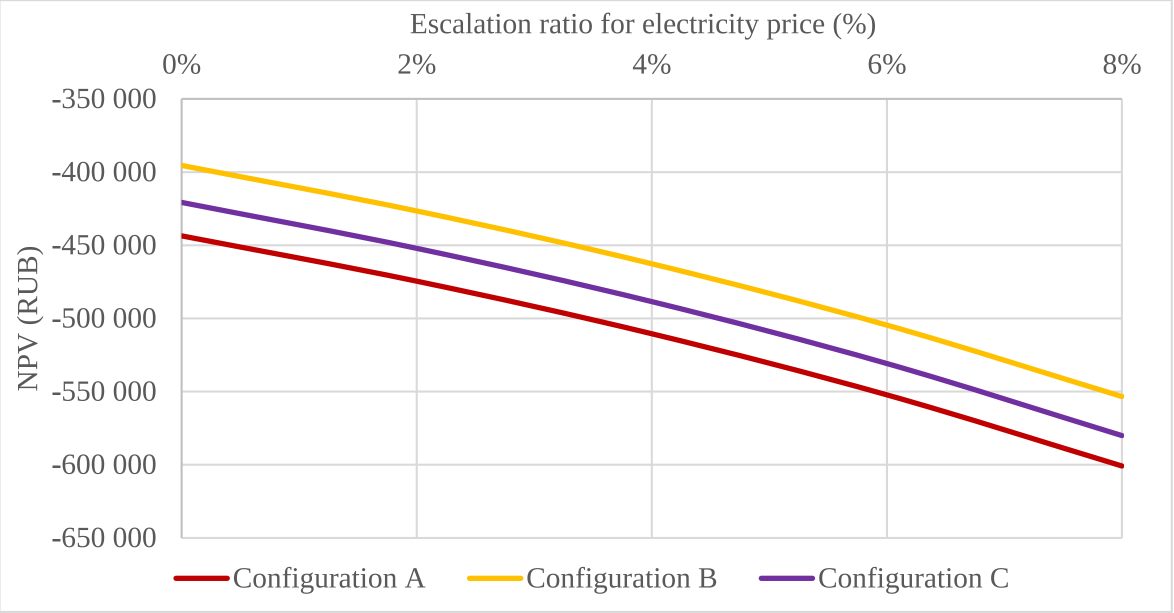


Figure 21 – Dependence of escalation rate on NPV

Dependence of escalation rate on NPV has the similar behavior like for inflation rate changes.

The graph in figure 22 has exponential characteristic for each configuration. The greater the discount rate the less NPV. Configuration B has the lowest NPV for each rate. These calculations are based on the assumption that discount rate should cover the inflation rate (6.53 %).

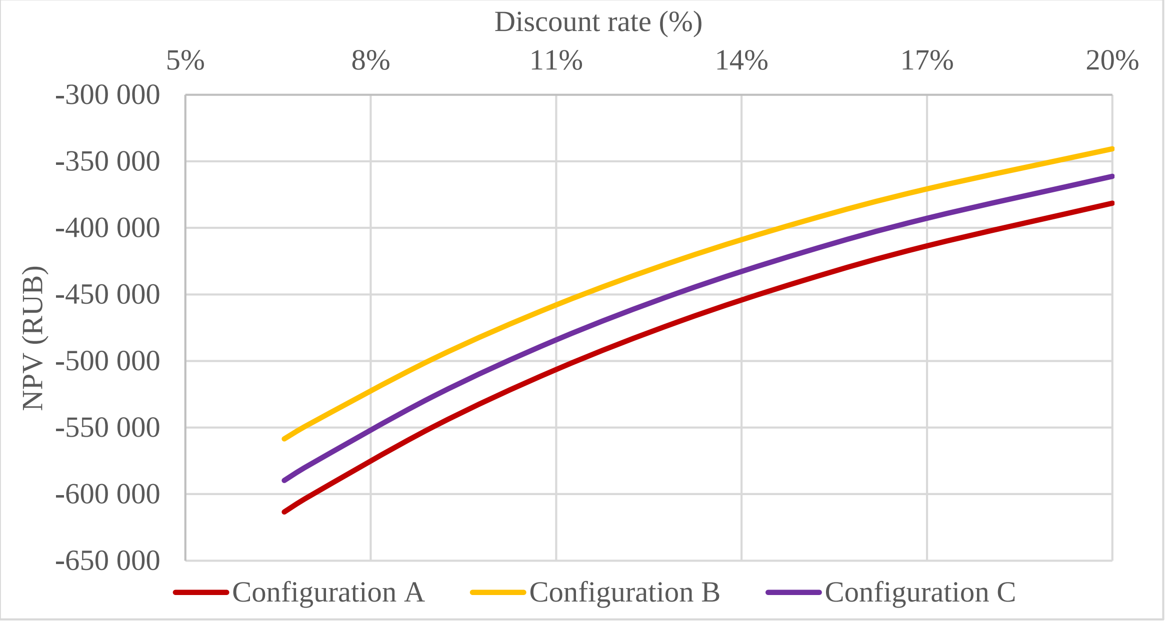


Figure 22 – Dependence of discount rate on NPV

But in this project, the NPV does not play as significant a role as the annual payments. The initial choice of equipment was based on a comparison of options according to these two criteria. The dependencies of the annual payments on the changing parameters are presented in Tables 15-18.

Table 15 – Dependence of cost of energy on EAA

Cost of energy, RUB per kWh	1.6	3.3	5.7	8.2	12.3	24.6
EAA for Configuration A, RUB	-46434.7	-64145.4	-90711.3	-117277.2	-161553.7	-294383.3
EAA for Configuration B, RUB	-39275.4	-57070.2	-83760.5	-110452.1	-154937.2	-288393.7
EAA for Configuration C, RUB	-42838.7	-60782.6	-87700.2	-114616.7	-159479.4	-294063.9

Table 16 – Dependence of inflation rate on EAA

Inflation ratio, %	3%	4%	5%	7%	9%	11%	11.40%
EAA for Configuration A, RUB	-71706.8	-72042.9	-72402.5	-73196.6	-74099.3	-75120.4	-75339.6
EAA for Configuration B, RUB	-65322.4	-65488.3	-65666.3	-66066.8	-66531.0	-67073.4	-67192.4
EAA for Configuration C, RUB	-68944.6	-69151.4	-69375.1	-69882.6	-70482.7	-71193.4	-71349.8

Table 17 – Dependence of escalation rate on EAA

Escalation ratio, %	0 %	2 %	4 %	6 %	8 %
EAA for Configuration A, RUB	-65115.34	-69662.58	-74937.03	-81067.13	-88203.91
EAA for Configuration B, RUB	-58044.33	-62612.98	-67912.81	-74071.28	-81241.14
EAA for Configuration C, RUB	-61766.36	-66373.49	-71717.81	-77928.00	-85159.19

Table 18 – Dependence of discount rate on EAA

Discount ratio, %	6.6%	7%	9%	11%	13%	15%	17%	20%
EAA for Configuration A, RUB	-68469.5	-68810.7	-70600.8	-72528.4	-74587.5	-76771.1	-79071.7	-82723.3
EAA for Configuration B, RUB	-62343.6	-62612.7	-64036.5	-65585.3	-67251.8	-69026.6	-70903.9	-73887.7
EAA for Configuration C, RUB	-65828.2	-66119.8	-67662.1	-69342.3	-71149.9	-73076.4	-75114.8	-78359.9

As can be seen from all the calculations above, all these configurations have a negative NPV, as the project does not generate any profit. The voltage regulators in this project are used to improve voltage quality and reduce electricity consumption. As can be seen from Table 13, it has been possible to reduce the electrical energy consumption by installing voltage stabilizers. In some configuration it has been possible to reduce by 199.03 kW/year and in some configuration by 52.23 kW year. But still, these values cannot cover the electricity consumption of the lamps themselves. For example, saving 199.03 kWh is much less than the consumption of 11 105.7 kWh. Therefore, I have decided to make sensitivity analysis on the impact of the parameters described in this chapter on covering the costs of purchasing electrical equipment and paying salaries to workers with the amount of energy that has been saved.

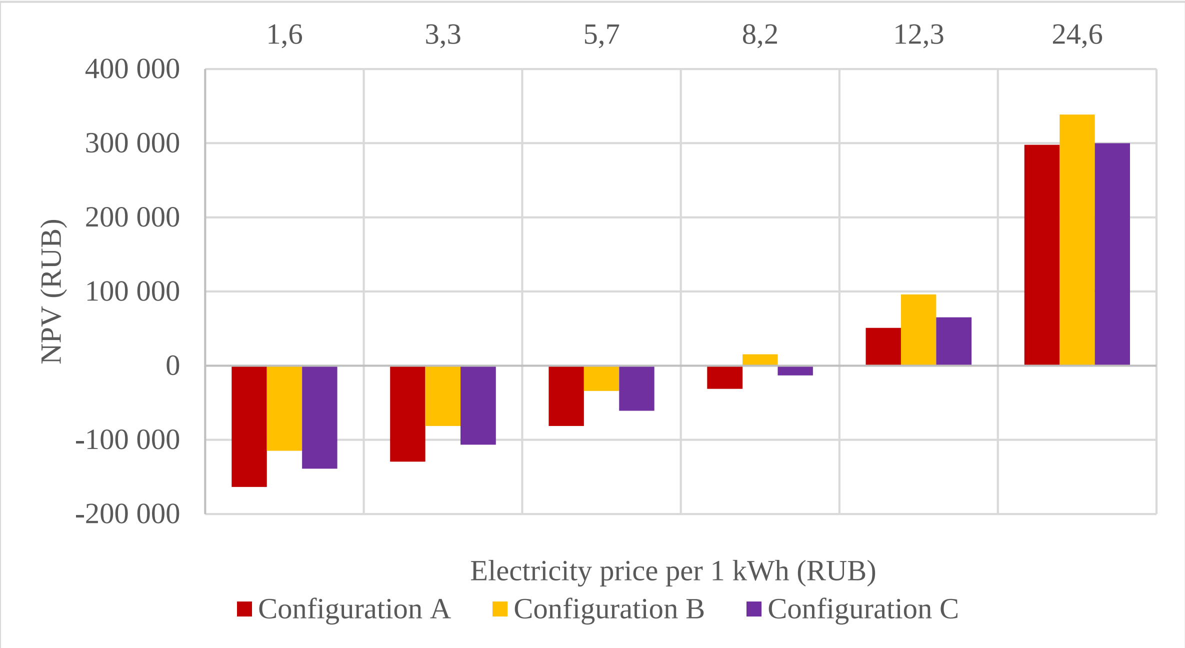


Figure 23 – Dependence of electricity price on NPV taking into account only electricity saving

The graph in figure 23 shows that for configuration B the NPV becomes positive when the price equals to 7.5 RUB per kWh. This means that by reducing electricity consumption by 146.67 kW per year it will be possible to cover the cost of lamps, voltage regulators and workers' wages for maintaining the equipment. According to this dependence configuration B has better economic parameters than others configurations.

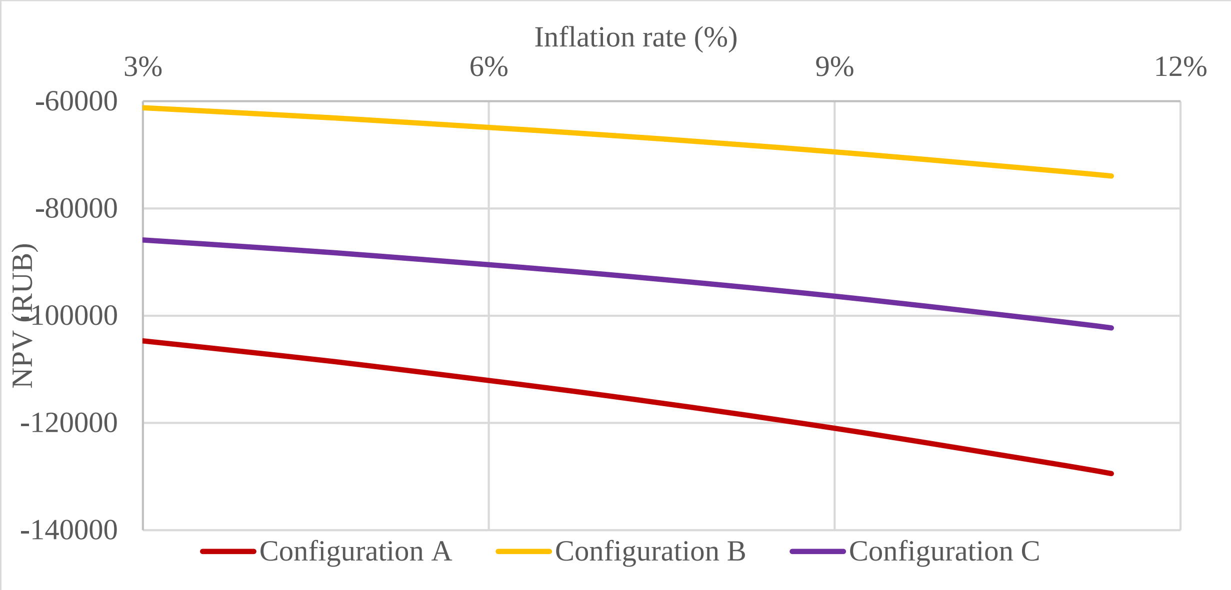


Figure 24 – Dependence of inflation rate on NPV taking into account only electricity saving

Figure 24 shows that as the interest rate increases, the cost of project also increases. Configuration B has the lowest NPV. These calculations are based on the assumption that inflation rate should be less than the calculated discount rate (11.47 %).

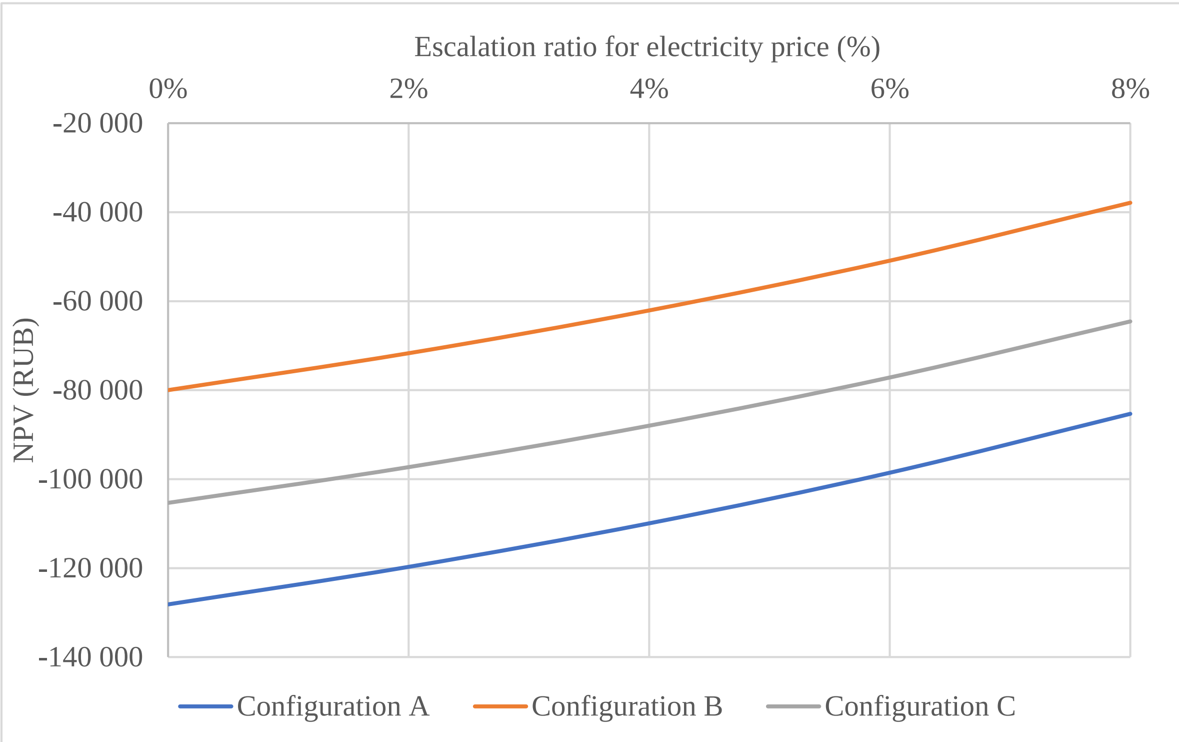


Figure 25 – Dependence of escalation rate on NPV taking into account only electricity saving

As can be seen from the graph, this indicator has a significant impact on changes in NPV. When escalation rate reaches 12.5% the NPV of configuration B equals to 0.

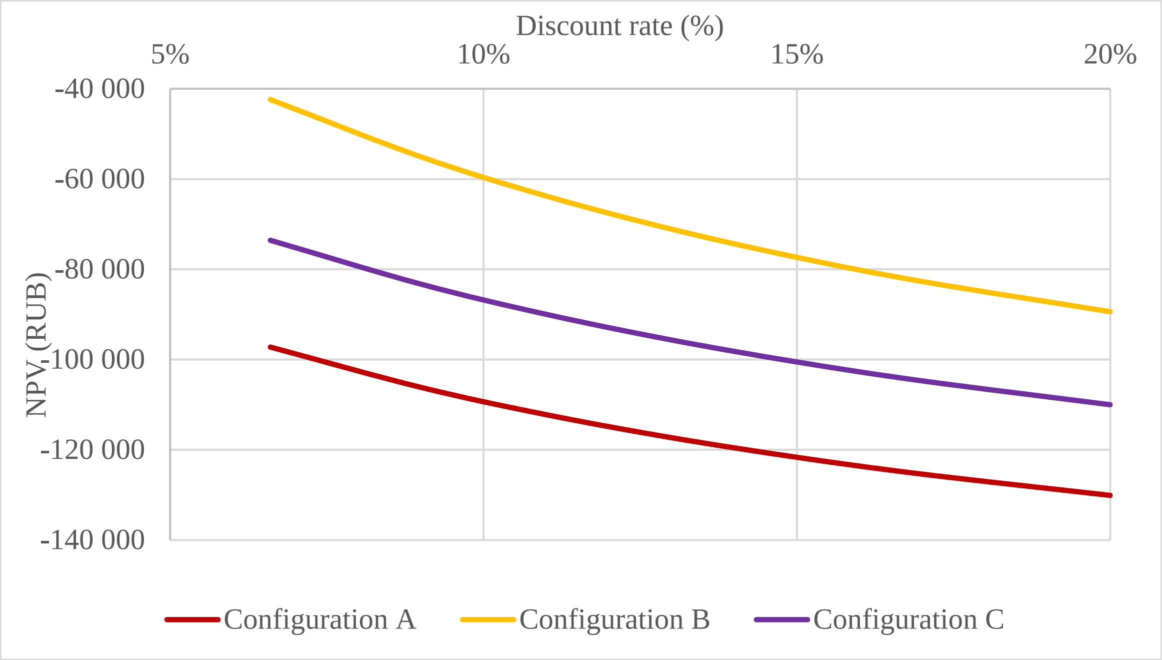


Figure 26 – Dependence of discount rate on NPV taking into account only electricity saving

The greater the discount rate the high NPV. This is due to the fact that as the discount rate increases, the discounted cash flow decreases over time. Configuration B has the lowest NPV for each rate. These calculations are based on the assumption that discount rate should cover the inflation rate (6.53 %).

According to the sensitivity analysis it was found that the most cost effective option is to use configuration B for industrial lighting. Tables 15-18 show that configuration B has lower annual payments in all considered dependences than other variants. This is due to the fact that the cost of relay stabilizer is many times lower than the cost of the others. Also, graphs show that changes in cost of electricity and escalation ratio of electricity price have significant impact on considered economic indicators. This result is logical because main expenses for illumination system are cited for electricity consumption.

Conclusion

The goal of this paper was to design a lighting system in an industrial environment, analyze the effects of voltage deviation on the characteristics of lighting sources and implement one of the local voltage regulation methods.

The first step during the implementation of this work was to collect technical information about the enterprise and familiarize with voltage quality problems in illumination systems. In this paper, only the effect of the input voltage on changes in electrical energy consumption and illumination levels has been considered. Also at this step, I have collected data about types of local voltage regulation devices and lamps as well as lamp's characteristic dependence on input voltage level.

The next step was the preliminary design of the lighting system. This had to be done in order to calculate the voltage deviation for all considered luminaires in maximum and minimum load modes because all luminaires have different wattages and illumination levels which changes the number of lamps that need to be installed that has a significant effect on the cost of the project and power load. As a result of these calculations, it was possible to determine by interpolation the permissible negative voltage deviation at which the minimum required illuminance level is achieved. Deviations below these limits are unacceptable according to [27]. As a result, new permissible voltage deviations were obtained for all sources of lighting, so for example for LED lamps permissible range is from -2.52 % to +10 % from the nominal voltage level. At this stage, it was found that installation of any type of lighting leads to the fall in the illuminance level below the permitted value when the voltage deviation is negative, which leads to the mandatory installation of stabilizing devices. Also, natural lighting has been calculated, the goal of natural illumination is to determine the minimum window's dimension.

With knowledge of the technical characteristics of the voltage regulators and light sources, as well as the individual parameters of the application of all considered lamps in the electrical workshop I proceeded to an economic calculation. At this stage, I have defined basic economic indicators, such as the historic inflation rate (6.53 %), discount rate (11.47 %) based on the CAPM, and historic escalation rate for electricity price (3.3 %). Based on these data I have calculated the net present value and equivalent annual payments for five types of lamps and five voltage regulators. The NPV has been negative in all options because all variants do not generate a profit. The lifetime of the electrical devices is different, so I have calculated NPV for fourteen years, which is the longest lifetime of one of the considered devices. For a correct comparison of net present value, I have assumed that equipment with a shorter lifespan will be bought again, and later in the fourteenth year, it will be sold at the residual value. As a result of the economic calculation and the technical information obtained above, I have declined from consideration four types of luminaires and two regulators with the worst performance, so I have reduced the number of assumed network configurations from twenty-five to three options.

Then I carried out technical analysis for three remaining options, which included the installation of LED luminaires and relay, servo, or triac stabilizers. Using this analysis, I calculated the monthly electricity consumption according to the daily load diagrams using the minimum daylight hours in Novosibirsk with and without the installation of stabilizers. As a result, it turned out that without the installation of stabilizers annual consumption of electricity increased by 282.9 kWh from nominal value and for example, with the installation of triac stabilizers it was possible to reduce this value by 199.03 kWh per year.

Next an economic analysis was performed for these configurations. So for the configuration of LED lamps with a triac stabilizer the NPV is -497 277.1 RUB and the EAA is -73 000.7 RUB. For the configuration of LED lamps with a relay stabilizer the NPV is -449 363 RUB and the EAA is -65 966.9 RUB. For the configuration of LED lamps with a servo stabilizer the NPV is -475 170.5 RUB and the EAA is -69 755.4 RUB.

The last step was the sensitivity analysis. In this analysis, I looked at how the NPV and EAA of project configurations would change with changes in electricity price, inflation rate, escalation rate for electricity price and discount rate. Also, I prepared another analysis of the change in NPV by changing the same parameters, but in this model instead of electricity consumption, I used the amount of saved energy by the installation of voltage stabilizers. In this case, I also received important information, for example, when assuming an electricity price is 9 RUB per kWh, the NPV for all options would be positive, meaning that the value of the saved energy would cover the cost of the initial investment in the project, maintenance and the purchase of new equipment over the lifetime of the project.

Finally, it can be concluded that the configuration of LED lamps with relay stabilizer is recommended for implementation in the electrical workshop of the reinforced concrete products plant. This option has satisfied technical requirements to maintain a stable voltage level for reducing energy consumption and maintaining illumination above the minimum permissible level. Also, this configuration has the lowest NPV and EAA due to the fact that the cost of the relay stabilizer is many times lower than the cost of the others.

The initial investment for full lighting of the building, which includes the installation of window openings, lighting fixtures and the necessary electrical equipment is 490 thousand RUB. EPV equals -800 thousand RUB, EAA equals -117.3 thousand RUB.

It is also possible to introduce the project in the European Union. According to EN 50160, the voltage deviation is similar to the GOST 32144-2013. Also, according to the EN 12464-1, the minimum illuminance for this building is also 300 lx. Therefore, it is recommended to install voltage regulators for LED lamps if the range of voltage deviation out of range -2.5% to +5%. With similar input data such as the same labor for maintenance and cost of electrical equipment, this project will be profitable, as with the cost of electricity above 7.5 RUB (0.092 EUR) per kWh the amount of energy saved will cover the cost of labor for equipment maintenance and for the purchase of equipment.

If this project had been originally designed for European union, then according to EN 12464-1 the use of natural light (installation of window openings) in the operation building would be an additional option to save electrical energy. Then, the cost of installing windows would have to be taken into account in the economic model. With the same input data, namely 3593 hours of natural lighting and the same duration of work in the facility, the economic model would additionally take into account the saving of electrical energy in the amount of 11 641.32 kWh per year. According to the SP 52.13330.2016, for Russia the installation of window openings is mandatory in production facilities where people have to work during a shift.

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Appendices

Appendix A – Financial models for selection of illumination system

Table A1 – Calculation of NPV and EAA for incandescent lamps, RUB

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Changes lamps per year		3	3	4	3	4	3	3	4	3	4	3	3	4	3
Initial investment	17031														
Energy consumption cost		600808	620634	641115	662272	684127	706703	730024	754115	779001	804708	831263	858695	887032	916304
Maintenance		13614	14503	20600	16459	23378	18679	19898	28264	22582	32075	25627	27301	38778	30983
Purchasing new equipment		54430	57984	82361	65804	93468	74679	79555	113000	90284	128240	102461	109151	155038	123872
Tax saved		122884	127027	132343	135746	141501	145076	149985	156476	160317	167357	171378	177199	185162	189457
Cash flow	-17031	-545967	-566094	-611733	-608789	-659473	-654984	-679494	-738903	-731551	-797667	-787973	-817948	-895687	-881701
Discounted CF	-17031	-506651	-487499	-488865	-451478	-453846	-418298	-402701	-406375	-373359	-377786	-346320	-333607	-339006	-309682
Net Present Value	-5 712 503.07														
Equivalent annual payments	-683 279.86														

Table A2 – Calculation of NPV and EAA for halogen incandescent lamps, RUB

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Changes lamps per year		0	1	0	1	0	1	0	1	0	1	0	1	0	1
Initial investment	142971														
Energy consumption cost		567050	585763	605093	625061	645688	666996	689007	711744	735231	759494	784557	810448	837193	864820
Maintenance			4834		5486		6226		7066		8019		9100		10328
Purchasing new equipment			162253		184135		208968		237150		269133		305429		346621
Tax saved		113410	118119	121019	126109	129138	134644	137801	143762	147046	153503	156911	163910	167439	175029
Cash flow	-142971	-453640	-634730	-484074	-688572	-516550	-747545	-551205	-812198	-588185	-883143	-627646	-961068	-669754	-1046739
Discounted CF	-142971	-420973	-546606	-386847	-510645	-355488	-477411	-326671	-446685	-300190	-418269	-275855	-391979	-253493	-367648
Net Present Value	-5 621 729.69														
Equivalent annual payments	-672 422.34														

Table A3 – Calculation of NPV and EAA for fluorescent lamps, RUB

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Changes lamps per year		0	0	0	0	0	0	0	1	0	0	0	0	0	0
Initial investment	103219														
Energy consumption cost		78183	80763	83428	86181	89025	91963	94998	98133	101371	104717	108172	111742	115429	119239
Maintenance		4538							7066						
Purchasing new equipment									171213						
Depreciation		29491	21065	15047	10748	8956	8956	8956	48918	34941	24958	17827	14856	14856	14856
Tax saved		22442	20366	19695	19386	19596	20184	20791	30823	27263	25935	25200	25320	26057	26819
Cash flow	-103219	-60279	-60397	-63733	-66796	-69429	-71779	-74207	-245588	-74109	-78782	-82972	-86422	-89372	-92420
Discounted CF	-103219	-55938	-52012	-50932	-49536	-47781	-45841	-43979	-135066	-37823	-37312	-36467	-35248	-33826	-32461
Net Present Value	-797 440.26														
Equivalent annual payments	-95 382.86														

Table A4 – Calculation of NPV and EAA for compact fluorescent lamps, RUB

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Changes lamps per year		0	0	0	0	0	1	0	0	0	0	0	1	0	0
Initial investment	92160														
Energy consumption cost		77247	79796	82429	85149	87959	90862	93860	96958	100157	103462	106877	110404	114047	117811
Maintenance		4538					6226						9100		
Purchasing new equipment							134702						196882		
Selling equipment															95210
Depreciation		30720	20480	13653	9102	9102	54003	29934	19956	13304	13304	13304	131255	43752	21876
Tax saved		22501	20055	19216	18850	19412	30218	24759	23383	22692	23353	24036	50152	31560	8895
Cash flow	-92160	-59284	-59741	-63213	-66299	-68547	-201572	-69101	-73575	-77465	-80109	-82841	-266234	-82487	-13705
Discounted CF	-92160	-55015	-51446	-50516	-49167	-47174	-128731	-40953	-40464	-39536	-37941	-36409	-108586	-31220	-4814
Net Present Value	-814 131.89														
Equivalent annual payments	-97 379.37														

Table A5 – Calculation of NPV and EAA for LED lamps, RUB

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Initial investment	133890														
Energy consumption cost		49157	50779	52455	54186	55974	57821	59729	61700	63736	65840	68012	70257	72575	74970
Maintenance		4538													
Purchasing new equipment															
Depreciation		19127	16395	14053	12045	10324	8849	7585	6502	6502	6502	6502	6502	6502	6502
Tax saved		14564	13435	13301	13246	13260	13334	13463	13640	14048	14468	14903	15352	15815	16294
Cash flow	-133890	-39131	-37344	-39153	-40940	-42714	-44487	-46266	-48060	-49689	-51371	-53110	-54905	-56760	-58676
Discounted CF	-133890	-36313	-32160	-31289	-30361	-29396	-28411	-27420	-26432	-25359	-24330	-23342	-22394	-21483	-20609
Net Present Value	-513 187.85														
Equivalent annual payments	-61 383.06														

Appendix B – Financial models for selection of voltage regulation device

Table B1 – Calculation of NPV and EAA for triac voltage stabilizer, RUB

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Investment	40749.5														
Cost of power losses		1869.2	1930.9	1994.6	2060.5	2128.5	2198.7	2271.3	2346.2	2423.6	2503.6	2586.2	2671.6	2759.7	2850.8
Maintenance		4538.0			21230.9				27343.6			104.3			39965.7
Purchasing new equipment												81717.1			
Selling equipment															63146.9
Depreciation		8149.9	6519.9	5215.9	4172.7	3338.2	2670.6	2670.6	2670.6	2670.6	2670.6	40858.6	20429.3	10214.6	10214.6
Tax saved		2911.4	1690.2	1442.1	5492.8	1093.3	973.9	988.4	6472.1	1018.8	1034.8	8709.8	4620.2	2594.9	-2023.1
Cash flow	-40749.5	-3495.8	-240.8	-552.5	-17798.5	-1035.1	-1224.9	-1282.9	-23217.7	-1404.8	-1468.8	-75697.8	1948.6	-164.9	18307.2
Discounted CF	-40749.5	-3136.1	-193.8	-398.9	-11528.0	-601.5	-638.5	-599.9	-9739.9	-528.7	-495.9	-22926.9	529.4	-40.2	4003.2
Net Present Value	-87 044.94														
Equivalent annual payments	-12 778.27														

Table B2 – Calculation of NPV and EAA for relay voltage stabilizer, RUB

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Investment	6507.7														
Cost of power losses		2361.1	2439.1	2519.6	2602.7	2688.6	2777.3	2869.0	2963.6	3061.4	3162.5	3266.8	3374.6	3486.0	3601.0
Maintenance		4538.0		7510.3			9079.8			91.9		4583.7			5541.5
Purchasing new equipment										11499.4					
Selling equipment															4201.9
Depreciation		1626.9	1220.2	915.1	686.4	514.8	514.8	514.8	514.8	3833.1	2555.4	1703.6	1135.7	1135.7	1135.7
Tax saved		1705.2	731.9	2189.0	657.8	640.7	2474.4	676.7	695.7	1397.3	1143.6	1910.8	902.1	924.3	1215.3
Cash flow	-6507.7	-5193.9	-1707.2	-7840.9	-1944.9	-2047.9	-9382.7	-2192.2	-2268.0	-13255.5	-2018.9	-5939.7	-2472.6	-2561.6	-3725.4
Discounted CF	-6507.7	-4659.5	-1373.9	-5661.0	-1259.7	-1189.9	-4890.8	-1025.1	-951.4	-4988.5	-681.6	-1799.0	-671.8	-624.4	-814.6
Net Present Value	-37 099.02														
Equivalent annual payments	-5 446.17														

Table B3 – Calculation of NPV and EAA for servo voltage stabilizer, RUB

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Investment	20312.1														
Cost of power losses		4263.2	4403.9	4549.2	4699.3	4854.4	5014.6	5180.1	5351.0	5527.6	5710.0	5898.4	6093.1	6294.2	6501.9
Maintenance		4538.0		12517.0			15132.7			91.9		20762.4			25101.1
Purchasing new equipment										35892.3					
Selling equipment															13115.1
Depreciation		5078.0	3808.5	2856.4	2142.3	1606.7	1606.7	1606.7	1606.7	11964.1	7976.1	5317.4	3544.9	3544.9	3544.9
Tax saved		2775.8	1642.5	3984.5	1368.3	1292.2	4350.8	1357.4	1391.5	3516.7	2737.2	6395.6	1927.6	1967.8	4406.5
Cash flow	-20312.1	-6025.3	-2761.4	-13081.7	-3331.0	-3562.2	-15796.5	-3822.7	-3959.5	-37995.1	-2972.8	-20265.2	-4165.5	-4326.3	-14081.3
Discounted CF	-20312.1	-5405.4	-2222.3	-9444.7	-2157.5	-2069.8	-8234.0	-1787.6	-1661.0	-14299.0	-1003.7	-6137.8	-1131.8	-1054.5	-3079.1
Net Present Value	-80 000.28														
Equivalent annual payments	-11 744.11														

Table B4 – Calculation of NPV and EAA for booster transformer, RUB

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Investment	23892.0														
Cost of power losses		9838.1	10162.8	10498.1	10844.6	11202.4	11572.1	11954.0	12348.5	12756.0	13176.9	13611.8	14061.0	14525.0	15004.3
Maintenance		4538.0			14717.6				18955.0			104.3			23089.7
Purchasing new equipment												47911.9			
Selling new equipment															37023.9
Depreciation		4778.4	3822.7	3058.2	2446.5	1957.2	1565.8	1565.8	1565.8	1565.8	1565.8	23955.9	11978.0	5989.0	5989.0
Tax saved		3830.9	2797.1	2711.3	5601.7	2631.9	2627.6	2704.0	6573.9	2864.4	2948.5	7534.4	5207.8	4102.8	1411.8
Cash flow	-23892.0	-10545.2	-7365.7	-7786.9	-19960.4	-8570.5	-8944.5	-9250.0	-24729.6	-9891.6	-10228.4	-54093.5	-8853.2	-10422.2	341.7
Discounted CF	-23892.0	-9460.1	-5927.8	-5622.0	-12928.2	-4979.9	-4662.4	-4325.5	-10374.2	-3722.6	-3453.2	-16383.5	-2405.5	-2540.4	74.7
Net Present Value	-110 602.56														
Equivalent annual payments	-16 236.55														

Table B5 – Calculation of NPV and EAA for thyristor voltage limiter, RUB

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Investment	28729.3														
Cost of power losses		4372.5	4516.8	4665.8	4819.8	4978.9	5143.2	5312.9	5488.2	5669.3	5856.4	6049.7	6249.3	6455.5	6668.6
Maintenance		4538.0			16586.6				21362.2			104.3			31223.2
Purchasing new equipment												57612.5			
Selling equipment															44520.1
Depreciation		5745.9	4596.7	3677.4	2941.9	2353.5	1882.8	1882.8	1882.8	1882.8	1882.8	28806.3	14403.1	7201.6	7201.6
Tax saved		2931.3	1822.7	1668.6	4869.7	1466.5	1405.2	1439.1	5746.6	1510.4	1547.8	6992.0	4130.5	2731.4	114.6
Cash flow	-28729.3	-5979.2	-2694.1	-2997.2	-16536.8	-3512.4	-3738.0	-3873.7	-21103.8	-4158.9	-4308.6	-56774.4	-2118.8	-3724.1	6743.0
Discounted CF	-28729.3	-5364.0	-2168.2	-2163.9	-10710.7	-2040.9	-1948.4	-1811.4	-8853.1	-1565.2	-1454.6	-17195.5	-575.7	-907.8	1474.5
Net Present Value	-84 014.25														
Equivalent annual payments	-12 333.36														

Appendix C – Financial models for illumination system configurations

Table C1 – Calculation of NPV and EAA for configuration A, RUB

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Initial Investment	174639.5														
Energy consumption cost		46990.1	48540.8	50142.6	51797.3	53506.6	55272.3	57096.3	58980.5	60926.9	62937.4	65014.4	67159.9	69376.1	71665.5
Salary for equipment maintenance		4538.0			5486.3				7065.9			8542.5			10327.6
Maintenance of equipment					15744.6				20277.7						29638.1
Purchasing new stabilizers												81717.1			
Selling stabilizers															63146.9
Lamp's Depreciation		19127.1	16394.7	14052.6	12045.1	10324.4	8849.5	7585.2	6501.6	6501.6	6501.6	6501.6	6501.6	6501.6	6501.6
Regulator's Depreciation		8149.9	6519.9	5215.9	4172.7	3338.2	2670.6	2670.6	2670.6	2670.6	2670.6	40858.6	20429.3	10214.6	10214.6
Tax saved		15761.0	14291.1	13882.2	17849.2	13433.8	13358.5	13470.4	19099.3	14019.8	14421.9	24183.4	18818.2	17218.5	13040.1
Cash flow	-174639.5	-35767.1	-34249.7	-36260.4	-55179.0	-40072.8	-41913.9	-43625.9	-67224.9	-46907.0	-48515.5	-131090.6	-48341.7	-52157.6	-35444.2
Discounted CF	-174639.5	-32086.7	-27563.9	-26179.3	-35738.9	-23284.1	-21847.9	-20400.4	-28201.1	-17652.9	-16379.5	-39703.9	-13134.9	-12713.5	-7750.6
Net Present Value	-497 277.10														
Equivalent annual payments	-73 000.70														

Table C2 – Calculation of NPV and EAA for configuration B, RUB

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Initial Investment	140397.8														
Energy consumption cost		47211.6	48769.6	50379.0	52041.5	53758.9	55532.9	57365.5	59258.6	61214.1	63234.2	65320.9	67476.5	69703.2	72003.4
Salary for equipment maintenance		4538.0		5150.0			6226.2			7527.3		8542.5			10327.6
Maintenance of equipment				2360.3			2853.5					3915.1			4733.2
Purchasing new regulators										11499.4					
Selling equipment															4201.9
Lamp's Depreciation		19127.1	16394.7	14052.6	12045.1	10324.4	8849.5	7585.2	6501.6	6501.6	6501.6	6501.6	6501.6	6501.6	6501.6
Regulator's Depreciation		1626.9	1220.2	915.1	686.4	514.8	514.8	514.8	514.8	3833.1	2555.4	1703.6	1135.7	1135.7	1135.7
Tax saved		14500.7	13276.9	14571.4	12954.6	12919.6	14795.4	13093.1	13255.0	15815.2	14458.2	17196.7	15022.8	15468.1	18099.9
Cash flow	-140397.8	-37248.9	-35492.7	-43317.9	-39086.9	-40839.3	-49817.3	-44272.4	-46003.6	-64425.6	-48775.9	-60581.7	-52453.7	-54235.1	-64762.4
Discounted CF	-140397.8	-33416.1	-28564.3	-31274.7	-25316.3	-23729.5	-25967.6	-20702.7	-19298.7	-24245.8	-16467.4	-18348.6	-14252.1	-13219.8	-14161.6
Net Present Value	-449 363.0														
Equivalent annual payments	-65 966.9														

Table C3 – Calculation of NPV and EAA for configuration C, RUB

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Initial Investment	154202.1														
Energy consumption cost		47611.2	49182.4	50805.4	52482.0	54213.9	56002.9	57851.0	59760.1	61732.2	63769.4	65873.8	68047.6	70293.2	72612.8
Salary for equipment maintenance		4538.0		5150.0			6226.2			7527.3		8542.5			10327.6
Maintenance of equipment				7367.0			8906.5					12219.9			14773.5
Purchasing new regulators										20312.1					
Selling equipment															7422.1
Lamp's Depreciation		19127.1	16394.7	14052.6	12045.1	10324.4	8849.5	7585.2	6501.6	6501.6	6501.6	6501.6	6501.6	6501.6	6501.6
Regulator's Depreciation		5078.0	3808.5	2856.4	2142.3	1606.7	1606.7	1606.7	1606.7	6770.7	4513.8	3009.2	2006.1	2006.1	2006.1
Tax saved		15270.9	13877.1	16046.3	13333.9	13229.0	16318.4	13408.6	13573.7	16506.4	14957.0	19229.4	15311.1	15760.2	19759.9
Cash flow	-154202.1	-36878.3	-35305.3	-47276.2	-39148.1	-40984.9	-54817.3	-44442.4	-46186.4	-73065.2	-48812.4	-67406.7	-52736.5	-54533.0	-70531.9
Discounted CF	-154202.1	-33083.7	-28413.4	-34132.5	-25355.9	-23814.1	-28573.9	-20782.2	-19375.4	-27497.2	-16479.7	-20415.7	-14329.0	-13292.5	-15423.2
Net Present Value	-475 170.5														
Equivalent annual payments	-69 755.4														

Appendix D – Financial models for illumination system configurations taking into account energy saving

Table D1 – Calculation of NPV and EAA for configuration A taking into account energy saving, RUB

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Initial Investment	174639.5														
Energy saved		842.1	869.9	898.6	928.3	958.9	990.6	1023.2	1057.0	1091.9	1127.9	1165.2	1203.6	1243.3	1284.3
Salary for equipment maintenance		4538.0			5486.3				7065.9			8542.5			10327.6
Maintenance of equipment					15744.6				20277.7						29638.1
Purchasing new stabilizers												81717.1			
Selling equipment															63146.9
Lamp's Depreciation		19127.1	16394.7	14052.6	12045.1	10324.4	8849.5	7585.2	6501.6	6501.6	6501.6	6501.6	6501.6	6501.6	6501.6
Stabilizer's Depreciation		8149.9	6519.9	5215.9	4172.7	3338.2	2670.6	2670.6	2670.6	2670.6	2670.6	40858.6	20429.3	10214.6	10214.6
Tax saved		15761.0	14291.1	13882.2	17849.2	13433.8	13358.5	13470.4	19099.3	14019.8	14421.9	24183.4	18818.2	17218.5	13040.1
Cash flow	-174639.5	12065.1	15161.0	14780.9	-2453.4	14392.7	14349.0	14493.7	-7187.3	15111.7	15549.9	-64911.1	20021.8	18461.8	37505.7
Discounted CF	-174639.5	10823.7	12201.5	10671.5	-1589.0	8362.8	7479.5	6777.5	-3015.1	5687.1	5249.8	-19659.9	5440.1	4500.1	8201.3
Net Present Value	-113 508.54														
Equivalent annual payments	-16 663.15														

Table D2 – Calculation of NPV and EAA for configuration B taking into account energy saving, RUB

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Initial Investment	140397.8														
Energy saved		620.6	641.1	662.2	684.1	706.6	730.0	754.1	778.9	804.6	831.2	858.6	887.0	916.2	946.5
Salary for equipment maintenance		4538.0		5150.0			6226.2			7527.3		8542.5			10327.6
Maintenance of equipment				2360.3			2853.5					3915.1			4733.2
Purchasing new regulators										11499.4					
Selling equipment															4201.9
Lamp's Depreciation		19127.1	16394.7	14052.6	12045.1	10324.4	8849.5	7585.2	6501.6	6501.6	6501.6	6501.6	6501.6	6501.6	6501.6
Regulator's Depreciation		1626.9	1220.2	915.1	686.4	514.8	514.8	514.8	514.8	3833.1	2555.4	1703.6	1135.7	1135.7	1135.7
Tax saved		14500.7	13276.9	14571.4	12954.6	12919.6	14795.4	13093.1	13255.0	15815.2	14458.2	17196.7	15022.8	15468.1	18099.9
Cash flow	-140397.8	10583.3	13918.0	7723.3	13638.7	13626.3	6445.6	13847.2	14033.9	-2406.9	15289.4	5597.8	15909.7	16384.4	8187.5
Discounted CF	-140397.8	9494.3	11201.1	5576.1	8833.6	7917.5	3359.8	6475.2	5887.3	-905.8	5161.9	1695.4	4322.8	3993.7	1790.4
Net Present Value	-65 594.4														
Equivalent annual payments	-9 629.3														

Table D3 – Calculation of NPV and EAA for configuration C taking into account energy saving, RUB

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Initial Investment	154202.1														
Energy saved		221.0	228.3	235.8	243.6	251.6	259.9	268.5	277.4	286.5	296.0	305.8	315.9	326.3	337.0
Salary for equipment maintenance		4538.0		5150.0			6226.2			7527.3		8542.5			10327.6
Maintenance of equipment				7367.0			8906.5					12219.9			14773.5
Purchasing new regulators										20312.1					
Selling equipment															7422.1
Lamp's Depreciation		19127.1	16394.7	14052.6	12045.1	10324.4	8849.5	7585.2	6501.6	6501.6	6501.6	6501.6	6501.6	6501.6	6501.6
Regulator's Depreciation		5078.0	3808.5	2856.4	2142.3	1606.7	1606.7	1606.7	1606.7	6770.7	4513.8	3009.2	2006.1	2006.1	2006.1
Tax saved		15270.9	13877.1	16046.3	13333.9	13229.0	16318.4	13408.6	13573.7	16506.4	14957.0	19229.4	15311.1	15760.2	19759.9
Cash flow	-154202.1	10953.9	14105.4	3765.1	13577.5	13480.6	1445.6	13677.1	13851.1	-11046.5	15253.0	-1227.2	15626.9	16086.5	2418.0
Discounted CF	-154202.1	9826.7	11351.9	2718.3	8794.0	7832.9	753.5	6395.7	5810.6	-4157.2	5149.6	-371.7	4246.0	3921.1	528.7
Net Present Value	-91 401.9														
Equivalent annual payments	-13 417.9														

Appendix E – Connection diagram