Форма № 24

МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ

Національний університет «Запорізька політехніка»

__Фізико-технічний інститут, Електротехнічний факультет__
(повне найменування інституту, факультету)

__Електричні та електронні апарати__
(повне найменування кафедри)

Пояснювальна записка

до дипломного проєкту (роботи)

бакалавр
(ступінь вищої освіти)

на тему ____Комплектний розподільний пристрій 10 кВ, 1600 А_____
____

Виконав: студент(ка) _4_курсу, групи Е-417а

Спеціальності _141 Електроенергетика,_____
електротехніка та електромеханіка
(код і найменування спеціальності)

Освітня програма (спеціалізація)
___Електричні та електронні апарати_____

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Форма № 25

МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ
Національний університет «Запорізька політехніка»
(повне найменування закладу вищої освіти)

Інститут, факультет ___Фізико-технічний інститут, Електротехнічний факультет_____
Кафедра ___Електричні та електронні апарати____
Ступінь вищої освіти _Бакалавр____
Спеціальність ___141__Електроенергетика, електротехніка та електромеханіка_______
____
(код і найменування)
Освітня програма (спеціалізація)___Електричні та електронні апарати_____________
____
(назва освітньої програми (спеціалізації)

ЗАТВЕРДЖУЮ
Завідувач кафедри ________________
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«_______» ________________2021_року

З А В Д А Н Н Я
НА ДИПЛОМНИЙ ПРОЄКТ (РОБОТУ) СТУДЕНТА(КИ)

________________________Лапшинов Євгеній Дмитрович________________________
(прізвище, ім'я, по батькові)
1. Тема проєкту (роботи)___Комплектний розподільний пристрій 10 кВ, 1600 А________
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керівник проєкту (роботи)___Жорняк Людмила Борисівна, доцент, к.т.н.______________,
(прізвище, ім'я, по батькові, науковий ступінь, вчене звання)
затверджені наказом закладу вищої освіти від «_11__»_березня__2021___року №_72____
2. Строк подання студентом проєкту (роботи)____
3. Вихідні дані до проєкту (роботи)__10 000 В, 1600 А, 50-60 Гц______________________
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4. Зміст розрахунково-пояснювальної записки (перелік питань, які потрібно розробити) 1 ОГЛЯД ІСНУЮЧИХ КОНСТРУКЦІЙ КРП; 2 РОЗРАХУНОК СТРУМОВЕДУЧОГО КОНТУРУ; 3 РОЗРАХУНОК ЗАГАЛЬНОГО ІЗОЛЯЦІЇ КРП; 4 ВИБІР АПАРАТУРИ ГОЛОВНИХ КІЛ; 5 ОХОРОНА ПРАЦІ; 6 ЕКОНОМІЧНЕ ОБГРУНТУВАННЯ ВИРОБНИЦТВА КРП____
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5. Перелік графічного матеріалу (з точним зазначенням обов'язкових креслень)
Комплектний розподільний пристрій КМ-1Ф. Складальне креслення ГКІЮ.674691.012 СК – А1, 1 лист; Заземлювач. Складальне креслення ГКІЮ.685543.012 СК – А1, 1 лист; Привід заземлювача. Складальне креслення ГКІЮ.304551.012 СК – А1, 1 лист; Шторковий механізм. Складальне креслення ГКІЮ.305362.012 СК – А1, 1 лист;_________
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6. Консультанти розділів проєкту (роботи)

Розділ	Прізвище, ініціали та посада консультанта	Підпис, дата	
		завдання видав	прийняв виконане завдання

7. Дата видачі завдання «_______» _________________2021_року.

КАЛЕНДАРНИЙ ПЛАН

№ з/п	Назва етапів дипломного проєкту (роботи)	Строк виконання етапів проєкту (роботи)	Примітка
1	Техніко-економічне обгрунтування проекту	19.04.2021	
2	Попередній розрахунок головних елементів апарата	26.04.2021	
3	Повірний розрахунок з висновками про роботоспроможність елементів апарата	30.04.2021	
4	Розрахунок економічної ефективності проекту	05.05.2021	
5	Розробка заходів з охорони праці	07.05.2021	
6	Виконання загального виду виробу, робочих креслень головних вузлів та деталей апарата	10.05.2021	
7	Оформлення розрахунково-пояснювальної записки проекту	14.05.2021	
8	Узгодження проекту з керівником проекту та консультантами з економіки та з охорони праці	17.05.2021	
9	Нормоконтроль та затвердження завідувачем кафедри	19.05.2021	
10	РЕЦЕНЗУВАННЯ ПРОЕКТУ	21.05.2021	
11	ЗАХИСТ ПРОЕКТУ	25.05.2021	

Студент(ка) _______________ ____Лапшинов Є.Д._____
(підпис) (прізвище та ініціали)

Керівник проєкту (роботи) _______________ ____Жорняк Л. Б.______
(підпис) (прізвище та ініціали)

ABSTRACT

EN: 95 pages, 11 figures, 15 tables.

COMPLETE SWITCHGEAR DEVICE, COMPLETE SWITCHGEAR, SWITCHGEAR, VACUUM SWITCH, MICROPROCESSOR RELAY PROTECTION AND AUTOMATION, PULL-OUT ELEMENT, CURRENT CIRCUIT, TEST VOLTAGE

The object of research is a 10 kV, 1600 A distribution switchgear panel.

The purpose of the work is to design a complete switchgear using new technical solutions and design developments.

The research method is a computational and analytical method with the formulation and satisfaction of a list of requirements.

In the diploma project, the design of a complete switchgear with a set of measuring transformers has been developed, which ensures the commercial metering of electricity. The use of new developments of relay protection devices, made on a microprocessor base, makes it possible to increase the number of control and diagnostic functions of a single switchgear cubicle, as well as to take into account the specifics of operation. To increase the reliability and reduce the overall dimensions of the switchgear, a new MRZS-05 protection is installed in the relay cabinet, and a BB/TEL–10–25/2000 type circuit breaker is installed on the withdrawable element, made by the Tavrida Electric Ukraine (TEL) enterprise.

CONTENT

INTRODUCTION

The main purpose of a complete switchgear of indoor or outdoor installation is the reception and distribution of electrical energy of three-phase alternating current of industrial frequency. Such complex switchgears have found wide application in switchgear for auxiliary needs of power plants, distribution substations of power systems, converter substations, traction substations of subways and electrified railways, traction substations of urban electric transport, substations of industrial and agricultural enterprises. Nowadays, relevant switchgears are those, that have a specific purpose, for example, switchgears for placing equipment for protection against atmospheric overvoltage, for sectioning overhead lines with a voltage of 10 kV, for reserve automatic switching on (RAS) of lines with a voltage of 10 kV, etc.

At present, the need has arisen to present new requirements for manufacturability of devices: simplicity of design, selection of the cheapest materials, the possibility of using progressive technical processes. Manufacturability, ultimately, determines the cost-effectiveness of the production of an already created structure.

The use of electrical devices, devices and instruments of a Ukrainian manufacturer in the switchgear set will allow to reduce the cost of the product, create jobs at Ukrainian enterprises, and increase the technical and economic indicators of the products being developed.

All of the above requirements are successfully implemented in the development of complete switchgears. Their designs have compact dimensions, are transportable, assembled from inexpensive materials and components, and are equipped with modern equipment and devices. The production of such complete devices is highly efficient in terms of economic indicators, and the consumer's costs are quickly recouped.

As a basic product in the diploma project, switchgear is considered, produced by ZZVA JSC, which is one of the largest in Ukraine and well-known in many countries of the world as an electrical engineering enterprise.

Thus, the purpose of the thesis project is to develop modified switchgear structures using modern design and technological solutions.

1 OVERVIEW OF EXISTING SWITCHGEAR DESIGNS

1.1 Overview of switchgear designs of the Ukrainian manufacturer companies

The main technical and economic requirements for switchgear are: high reliability, low time consumption for installation and maintenance, increased resistance to environmental factors, the profitability of the design in terms of economic efficiency indicators.

The experience gained during the development of switchgear, both domestic and foreign production, is taken into account when designing a switchgear. As examples below, there are considered switchgears of a similar type with vacuum circuit breakers manufactured by Ukraine, Germany, Japan, Austria, Italy, Switzerland, Holland – countries that are leading in the development and production of switchgears.

Among domestic manufacturers, there are several largest manufacturers of electrical products in Ukraine specializing in the production of switchgear. Among them are "Zaporizhzhia High Voltage Apparatus" JSC (ZZVA) Zaporizhzhia, "South Electrotechnical Company" LLC (UEK) Odessa, "Rivne High Voltage Apparatus" JSC (RZVA) Rivne, "ABM Amper" LLC Kremenchug, "Electrograd" LLC Krivoy Rog, "UkrElektroApparatus" LLC Khmelnitsky, etc. [1, 2, 3, 4, 5, 6].

Let’s consider a switchgear for indoor installation of the КУ10(6) С series (RZVA JSC) with vacuum switches. They are designed to operate in three-phase alternating current networks of voltage class 6; 10 kV with a frequency of 50 and 60 Hz in systems with an isolated or grounded neutral connected through an arc suppression reactor or resistance [3].

Switchgear cabinets are available in two standard designs:

a) for general industrial use – in switchgears for auxiliary needs of power plants of all types, at electrical substations, in electrical installations of industrial enterprises;

b) for nuclear power plants (NPP) in non-earthquake-resistant and earthquake-resistant design;

Switchgear cabinets in NPP design are designed to operate in auxiliary switchgears at Thermal Power Plants and NPPs with turbine units with a power up to 1200 MVA. They are designed to operate indoors at a height of up to 20.4 m with a maximum design earthquake of up to 7 points on the MSK-64 scale, and with the use of low-voltage seismic-resistant equipment in auxiliary circuits – up to 9 points.

КУ10(6) С switchgear cabinets can be operated in temperate or tropical climates (climatic version and location category У3 and Т3 in accordance with State Standard ГОСТ 15150-69) [7].

ZZVA JSC is one of the largest in Ukraine and well-known in many countries of the world electrical engineering enterprise, which currently produces complete switchgears: КМ-1Ф, КМ-2Ф, КРУВ, КРУ РТП, КРУЭ, КРУ ПЭ, with low oil, SF6 or vacuum circuit breakers [1]. Let’s consider them below:

КМ-1Ф, КМ-1ФМ switchgears are designed to receive and distribute electrical energy of three-phase alternating current with a frequency of 50 and 60 Hz in networks with an isolated or grounded neutral through an arc suppression reactor.

КРУВ-10 switchgears are intended for powerful excavator complexes, oil rigs with placement in special box houses; in three-phase alternating current networks for systems with isolated neutral.

КРУ РТП-10 switchgears are intended for provide complex control of reversible electric drives of heavy mechanisms.

КРУЭ-10В switchgears are intended for operate on excavators of medium power.

КРУПЭ-10-20 switchgears are intended for operate at mobile power plants.

КСО-285 switchgears are intended for the reception and distribution of electrical energy of three-phase alternating current with a frequency of 50 and 60 Hz, a voltage of 6 and 10 kV in networks with an isolated or grounded neutral through an arc suppression reactor.

Figure 1.1 – Complete switchgear of КМ-1Ф series [1]

КРУ2-10 Э/Э-20 intended for the reception and distribution of electrical energy of alternating three-phase current with a frequency of 50 and 60 Hz in electrical installations with frequent switching operations in networks with an isolated or grounded neutral through an arc suppression coil (systems with low earth fault currents) [1].

Characteristics of mentioned switchgears are shown in Table 1.1.

The products of "South Electrical Engineering Company" (UEK) LLC are distinguished by their dimensions and a large selection of cabinet configurations.

The company produces the following indoor switchgear series of КМ-1ФП, КРУ2-10, КРУ2-10Е, K-XXVI, K-XXVII types and others for currents up to 3150A, with a breaking current up to 40 kA. The latest development –КМ-1ПК switchgear [2].

Table 1.1 – Characteristics of switchgear manufactured by ZZVA JSC [1]

Type	Rated voltage, kV	The highest operating voltage, kV	Rated current, A	Rated breaking current, kA			
				Oil	Vacu-um	SF6 gas	Vacuum contactor
1	2	3	4	5	6	7	8
КМ-1Ф КМ-1ФМ КМ-2Ф	6.0; 10.0 6.6;6.9 10.0;11.0	7.2; 12.0	400; 630; 1000; 1250; 1600; 2000; 2500; 3150	20.0 31.5	20.0 31.5 40.0	20.0 31.5 40.0	
КСО-293	6.0; 10.0	7.2; 12.0	400; 630; 1000	20.0	20.0		
КСО-285	6.0; 10.0	7.2; 12.0	400; 630; 1000		20.0		
КРУВ-10	6.0;6.3; 6.6;10.0	7.2; 12.0	300; 400; 630; 800		20.0		5.0
КРУ РТП	6.0; 6.3; 6.6; 10	7.2; 12.0	100				4.0; 5.0
КРУЭ-10В	6.0-11.0	7.2; 12.0	400; 630		20.0		
КРУПЭ	6.0-11.0	7.2; 12.0	630		20.0; 31.5		
КРУ-35	35	40.5	630; 1600; 2500		31.5	31.5	
КРУ2-10Э/-20	6.0-10.0	7.2; 12.0	400; 630; 1000	20.0			

"Tavrida Electric" CJSC specializes in the production of complete "Classica" switchgears of D-12P and D-12PT series. They are used as switchgears with a voltage of 6-10 kV in transformer substations, including package and container, voltage 110/35/6-10 kV, 110/6-10 kV, 35/6-10 kV and 6-10/0.4 kV, as well as distribution points [8].

Switchgears of D-12P series are designed for indoor operation under the following conditions [8]:

a) height above sea level up to 1000 m,

b) the upper operating value of the air temperature is not higher than +45 °C,

c) the lower operating temperature value is not lower than 25 °C,

d) atmosphere type II in accordance with State Standard ГОСТ 15150-69 [7].

Figure 1.2 – Complete switchgear of D-12P series [8]

The internal volume of the "Classica" switchgear cabinet of the D-12PT series, in contrast to the D-12P series, is divided by fireproof metal partitions into three functional isolated compartments, combining the connection and electrical compartments into a single high-voltage compartment. This design made it possible to significantly improve the convenience of maintenance of switchgear cabinets and at the same time to reduce their overall dimensions. Each compartment has its own channel for the organization of directed upward discharge of gases, which ensures the safety of the operating personnel. The use of a fiber-optic arc protection system in combination with emergency overpressure relief valves allows the power to be cut off as quickly as possible, thereby reducing the time of the destructive effect of an electric arc.

The parameters of the D-12PT switchgear are shown in Table 1.2.

In the domestic complete switchgear manufacturing there are used structures that were developed back in the 80s, which are, for example, switchgear of the KM1 series (modification of KM1Ф and KMB), K-104, K-63. Over the past 25 years, work on the modification of these structures has been carried out in the field of adaptation, replacement of low-oil circuit breakers with vacuum and SF6 circuit breakers of various types, as well as the installation of current transformers, voltage transformers, medium voltage transformers, electronic and microprocessor-based relay protection and automation devices.

Table 1.2 – Characteristics of D-12PT switchgear [8]

Rated voltage, kV	6.0; 10.0
The highest operating voltage, kV	7.2; 12.0
Rated current of the busbars, A	630, 800, 1250,1600
Rated current of main circuits, A	630, 800, 1250,1600
Rated breaking current of circuit breakers built into the switchgear, kV	20; 25
Electrodynamic stability current, kA	Up to 63
Thermal resistance current, kA	20; 25
Thermal resistance current flow time, s	1
Rated voltage of auxiliary circuits, V	Up to 220
Dimensions, mm	600-750×1100×2245

1.2 Overview of foreign switchgear design analogs

In foreign production, preference is given to switchgear, where the circuit breaker is mounted on a small trolley that rolls into the middle compartment of the switchgear cabinet. Actually, the term "roll-out element" in these switchgear is leveled. The name "pull-out element" is more appropriate. The term "cassette-type switch" is gaining popularity. Due to their small dimensions, such switches fit well into the compartment in the middle of the cabinet, which radically changes the cabinet architecture.

"Schneider Electric" JSC offers for use and implements equipment with an increased resource, which does not require additional maintenance, is convenient in operation, and meets the technical standards and requirements of operation. Among them, medium voltage switchgear (MV) cells of the FLUAIR, SM6, MCset types with SF6 circuit breakers, equipped with SEPAM digital devices that perform the functions of relay protection, monitoring and control [9].

Figure 1.3 – Appearance of SM6 series switchgear cabinets [9]

Siemens offers a number of air-insulated switchgear of 8BT2, 8DAB12, SIMOSEC, NXAIR, NXAIR S series [10].

The company manufacturing medium voltage switchgears in Italy is G&W Electric "TOZZI". A characteristic feature is that they are two-sided service and all have a cabinet version with front doors. The sliding element of the switchgear cabinet can have a working and control fixed position with the doors closed. In the series there is a variant of a switchgear cabinet with a two-tier arrangement of switches, that is, for two outgoing lines. The minimum dimensions of the switchgear are achieved due to the widespread introduction of cast solid insulation [11].

AEG is one of the leaders in the production of vacuum circuit breakers and, along with switchgear with low oil circuit breakers and other switching devices, produces switchgear with vacuum switches. Let's consider one of the main types of switchgear cells from this company [12].

Cells of the WK series with metal partitions, type C (Fig. 1.2), with power switching devices and without disconnectors. Designed for free-standing, back-to-back and wall-mounted switchgear in closed electrical or normal work areas. They have the following switching devices: vacuum circuit breakers, vacuum contactors or circuit breakers on withdrawable elements and grounding switches [12].

Figure 1.4 – Cell of the WKC type series [12]

The parameters of the switchgear used in the company's package transformer substation are given in Table. 1.3.

Table 1.3 – AEG switchgears used in various types of package transformer substations [12]

Type	FRA	WKA	WKB	WKE	WKC
Rated voltage, kV	12 24	12	24 12	17,5 24	12 17 24
Switching devices	Disconnector, fuse, grounding switch	Disconnector on busbars; low oil on feeders, vacuum switch, vacuum contactor or disconnector, fuse, grounding switch			Low oil or vacuum circuit breaker
Rated current of branch busbars, A	400 400	1250	1250 1300	2300 2000	3000 2100 2100 1850
Rated breaking current, kA		25	25 31,5	31,5 31,5	31,5
Dimensions, mm: Height Width Depth	2100 1300 1000	2100 600 890 800 1000	2100 890 600 1060 890 1000 1150	2330 1330 890 600 890 1150	2300 600 or 890 1000 1150

Driescher (Germany) manufactures air-insulated switchgear of WEL/E2K/E3K types for 12 kV, as well as prefabricated chambers of one-sided service (КСО) LDTC type for 12 kV using a disconnector with fuses as a load switch [13].

1.3 Choosing the direction of design development

Nevertheless, the appearance of the new switchgear layout did not entail the abandonment of the architecture with a pull-out element in the lower part of the cabinet. It also has a number of advantages. First, these cells are more compact, albeit at the expense of ease of maintenance. In some cases – installation of switchgear at underground metro substations, in the cramped conditions of industrial production, etc. – their use is preferable. In addition, newer cells are relatively expensive, which in domestic conditions is an important factor when choosing equipment. During their lifetime, cells with a pull-out element have undergone a sufficiently deep modernization, taking into account the operation, and in modern series of such switchgear, as far as possible, the requirements arising from practical operation are taken into account.

Since Ukraine gained independence, due to the prevailing economic circumstances, there has been no significant renewal of electrical equipment, and only recently has an intensive modernization and replacement of morally and physically obsolete equipment has begun.

The need for switchgear with load currents of 1600 A is still a rather high percentage when they are performed for linear connections, which reflects the relevance of the development and production of cabinets for a rated current of 1600A. Such a design of the switchgear provides savings in material resources not only in factories, but also among consumers due to new design solutions.

Let's compare the characteristics of the technical parameters of various types of switchgear cabinets (Table 1.4).

Analyzing the data given in Table 1.4, it can be concluded that complete switchgears of domestic manufacturers are at the level of foreign counterparts.

The switchgear device manufactured by ZZVA JSC is chosen as the basic design.

Satisfying consumers in terms of output parameters (rated current and voltage), domestic general industrial switchgears, in the main mass series, contain a number of constructive solutions that are outdated to date, which do not allow for effective measures to reduce materiality and labor intensity, for example: in existing switchgear structures manufactured by ZZVA JSC, the relay contact equipment is placed in the relay compartments located in the upper part of the relay cabinet. Control devices, signal lamps and relays, control keys, counters are installed on the door of the relay compartment. On the back wall there are automatic switches, relays, starters. Clamp blocks are installed on the floor, through which an electrical connection is established between the equipment installed on the doors of the cabin of the outgoing lines cabinets.

Table 1.4 – Comparative characteristics of the technical parameters of the switchgear [1, 3, 10, 11]

Parameter name	КМ–1Ф (ZZVA)	GWElectric	Siemens	КУ10(6)С (RZVA)	Designed switchgear
1	2	3	4	5	6
1 Rated voltage, kV.	10	12	30	10	10
2 Rated current, A	1250	4000	1250	1 000	1600
3 Rated breaking current, kA	20	50	31,5	31,5	20
4. Thermal withstand current, kA	16, 25	40	31.5	31,5	20
5 Dynamic withstand current, kA	52	125	100	51	52
6 Short-circuit current flow time, s	3	3	3	3	3
7 Width, m	0,75	1,4	1,54	0,75; 0,9	0,75
8 Depth, m	1,3	3	2,2	1,4; 1,5	1,025
9 Height, m	2,15	2,25	2,2	2,3	2,05
11 Weight, kg	850	1250	960	600	800

As the preliminary calculations of the elements of the current-carrying circuit show below in the next chapter, there is a certain margin for their thermal state. Still, the busbars and, in particular, their contact connections are the most loaded in terms of heat. In practice, the cause of failures is overheating of the contact connection due to an increase in the contact resistance. The main reasons for this negative phenomenon are the oxidation of the contact surfaces, the weakening of fasteners, etc. Thus, the reliability of contact can be increased by achieving the stability of contact pressure during operation, monitoring the thermal state of the contact assembly.

At the present stage, the modernization of old switchgear is underway. In particular, control cabinets, which have a number of disadvantages, namely:

a) outdated relay (electromechanical) installations;

b) high costs for repair and maintenance;

c) lack of a unified remote control and monitoring system.

d) the high cost of finished products.

To eliminate these shortcomings, in this work, it is proposed to introduce a new protection system based on the MRZS-05 of the "Kyivprylad" production association. This series is fully adapted to provide monitoring and control of electrical substations, and has a full range of relay protection, measurement, control, monitoring and signaling functions [14].

The advantages of microprocessor terminals for equipment protection are their multifunctionality, compactness and measurement accuracy.

Also, the advantage of microprocessor technology is that the presence of various communication interfaces allows the devices to be integrated into the ACS system, which makes it possible to have operational information about the state of various circuit elements, control switches, configure relay protection, receive data on an emergency, oscillograph, etc. The possibility of fixing the current values of the monitored currents and voltages allows for a clearer analysis of emergency situations.

The disadvantage of microprocessor devices is their high cost. In addition, significant expenses of the enterprise are allocated for the maintenance of microprocessor devices: it is necessary to have expensive equipment, software, as well as specialists with appropriate qualifications.

An integral part of the switchgear is a switch, the reliability of which determines the reliability of the entire switchgear. Therefore, in this work, it is proposed to install a vacuum switch. These circuit breakers are highly reliable, fast and have high breaking capacity.

2 CALCULATION OF THE CURRENT-CARRYING CIRCUIT

The main task of calculating a current-carrying circuit is to determine the dimensions of the cross-section of its current-carrying parts so that its heating temperature does not exceed the permissible one. Mainly copper or aluminum is chosen as a material for live parts of electrical devices. Copper is used when the environment inside the cabinet is heavily polluted and has lower losses compared to aluminum. However, taking into account the high cost of copper, it was made a decision to choose the material aluminum for the manufacture of busbars.

The choice of the cross-sectional shape and surface of the elements of the current-carrying system is made taking into account the reduction of additional losses, ensuring the necessary heat removal and mechanical strength. In this regard, busbars of rectangular cross-section with rounded edges were selected, which ensures equalization of the electric field and provides dielectric strength at a minimum distance of 0.13 m between the busbars [30].

For dismountable contacts (screw and bolted connection), which must have stable resistance at an operating temperature of up to 120 °C, copper is used. The connection of aluminum busbars to the copper (brass) clamps of the apparatus is carried out using copper-aluminum busbars, which prevent the formation of an electrolytic copper-aluminum pair [20].

2.1 Pre-selection and calculation of the elements of the current-carrying circuit

The cross-sections of the busbars used in switchgear are standardized and selected according to ready-made tables given in [21].

For a preliminary calculation of the cross-section of busbars capable of withstanding rated current loads, the formula [22] is used:

$$\theta_{perm} - \theta_{env} = \frac{I_r^2 \cdot \rho_0 \cdot \left(1 + \alpha \cdot \theta_{perm}\right)}{\kappa_{ht} \cdot P \cdot S}, \quad (2.1)$$

where θ_{perm} – permissible heating temperature of aluminum current buses. According to [24] θ_{perm} is chosen equal to 120 °C;

θ_{env} – ambient temperature in the cabinet;

I_r – rated current load equal to 1600 A;

ρ_0 – resistivity at 0 °C. According to [24], the resistivity for aluminum is $2.62 \cdot 10^{-8}$ $Ohm \cdot m$;

α – temperature coefficient of material resistivity. For aluminum, according to [21], the coefficient is 0.0042 K^{-1};

κ_{ht} – heat transfer coefficient, which, according to [21], with natural free air movement for aluminum busbars, it was taken 10.5 $\frac{W}{m^2 \cdot °C}$;

P – busbar cross-section perimeter;

S – cross-sectional area of busbar.

The ambient temperature in the cabinet θ_{env} according to [24] is determined by the formula:

$$\theta_{env} = \theta_0 + \tau_o, \quad (2.2)$$

where θ_0 – ambient temperature equal to 40 °C from the initial data;

τ_0 – the excess of the air temperature in the cabinet over the ambient temperature, equal to 15 °C.

Substituting the numerical values into formula (2.2), we obtain:

$$\theta_{env} = 40 + 15 = 55 \text{ °C}.$$

To determine the main dimensions of the busbar from the formula (2.1), express:

$$P \cdot S = \frac{I_r^2 \cdot \rho_0 \cdot (1 + \alpha \cdot \theta_{perm})}{\kappa_{ht} \cdot (\theta_{perm} - \theta_{env})} \quad (2.3)$$

For a conductor with a rectangular cross-section with sides *a* and *b*, taking into account the aspect ratio *m = b/a = 0.4*, the following replacement is introduced:

$$P \cdot S = 2m\,(1 + m) \cdot a^3 \quad (2.4)$$

Then, substituting (2.4) for (2.3), we'll obtain:

$$a = \sqrt[3]{\frac{I_r^2 \cdot \rho_0 \cdot (1 + \alpha \cdot \theta_{perm})}{2m \cdot (m + 1) \cdot \kappa_{ht} \cdot (\theta_{perm} - \theta_{env})}} \quad (2.5)$$

Substituting the numerical values into the formula (2.5), we'll get:

$$a = \sqrt[3]{\frac{1600^2 \cdot 2.62 \cdot 10^{-8} \cdot (1 + 0.0042 \cdot 120)}{2 \cdot 0.4 \cdot (0.4 + 1) \cdot 10.5 \cdot (120 - 55)}} = 50.9\,mm$$

Based on the accepted aspect ratio:

$$b = 0.4 \cdot 50.9 = 20.4\,mm$$

The cross-sectional area of the busbars S_{calc}, which are capable of withstanding the rated current load is:

$$S_{calc} = a \cdot b = 50.9 \cdot 20.4 = 1036.04\, mm^2$$

To improve the heat dissipation by increasing the conductor cooling area, it is proposed to use three-strip buses in the diploma project.

The cross-sectional area of one strip is $S_{calc}/3$ = 346 mm^2.

According to [22], three-strip aluminum busbars with a cross-section (60 × 6) mm^2, with a total cross-sectional area of 1080 mm^2 are selected.

$$S_{strip} = \frac{S}{3} = \frac{a \times b}{3} = 60 \times 6 = 360\, mm^2 > \frac{S_{calc}}{3} = 346\, mm^2$$

$$S_{bus} = a \times b = (60 \times 6) \times 3 = 1080\, mm^2 > S_{calc} = 1036\, mm^2$$

Having chosen the busbars, it is necessary to carry out a verification calculation of the busbars when the long-term permissible current passes, that is, the current corresponding to the steady-state heating temperature of the current-carrying buses.

2.2 Verification calculation of the elements of the current-carrying circuit

2.2.1 Calculation of busbar heating temperature

Verification of busbars during the passage of a long-term permissible load current is carried out on the basis of equation (2.1) relative to the permissible current and temperature, taking into account the parameters of the selected busbars [27].

Let us solve equation (2.1) with respect to the maximum allowable temperature that the conductor can withstand.

$$\theta_{\max perm} = \theta_{env} + \frac{I_r^2 \cdot \rho_0 \cdot (1 + \alpha \cdot \theta_{perm})}{\kappa_{ht} \cdot P' \cdot S'}, \tag{2.6}$$

where $\theta_{\max perm}$ – the maximum allowable temperature that the busbars can withstand;

P' – the perimeter of the cross-section of the selected busbars equal to 0.228 m;

S' – cross-sectional area of the selected busbars equal to $1080 \cdot 10^{-6}$ m^2.

$$\theta_{\max perm} = 55 + \frac{1600^2 \cdot 2.62 \cdot 10^{-8} \cdot (1 + 0.0042 \cdot 120)}{10.5 \cdot 0.228 \cdot 1080 \cdot 10^{-6}} = 94.01\ ℃ .$$

Let us determine the long-term permissible current corresponding to the steady-state heating temperature of the busbars. To do this, an equation (2.1) is solved with respect to the permissible current.

$$I_{perm} = \sqrt{\frac{\kappa_{ht} \cdot P' \cdot S' \cdot (\theta_{perm} - \theta_{env})}{\rho_0 \cdot (1 + \alpha \cdot \theta_{perm})}}, \qquad (2.7)$$

where I_{perm} – continuous current.

$$I_{perm} = \sqrt{\frac{10.5 \cdot 0.228 \cdot 1080 \cdot 10^{-6} \cdot (120 - 55)}{2.62 \cdot 10^{-8} \cdot (1 + 0.0042 \cdot 120)}} = 2065\ A$$

The calculated values are below the permissible values, i.e.

$$94.01\ ℃ < 120\ ℃ ,$$
$$1600\ A < 2065\ A .$$

This means that the selected section meets the conditions of the thermal regime.

2.2.2 Verification of busbars for thermal and dynamic resistance

Checking busbars for thermal resistance consists in determining the heating temperature of the busbars by short-circuit current.

The calculation is carried out by the graphic-analytical method, so the total thermal impulse from the action of the long-term load current and the short-circuit current is determined, and then the heating temperature of the busbars by the short-circuit current is found from the heating curves [24].

The calculated aluminum bus has a heating temperature with a continuous load current of 94.01 °C. Taking into account the degree of responsibility of busbars during operation, the calculation is carried out at the value of the maximum permissible temperature of busbar heating, that is, 120 °C.

For the above temperature, according to [24], the thermal impulse A_h is determined, which is equal to $0.75 \cdot 10^4 \frac{A^2 \cdot s}{mm^4}$.

The thermal impulse from the action of the short-circuit current is determined by the formula:

$$A_{s.c} = \left(\frac{I_{s.c.}}{S}\right) \cdot t_{s.c.}\,, \tag{2.8}$$

where $I_{s.c.}$ – thermal resistance current, according to the operating conditions and technical data of the switching element, the current is 20 kA;

S – cross-section of the current-carrying bus equal to 1080 mm^2;

$t_{s.c.}$ – short-circuit current duration of 3 s.

Thus, the thermal impulse from the action of the short-circuit current is:

$$A_{s.c.} = \left(\frac{20000}{1080}\right)^2 \cdot 3 = 0.1028 \cdot 10^4 \cdot \frac{A^2 \cdot s}{mm^4}.$$

The resulting value of heat impulses is summed up:

$$A_h = (0.75 + 0.1028) \cdot 10^4 = 0.8528 \cdot 10^4 \cdot \frac{A^2 \cdot s}{mm^2}.$$

The obtained value corresponds, according to [24], to the busbar heating temperature with a short-circuit current equal to 150 ℃.

According to [23], the permissible heating temperature by the short circuit current of current carrying buses made of aluminum is 200 ℃.

Thus, the found temperature value is less than the allowable one, that is, the busbar is thermally resistant.

$$150\ ℃ < 200\ ℃$$

In the event of a short circuit in the network, currents that are tens of times higher than the nominal ones can pass through the live part of the apparatus. When these currents interact with the magnetic field of other live parts of the apparatus, electrodynamic forces are created. These efforts tend to deform both the conductors of live parts and the insulators on which they are attached. At rated currents, these forces are small and can be neglected, however, in the short-circuit mode, these forces increase sharply and the calculation for dynamic resistance is very important.

Electrodynamic resistance is understood as the ability of live parts to withstand the forces arising from the action of the shock current for the period after the initial short circuit, that is, it is necessary to calculate the bending stress of the bus material and compare it with the permissible value [23, 27].

$$\sigma_p \leq [\sigma], \tag{2.9}$$

where σ_p – the calculated value of the bending stress of the material, Pa;

[σ] – permissible bending stress of the busbar material, Pa. For an aluminum bus, the bending stress according to [18] is $10.8 \cdot 10^7$ Pa.

The bending stress is determined by the formula given in [24]:

$$\sigma_p = \frac{F \cdot l}{10 \cdot W}, \tag{2.10}$$

where *F* – electrodynamic force of interaction between adjacent phases;

l – the length of the current-carrying bus between the support insulators, equal to 0.75m;

W – moment of resistance relative to the bending axis, m^3.

The electrodynamic force is determined by the formula:

$$F = 17.6 \cdot {i_{sh}}^2 \cdot \frac{l}{A} \cdot k_f \cdot 10^{-7}, \tag{2.11}$$

where *l* – length of the current-carrying bus, m;

A – the distance between the phases, according to the analogue data, equal to 0.25m;

k_f – form factor equal to 1;

i_{sh} – value of shock current at short circuit, kA.

The short-circuit surge current is determined by the formula:

$$i_{sh} = 1.8 \cdot \sqrt{2} \cdot I_{th.r}, \tag{2.12}$$

where $I_{th.r}$ – thermal resistance current equal to 20 kA.

Determine the value of the shock current:

$$i_{sh} = 1.8 \cdot \sqrt{2} \cdot 20 = 51\ kA.$$

The moment of resistance is found by the formula:

$$W = \frac{b \cdot h^2}{6}, \tag{2.13}$$

where b and h – respectively, the smaller and larger side of the busbar, m.

According to the formula (2.13), the moment of resistance of busbars located flat on insulators is determined:

$$W = \frac{0.008 \cdot 0.12^2}{6} = 1.9 \cdot 10^{-5}\ m^3\ .$$

According to the formula (2.11), the value of the electrodynamic force is found:

$$F = (51 \cdot 10^3)^2 \cdot \frac{0.75}{0.25} \cdot 10^{-7} = 1373\ H\ .$$

Substituting the obtained values into the formula (2.10), the bending stress is found, equal to:

$$\sigma_p = \frac{1373 \cdot 0.75}{10 \cdot 1.9 \cdot 10^{-5}} = 0.54 \cdot 10^7\ \frac{H}{m^2}\ .$$

Since the condition (2.9) of busbar stability is fulfilled, the calculated busbar is electrodynamically stable.

$$0.54 \cdot 10^7 < 10.8 \cdot 10^7\ Pa$$

2.2.3 Calculation of contact connection

In modern switchgear, socket-type contact connections are used. The number of lamellas depends on the rated current. For the designed switchgear, the number of lamellas equal to 12 were chosen [29]. Then the value of the current flowing through one lamella is determined by the formula:

$$I_l = \frac{I_r \cdot k}{n_l} \ , \tag{2.14}$$

where I_r – rated current load equal to 1600 A;

n_l – number of lamellas equal to 12;

k – coefficient of uneven current flow equal to 1.3.

Substitute the numerical values into the formula (2.14) and get:

$$I_l = \frac{1600 \cdot 1.3}{12} = 173.3\ A\ .$$

The actual surface, on which the mechanical contact of two contact details (CDs) occurs, is very heterogeneous. Therefore, the conductivity in the contact zone of two CDs is equal to the sum of the conductivity of the constriction zone and the quasi-metallic zone.

$$\frac{1}{R_{trans}} = \frac{1}{R_{con}} + \frac{1}{R_{q.m.}} \ , \tag{2.15}$$

Transitional contact resistance:

$$R_{trans} = \frac{R_{con} \cdot R_{q.m.}}{R_{con} + R_{q.m.}} \ , \tag{2.16}$$

However, the resistance of the quasi-metallic zone significantly exceeds the resistance of the constriction zone in copper and aluminum CDs, therefore, the resistance of the quasi-metallic zone can be neglected in engineering calculations. Then

$$R_{trans} = R_{con} \ , \tag{2.17}$$

The transient resistance of a well-cleaned contact and contact of any kind at a temperature of 20 ℃ is determined by the empirical formula [24]:

$$R_{trans\,20} = \frac{k_{nx}}{(0.102 \cdot F_c)^m} \ , \tag{2.18}$$

where k_{nx} – coefficient taking into account the physical properties of the metal, which according to [22] is $0.18 \cdot 10^{-3}$;

m – coefficient obtained empirically. For socket contact *m* is equal to 0.75;

F_c – contact pressure.

Contact pressing determines the transition resistance, and therefore the temperature of the CD. It can be calculated using the following formula:

$$F_k = \frac{I_l^2 \cdot \rho^2 \cdot \pi \cdot H'}{4 \cdot U_c^2} \ , \tag{2.19}$$

where I_l – rated current load for one lamella equal to 173.3 A;

ρ – specific resistance of the contact connection;

U_k – voltage drop across contacts;

H’ – microhardness of the metal at a permissible temperature of 120 ℃.

Resistivity ρ at an allowable temperature is determined from the formula:

$$\rho = \rho_0 \cdot (1 + \alpha \cdot \theta_{perm}) \,, \tag{2.20}$$

where ρ_0 – resistivity at 0℃, equals to $1.58 \cdot 10^{-8}$ Ohm·m [29];

α – temperature coefficient of electrical resistance, according to [21] equal to 0.0042 K^{-1};

$$\rho = 1.58 \cdot 10^{-8} \cdot (1 + 4.2 \cdot 10^{-3} \cdot 120) = 2.4 \cdot 10^{-8}\ Ohm \cdot m$$

The voltage drop U_k is expressed through the softening voltage. For reliable operation of the contacts, it is necessary that at rated current the voltage U_k does not exceed 0.1-0.2 $U_{k\,soft}$. Accepting:

$$U_k = 0.1 \cdot U_{k\,soft}, \tag{2.21}$$

where $U_{k\,soft}$ – softening voltage, for these contacts equal to 0.12 V.

$$U_k = 0.1 \cdot 0.12 = 1.2 \cdot 10^{-2}\ V \,.$$

The microhardness of the metal at the permissible temperature is determined from the formula:

$$H' = \frac{H_0 \cdot \left[1 - \left(\frac{\theta_{perm}}{\theta_{melt}}\right)^{\frac{2}{3}}\right]}{1 - \left(\frac{\theta_0}{\theta_{melt}}\right)^{\frac{2}{3}}}, \qquad (2.22)$$

where H_0 – 750 MPa – microhardness at temperature θ_0 equals 0 ℃;

θ_{perm} – permissible heating temperature, equal to 393 °K;

θ_{melt} – the melting temperature of the metal of contacts, according to [22], equal to 1356 °K.

Substituting the obtained values into the formula (2.22), the microhardness of the metal is found, equal to:

$$H' = 750 \cdot \frac{1 - \left(\frac{393}{1356}\right)^{\frac{2}{3}}}{1 - \left(\frac{273}{1356}\right)^{\frac{2}{3}}} = 645.86\ MPa\ .$$

Substituting the obtained values into the formula (2.22), the microhardness of the metal is found, equal to:

$$F_k = \frac{173.3^2 \cdot (2.3 \cdot 10^{-8})^2 \cdot 3.14 \cdot 645.86 \cdot 10^6}{4 \cdot (1.2 \cdot 10^{-2})^2} = 60.9\ H$$

The contact transient resistance of the contact is determined by the formula (2.19):

$$R_{trans\,20} = \frac{0.18 \cdot 10^{-3}}{(0.102 \cdot 60.9)^{0.75}} = 4.56 \cdot 10^{-5}\ Ohm$$

The contact transient resistance for the permissible temperature is determined by the following formula:

$$R_{trans} = R_{trans\,20} \cdot \left[1 + \frac{2}{3} \cdot \alpha_{el\,res} \cdot \left(\theta_{perm} - 20\right)\right], \qquad (2.23)$$

where $\alpha_{el\,res}$ – temperature coefficient of electrical resistance equal to 0.0042 K^{-1};

$$R_{trans} = 4.56 \cdot 10^{-5} \cdot \left[1 + \frac{2}{3} \cdot 4.2 \cdot 10^{-3} \cdot (120 - 20)\right] = 6.48 \cdot 10^{-5}\ Ohm$$

The contact heating temperature should not exceed the permissible temperature, which according to [24] is 120 °C. According to [29], the contact heating temperature is calculated by the formula:

$$\theta_c = \theta_{env} + \frac{I_l^2 \cdot \rho_\vartheta}{S \cdot p \cdot k_{ht}} + \frac{I_l^2 \cdot R_{trans}}{\sqrt{\lambda \cdot S \cdot p \cdot k_{ht}}} + \frac{I_l^2 \cdot R_{trans}^2}{8 \cdot \lambda \cdot \rho_\vartheta}, \qquad (2.24)$$

where θ_{env} – ambient temperature in the cabinet equal to 55 °C;

k_{ht} – heat transfer coefficient from the surface of conductive conductors, equal to 10.5 $\frac{W}{m^2 \cdot °C}$

ρ_ϑ – resistivity of the contact or contact area;

λ – specific thermal conductivity of conducting conductors;

S – cross-sectional area of the conductor equal to 1080 mm^2;

p – perimeter of the cross-section of the conductor equal to 228 mm.

The resistivity of the contact or contact area is determined by the formula:

$$\rho_\vartheta = \rho_0 \cdot (1 + \alpha \cdot \theta_{bus}), \tag{2.25}$$

where θ_{bus} – bus heating temperature is equal to 94.1 °C;

$$\rho = 1.58 \cdot 10^{-8} \cdot (1 + 4.2 \cdot 10^{-3} \cdot 94.1) = 2.21 \cdot 10^{-8}\ Ohm \cdot m$$

The specific thermal conductivity of conductive conductors is calculated using the following formula:

$$\lambda = \lambda_0 \cdot (1 + \alpha \cdot \theta_{bus}), \tag{2.26}$$

where coefficient λ_0 equals to 210 $\frac{W}{K \cdot m}$.

$$\lambda = 210 \cdot (1 + 4.2 \cdot 10^{-3} \cdot 94.1) = 292.99\ \frac{W}{K \cdot m}.$$

Substitute numerical values into the formula (2.24):

$$\theta_c = 55 + \frac{173.3^2 \cdot 2.21 \cdot 10^{-8}}{10.8 \cdot 10^{-4} \cdot 0.228 \cdot 10.5} + \frac{173.3^2 \cdot 6.48 \cdot 10.5^{-5}}{\sqrt{292.99 \cdot 10.8 \cdot 10^{-4} \cdot 0.228 \cdot 10.5}} + \frac{173.3^2 \cdot (6.48 \cdot 10^{-5})^2}{8 \cdot 292.99 \cdot 2.21 \cdot 10^{-8}} = 59.98\ °C$$

The calculated temperature does not exceed the permissible, that is:

$$59.98\ °C < 120\ °C$$

The selected contact connection must be tested for thermal resistance.

The area of the transverse contact connection, consisting of 12 lamellas, is equal to 2828 mm^2. The heating temperature of the lamellas by the short-circuit current is through a thermal pulse.

The thermal impulse of the lamella $A_{l\ l}$ during the passage of a long load current according to [29] has the value $0.6 \cdot 10^4\ \frac{A^2 \cdot s}{mm^4}$.

$$A_{sc} = \left(\frac{I_{th}}{S}\right)^2 \cdot t_{sc}\ , \qquad (2.27)$$

where S – cross-sectional area of the contact connection equal to 2828 mm2;

I_{th} – thermal current. For this product, the current is 20 kA.

The thermal impulse is determined at a short-circuit time based on the technical data of the switching element equal to 3 s.

Substituting the values into formula (2.27), we'll get:

$$A = \left(\frac{20000}{2828}\right)^2 \cdot 3 = 0.02 \cdot 10^4\ \frac{A^2 \cdot s}{mm^4},$$

The sum of heat impulses is found:

$$A_{\Sigma} = A_{l\,l} + A_{sc} \qquad (2.28)$$

$$A = 0.6 \cdot 10^4 + 0.02 \cdot 10^4 = 0.62 \cdot 10^4\ \frac{A^2 \cdot s}{mm^4}.$$

Knowing the thermal impulse by [29], the temperature of heating the lamellas by the short-circuit current is found, equal to 165 ℃ .

This satisfies the condition, since the value obtained when calculating the heating temperature of the lamellas by the short-circuit current is lower than the permissible temperature of the live parts in contact with organic insulation. According to [29], the admissible temperature is 250 °C.

The contact connection is also checked for dynamic resistance, that is the current at which the contacts can be welded.

The welding current flowing through one lamella is calculated by the formula:

$$I_{weld} = K_{weld} + \sqrt{F_{press}}\,, \qquad (2.29)$$

where I_{weld} – peak value of the shock current, A;

K_{weld} – coefficient for calculating the dynamic resistance of contacts. According to [29], the value of the coefficient is 1900 $\frac{\text{A}}{\sqrt{H}}$;

F_{press} – actual value of pressing force, N.

Pressing force is determined by the formula:

$$F_{press} = F_c + F_{ed1} + F_{ed2}\,, \qquad (2.30)$$

where F_c – force of contact pressure, calculated according to the formula (2.19) and equal to 60.9 N;

F_{ed1} – electrodynamic force tending to open the contact surfaces, N;

F_{ed2} – electrodynamic force tending to close contact surfaces, N.

$$F_{ed1} = \frac{I_{max}^2 \cdot 10^{-7}}{n_c} \cdot ln\frac{S}{S_o}\,, \qquad (2.31)$$

where I_{max} – the actual value of the through current flowing through one lamella during a short circuit, kA;

S_o – actual contact area, m^2;

S – cross-sectional area of one lamella equal to 117 mm^2;

n_c – number of contact points for line contact equal to 2.

The actual value of the through current is found by the formula:

$$I_{max} = \frac{i_{sh} \cdot k}{n}, \quad (2.32)$$

where k – coefficient taking into account the uneven distribution of the current along the lamellae. According to [31], it is taken equal to 1.3;

n – number of lamellas equal to 12;

i_{sh} – through current at short circuit equal to 51 kA according to the formula (2.12).

Thus:

$$I_{max} = \frac{51 \cdot 10^3 \cdot 1.3}{12} = 5.25\ kA$$

The actual contact area is determined by the formula:

$$S_o = \frac{F_k}{\sigma}, \quad (2.33)$$

where σ – temporary resistance of the material to crushing. According to [21] it is equal to $3038 \cdot 10^5$ Pa.

The force tending to close the contact is determined by the formula:

$$F_{ed2} = I_{max}^2 \cdot 10^{-7} \cdot 2 \cdot \frac{1}{a}, \quad (2.34)$$

where I_{max} – the actual value of the through current flowing through one lamella in case of a short circuit. According to formula (2.32), the current value is $5.25\ 10^3$ A;

l – the length of the current line of the lamella, equal to 45 mm;

a – the distance between the centers of the contact surfaces. According to [22], the distance is 0.036 m.

According to formulas (2.30), (2.31), and (2.34), the following equation is composed:

$$F_{press} = F_K + I_{max}^2 \cdot 10^{-7} \cdot 2 \cdot \frac{l}{a} - \frac{I_{max}^2 \cdot 10^{-7}}{n_k} \cdot ln\frac{S \cdot \sigma}{F_k}, \qquad (2.35)$$

Substituting the values in (2.36), we'll get:

$$F_{press} = 60.9 + (5.25 \cdot 10^3)^2 \cdot 10^{-7} \cdot 2 \cdot \frac{0.045}{0.036} - \\ - \frac{(5.25 \cdot 10^3)^2 \cdot 10^{-7}}{2} \cdot ln\frac{117 \cdot 10^{-6} \cdot 3038 \cdot 10^5}{60.9} = 59.01\ H$$

The welding current per one lamella is determined by the formula (2.29).

$$I_{weld} = 1900 \cdot \sqrt{59.01} = 14.6\ kA$$

Since the actual value of the through current I_{max} flowing through one lamella is less than the value of the welding current I_{weld},

$$5.25\ kA < 14.6\ kA\ .$$

Thus, contact welding will not occur, and the contact connection will be dynamically resistant.

3 CALCULATION OF THE TOTAL SWITCHGEAR INSULATION

3.1 Selection of basic clearances

The insulation design is the most important element of a complete switchgear, which largely determines the overall dimensions and reliability of the device in operation. In the electrical circuits of the cabinet under development, the switchgear must provide an appropriate level of isolation between live parts and grounded elements, as well as between live parts of adjacent live poles.

The required insulation level is ensured by choosing the appropriate length of the gap. Insulation distances are taken in such a way that the apparatus or its part can withstand the test voltage of industrial frequency or full lightning impulses and at the same time remain suitable for further operation. The dielectric strength of the insulation is characterized by the breakdown voltage in the air corresponding to the medium and over the surface of a solid dielectric. Electrical insulation is designed for the appropriate voltage class, taking into account the specific operating conditions.

In the developed complete switchgear, the main insulating gaps, the size of which must be calculated, are air, along the surface of insulators, and through the thickness of dielectrics. The following insulation gaps are distinguished:

S1 – air gaps between busbars of different phases;

S2 – air gaps between the grounded parts of the cabinet and live parts;

S3 – the height of the bushing;

S4 – the height of the support insulator;

S5 – air gaps between the contacts of the plug-in disconnector at the control position of the withdrawable element;

d – the thickness of the insulating barriers.

The main clearances in the complete switchgear are shown in Figure 3.1.

Determination of the values of discharge voltages in accordance with the standards [26] for switchgear of 10 kV class:

a) one-minute test voltage of industrial frequency is 42 kV, including for insulators tested separately;

b) withstand voltage Up2 of industrial frequency between contacts of the same pole in open state is 53 kV.

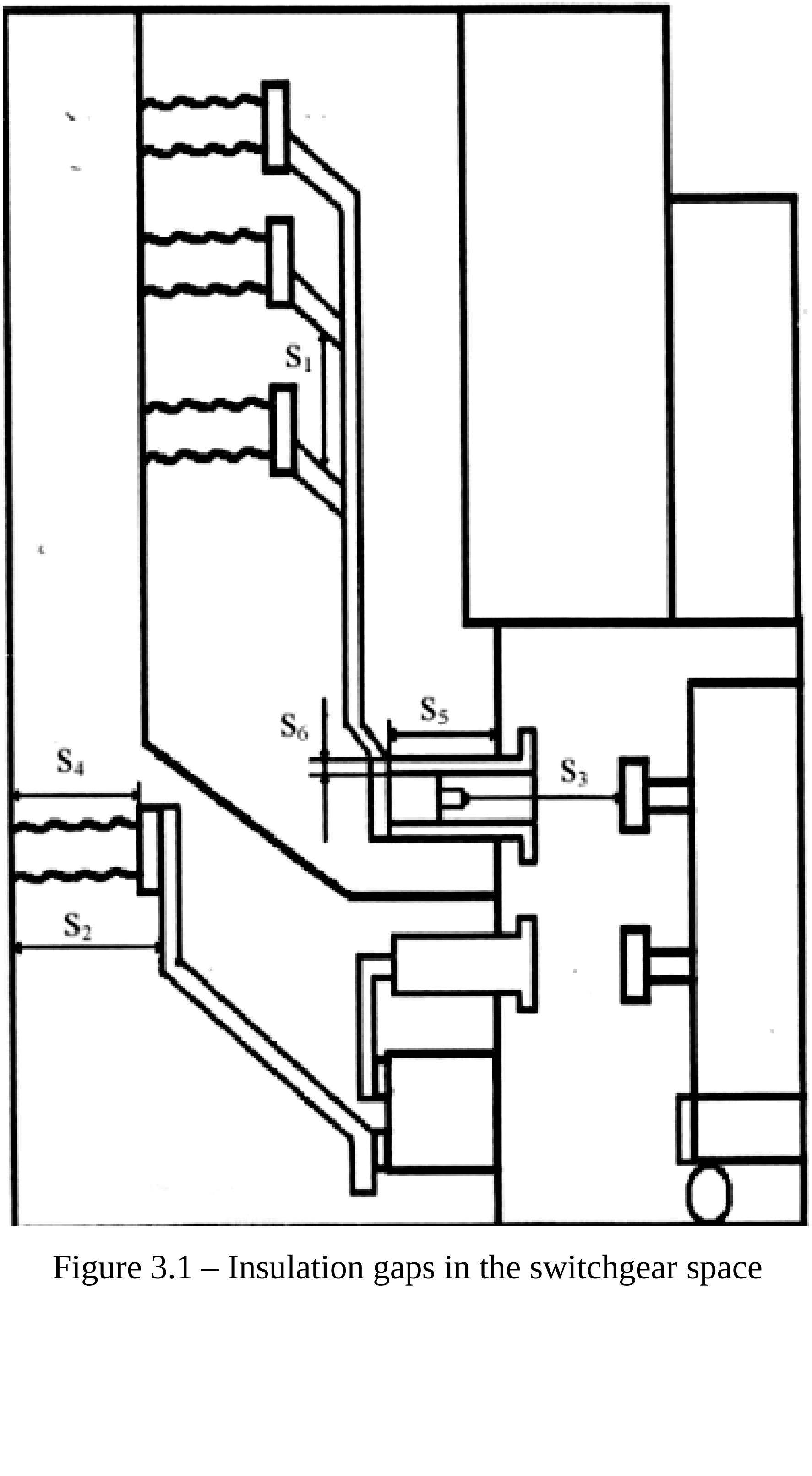

Figure 3.1 – Insulation gaps in the switchgear space

The calculated discharge voltages are determined as follows:

$$U_{d\,n} = K_s \cdot U_{test}\ , \tag{3.1}$$

where K_S – safety factor;

n – the number of the selected interval;

U_{test} – the accepted value of the test voltage.

Accordingly, to the formula (3.1), the calculated discharge voltages for the gaps are following:

a) dry discharge voltage for the gap S1:

$$U_{d1} = 1 \cdot 42 = 42\ kV$$

b) dry discharge voltage for S5:

$$U_{d5} = 1.1 \cdot 53 = 58.3\ kV$$

3.2 Calculation of clearances

3.2.1 Calculation of the clearance along the surface of the supporting insulator

The calculated discharge voltage for the supporting insulator is determined according to [26] and is assumed U_{calc} equal to 42 kV.

The active height of the supporting insulator for indoor installation h_{act} (gap S_4) for rated voltage up to 35 kV inclusive at industrial frequency voltage of 50 Hz is determined by the empirical formula:

$$h_{act} = 115 - \sqrt{13225 - 50 \cdot U_{calc}}\ , \tag{3.2}$$

$$h_{act} = 115 - \sqrt{13225 - 50 \cdot 42} = 9.52\ cm$$

For the full lightning impulse test voltage:

$$U_{calc\ lt} = 1.1 \cdot 75 = 83\ kV$$

The active height of the support insulator for the full lightning impulse test voltage is calculated by the formula:

$$h_{act} = 26.1 - \sqrt{718 - 5 \cdot U_{calc\ th}}\ , \qquad (3.3)$$

$$h_{act} = 26.1 - \sqrt{718 - 5 \cdot 83} = 9\ cm$$

The greater of the values obtained from expressions (3.2) and (3.3) is taken as the active height of the insulator.

$$h_{act} = 9.52\ cm$$

The length of the leak distance along the surface of a solid dielectric is determined, taking into account the mode of operation of the neutral. According to [32], for reinforced insulation of category B, the specific leak distance l_{leak} on external insulation for networks with isolated neutral is taken at least 0.03 m/kV.

Then the length of the leak distance is determined by the formula:

$$l_{leak} = l_{sp} \cdot U_{r\ c}\ , \qquad (3.4)$$

$$l_{leak} = 0.03 \cdot 10 = 0.3\ m$$

Taking into account the peculiarities of operation and recommendations [33], the following value of the leak distance is selected l_{leak} = 0.3 m.

Indoor insulators are provided with ribs on the outer surface. The recommended [26] number of ribs is selected based on the rated voltage class and, in particular, for a 10 kV voltage class, no more than one is recommended. With increased environmental pollution, the number of ribs can be increased to four.

According to the voltage class and height, it is selected a support insulator of the type ИОР-10-3.75, 12 cm high and the number of ribs equal to 4.

Figure 3.2 – Appearance of support insulator of ИОР-10-3.75 type [15]

Let's check the selected support insulator for its permissible load. In this case, the following condition must be met:

$$F_{calc} \leq 0.6 \cdot F_d \ , \tag{3.5}$$

where F_{calc} – force acting on the insulator,

F_d – breaking load on bending for insulator ИОР-10-3.75, equal to 3750 N.

With a horizontal arrangement of insulators of all phases, the design force, N:

$$F_{calc} = \sqrt{3} \cdot \frac{i_{st}^2}{a} \cdot l \cdot k_h \cdot 10^{-7} \ , \tag{3.6}$$

where i_{st} – shock current of three-phase short circuit equal to 51000A;

l – the distance between insulators along the busbars, equal to 0.75;

a – the distance between the axles of the busbars of adjacent phases, equal to 0.25 m;

k_h – a correction factor for the busbar height equal to 1.

$$F_{calc} = 1.73 \cdot \frac{51000^2 \cdot 0.75}{0.25} \cdot 1 \cdot 10^{-7} = 1368.28\ N$$

Substitute the obtained values into (3.5):

$$1373.28\ N \leq 2250\ N$$

Thus, the conditions for mechanical strength are met. The insulator is correctly selected.

3.2.2 Choice of bushing insulator

The calculated discharge voltage for the bushing is determined according to [30] and is assumed U_{calc} equal to 42 kV.

The active height of the insulator at industrial frequency voltage is determined by the empirical formula according to [31]:

$$S_3 = 0.285 \cdot U_{calc} - 2.85\ , \tag{3.7}$$

$$S_3 = 0.285 \cdot 46.2 - 2.85 = 10.32\ cm$$

Bushings are selected according to voltage, rated current and permissible load. Accordingly, the following conditions must be met:

$$U_{set} \leq U_r \,, \qquad I_{max} \leq I_r \,, \qquad F_{calc} \leq F_{perm} \,, \tag{3.8}$$

where F_{perm} – the permissible load on the insulator is determined by the formula (3.5);

F_{calc} – design force is determined by the formula (3.9).

According to the voltage class and rated current, the ИПК-10-1600-5 УЗ bushing insulator is selected.

Figure 3.3 – Appearance of bushing insulator of ИПК-10-1600-5 type [15]

Design force is determined by the formula:

$$F_{calc} = 0.5 \cdot \sqrt{3} \cdot \frac{i_{st}^2}{a} \cdot l \cdot 10^{-7} \,, \tag{3.9}$$

$$F_{calc} = 0.5 \cdot 1.73 \cdot \frac{51000^2 \cdot 0.75}{0.25} \cdot 10^{-7} = 648 \, N$$

$$F_{perm} = 0.6 \cdot 5000 = 3000 \, N$$

Substitute the obtained values into (3.5):

$$684 \, N \leq 3000 \, N$$

Thus, conditions (3.5) are satisfied. Therefore, the insulator is correctly selected.

3.2.3 Determination of the distance between taps from the busbars

The "needle – grounded needle" electrode system is taken as the calculated model of the gap. The dry discharge voltage for the air gap S_2 is determined by the formula

$$U_{d\,2} = 1.1 \cdot 42 = 46.2\ kV$$

According to the empirical formulas given in [25], the size of the air gap S_2 is determined:

$$S_2 = 0.285 \cdot U_{calc} - 2.85\,, \quad (3.10)$$

$$S_2 = 0.285 \cdot 46.2 - 2.85 = 10.32\ cm$$

3.2.4 Calculation of the clearance between the contacts of the plug-in disconnector

When calculating, the movable and fixed contacts of the plug-in disconnector are considered as a "needle – grounded plane" electrode system. Dry discharge voltage U_{dry} for S_5 gap is 58.3 kV.

From the empirical formulas given in [25], the size of the air gap S_5 is determined:

$$S_5 = 0.27 \cdot U_{dry} - 2.7\,, \quad (3.11)$$

$$S_5 = 0.27 \cdot 58.3 - 2.7 = 13.01\ cm$$

3.2.5 Calculation of the thickness of the insulation barriers

The busbar compartment must be separated from other compartments by partitions. The thickness of the insulation barriers is determined as follows:

$$d \geq \frac{U_{br}}{E_{br}}, \tag{3.12}$$

where U_{br} – breakdown voltage equal to 46.2 kV;

E_{br} – dielectric dielectric strength for getinax equal to $12 \cdot 10^6\ \frac{V}{m}$.

$$d \geq \frac{46.2 \cdot 10^3}{12 \cdot 10^6} \geq 4 \cdot 10^{-3}\ m$$

The thickness of the insulating barriers is structurally assumed to be $6 \cdot 10^{-3}$ m.

4 SELECTION OF MAIN CIRCUITS APPARATUS

When developing and manufacturing a complete switchgear, various electrical devices are used as its component parts. Reliable operation of the switchgear cubicle can only be ensured if each accessory device is correctly selected both under the conditions of normal operation, and under the conditions of operation during short circuits and in overload mode.

In addition, when choosing equipment, it is necessary to take into account the operating conditions of the switchgear cabinet, depending on its purpose [14, 24, 28].

4.1 Selection of the circuit-breaker

To select the preferred type of circuit breaker there will be considered three types of circuit breakers – oil, SF6 gas and vacuum:

a) oil circuit breakers require oil maintenance, are explosion and fire hazard. Low-oil circuit breakers have a significantly lower oil volume than tank circuit breakers, but they have another disadvantage: the number of operations is limited, since with frequent shutdowns, a small amount of oil is quickly contaminated by carbon particles formed during the arc burning.

b) SF6 gas circuit breakers. The most effective use is the arc suppression ability of SF6 gas in the case when a gas jet at a high speed washes the burning arc; therefore, mechanisms for holding SF6 gas under pressure are required.

The disadvantage of SF6 gas is the high liquefaction temperature. So, for example, at a pressure of 1.31 MPa, it changes from a gaseous state to a liquid at a temperature of 0 °C. This forces either resort to heating devices or use gas at low pressure. At a pressure of 0.35 MPa, the liquefaction temperature is 40 °C. To obtain good results, a gas of high purity (without impurities) is required. This complicates and increases the cost of gas production.

c) in vacuum circuit breakers, the contacts diverge in air with a pressure of 10^{-4} Pa. The dielectric strength of a gap of 1 mm in vacuum at a pressure of 10^{-4} Pa reaches 100 kV.

The low density of the gas in the flask leads to a very high rate of charge diffusion due to the large difference in particle densities in the discharge and vacuum. Fast diffusion of particles, high dielectric strength of the vacuum allows vacuum circuit breaker to effectively extinguish the arc.

A great advantage of vacuum switches is the rapid increase in the dielectric strength of the gap after the current passes through zero. Therefore, vacuum circuit breakers are beginning to be widely used for disconnecting capacitor banks.

The contact system of the vacuum circuit-breaker works in harsh conditions. The presence of a vacuum surrounding the contacts impairs the cooling that occurs, mainly due to the thermal conductivity of the contact body and radiation.

Existing experience in the operation and development of vacuum switching devices suggests that the main advantage of vacuum circuit breakers is the large number of permissible operations.

Based on the above information a circuit breaker of vacuum type is selected.

The circuit breakers are selected according to their rated current and voltage, by the type and kind of installation, according to their technical and economic indicators, and are tested for their dynamic and thermal resistance to breaking capacity in short-circuit mode. When choosing a circuit breaker based on breaking capacity, the requirement must be met that the effective value of the total current expected at the time of contact divergence does not exceed the breaking current set by the manufacturer (for a given voltage) [16].

Table 4.1 shows the characteristics of the vacuum circuit breakers most suitable for the designed switchgear cabinet.

BB/TEL-10 circuit breakers have a service life of at least 25 years, while they do not require preventive repairs and maintenance during operation; warranty period of operation - 5 years. Weight of this type of circuit breaker equals 55 kg [16].

Table 4.1 – Technical data of switches [3, 16, 17]

Name of the main parameters	ВВ/TEL-10 (Tavrida Electric Ukraine)	ВБЭ-10-31.5/2000 (Electro-Contact)	ВРС-10-20/1600 У2 (RZVA)
1	2	3	4
Rated voltage, kV	10	10	10
The highest operating voltage, kV	12	12	12
Rated current, A	2000	2000	1600
Rated breaking current, kA	25	31.5	20
Critical through current, peak value,	63	51	52
Critical current of thermal stability for a period of time 3 seconds, kA	25	31.5	20
Electrodynamic stability current, kA	63	80	52
Switch-on current, kA	25	20	20
Full shutdown time, ms, no more	25	40	65
Own shutdown time, ms, no more	15	40	35-50
Industrial frequency test voltage, kV	42	42	42
Switching resource (number of "On –Off" cycles) at disconnection of current, thousand	50	50	50
Resource for mechanical resistance, thousand	30	50	30
Drive rated voltage, V	220	220	220
Service life before write-off, years	25	15	20
Weight, kg	55	150	135

ВБЭ-10 circuit breakers have a service life of at least 15 years; warranty period of operation - 5 years from the date of commissioning. Weight of such type of circuit breaker equals 150 kg [17].

BPC-10 circuit breakers are designed to operate in cabinets of indoor switchgears of the КУ10С series, manufactured by the “High-Voltage Union” Concern and switchgears from other manufacturers. Weight of this type circuit breaker is 135 kg [3].

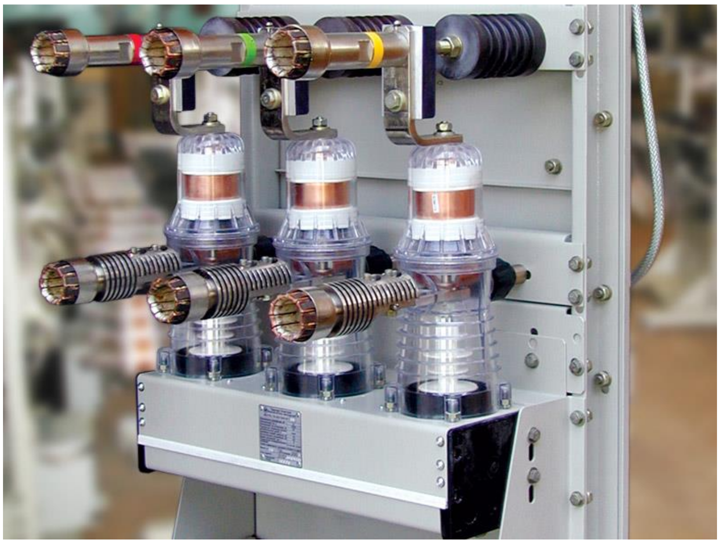

Figure 4.1 – Vacuum circuit-breaker BB/TEL series on withdrawable unit [16]

Figure 4.3 – Vacuum circuit breaker ВБЭ-10 series [17]

Figure 4.2 – Vacuum circuit breaker BPC-10 series [3]

Based on a comparison of the main parameters given in the Table 4.1 and satisfaction of technical parameters in formulas (4.1), a circuit breaker of the BB/TEL-10–25-2000 type, made by the Tavrida Electric Ukraine enterprise, is selected for installation in the designed switchgear cabinet. It is a switching device, protected by UA patent No. 102019 dated 27.05.2013, since this switch has higher performance parameters.

$$Ir \geq Iop, \qquad Ur \geq Umax = 1.15 \cdot Ur,$$
$$Id.st \geq ish, \qquad Ith.st \geq Ith \tag{4.1}$$

where Ir – rated current of circuit breaker, A;

Iop – operating current of switchgear installation, A;

Ur – rated voltage of circuit breaker, V;

Umax – maximum operating voltage of switchgear installation, V;

Id.st – dynamic stability current, kA;

ish – value of shock current at short circuit, kA

Ith.st – thermal stability current, kA;

Ith – thermal resistance current equal to 20 kA.

$$2000\ A \geq 1600\ A, \qquad 12\ kV \geq 1.15 \cdot 10 = 11.5\ kV,$$
$$53\ kA \geq 51\ kA, \qquad 25\ kA \geq 20\ kA$$

The selected BB/TEL circuit breaker is intended for operation in areas with a temperate and cold climate for operation in rooms with free access to outside air at a nominal value of climatic factors and operating parameters:

a) height above sea level up to 1000 m;

b) ambient temperature, 0 C from + 40 to (- 50);

c) relative air humidity: 98% at 25 °C (upper value); 80% at 150 °C (average annual value);

d) the environment is not explosive, does not contain conductive dust in concentrations that reduce the parameters of the circuit breaker.

The control principle of the BB/TEL circuit breaker is based on the use of phase-by-phase electromagnetic drives with a "magnetic latch", mechanically connected by a common shaft. This design of the circuit breaker made it possible to achieve the following relative features of the apparatus in comparison with traditional vacuum circuit breakers (VB):

a) high mechanical life;

b) small power requirements for on and off circuits;

c) small dimensions and weight;

d) the ability to control both the operational direct current and operational alternating current circuits;

e) no need for repairs during the entire service life;

f) low labor intensity of production and reasonable price.

The use of a BB/TEL switch is advisable. Its use significantly reduces the weight and dimensions of the switchgear cabinet, significantly reduces its cost and improves such indicators as reliability, service life, etc. [16].

4.2 Selection of current transformers

The use of cast epoxy insulation can greatly simplify the design and production technology.

The main advantages of dry-type cast resin transformers:

a) environmental Safety. The absence of oil in a dry transformer eliminates the threat of environmental pollution from oil leaks. In case of fire, no toxic or corrosive gases are emitted. Thus, the threat of environmental pollution is excluded.

b) operational safety. The windings of dry transformers are not flammable and cannot become sources of fire; And in the event of a fire from an external source, the resin will not support combustion and will provide a fire-fighting effect.

c)- no additional fire safety measures are required in the places where the dry transformer is installed.

d) small overall dimensions, which makes it possible to install a dry transformer of higher power in the existing transformer compartment, for example, during the reconstruction of a substation.

e) resistant to moisture and moisture.

f) minimum operating costs as there is no need for periodic inspection and replacement of the dielectric fluid.

g) high reliability of the equipment.

h) dry-type transformers are more compact, convenient and easy to operate.

j) low noise and vibration.

Selection of current transformers consists in choosing the type, compiling the expected and rated load and checking for thermal and dynamic resistance. The type of current transformer is determined by the nominal voltage of the installation, the rated operational current of the connection, the requirement for measurement accuracy and the type of installation. These requirements are described in formulas below (4.2):

$$Ir \geq Iop, \qquad Uop \geq Umax = 1.15 \cdot Ur$$
$$Id.st \geq ish, \qquad Ith.st \geq Ith \tag{4.2}$$

where Ir – rated current of circuit breaker, A;

Iop – operating current of switchgear installation, A;

Ur – rated voltage of circuit breaker, V;

Umax – maximum operating voltage of switchgear installation, V;

Id.st – dynamic stability current, kA;

ish – value of shock current at short circuit, kA

Ith.st – thermal stability current, kA;

Ith – thermal resistance current equal to 20 kA.

$$2000\ A \geq 1600\ A, \qquad 12\ kV \geq 1.15 \cdot 10 = 11.5$$
$$102\ kA \geq 51\ kA, \qquad 31.5\ kA \geq 20\ kA$$

Three current transformers of the ТЛШ-10 type were selected for installation in the designed switchgear cabinet. Their characteristics are summarized in Table 4.2.

This current transformer is intended for connection of the protection cabinet and measuring instruments, has increased resistance to the action of short-circuit currents and is consistent with the technical characteristics of the main circuits of the switchgear [23, 25].

Advantages of current transformer type ТЛШ-10 type:

a) complete sealing of windings and high moisture resistance;

b) low damageability of the insulation surface during installation and storage;

c) less labor intensity of manufacturing;

d) reduction of dimensions and weight of the product.

Figure 4.2 – Current transformer ТЛШ-10 [18]

Table 4.2 – Characteristic of current transformer ТЛШ-10 type [18]

Main parameter name	Value
Rated voltage, kV	10
The highest operating voltage, kV	12
Rated primary current, A	2000
Rated secondary current, A	5
Number of secondary windings, pcs.	4
Secondary accuracy class	0,5; 10P
Rated secondary load at measuring winding, VA	20
Rated secondary load with protective winding, VA	30
Thermal three-second durability, kA	31,5
Dynamic resistance, kA	102
Rated frequency, Hz	50
Weight, kg	26

4.3 Selection of relay cabinet hardware

Currently, approximately 80% of 6 (10) kV switchgear units are manufactured with microprocessor devices, and the production of medium voltage switchgear units with electromechanical relays is decreasing every year [14].

The advantages of microprocessor terminals for equipment protection are their multifunctionality, compactness and measurement accuracy.

Also, the advantage of microprocessor technology is that the presence of various communication interfaces allows the devices to be integrated into the ACS system, which makes it possible to have operational information about the state of various circuit elements, control switches, configure relay protection, receive data on an emergency, oscillograph, etc. The possibility of fixing the current values of the monitored currents and voltages allows for a clearer analysis of emergency situations.

The disadvantage of microprocessor devices is their high cost. In addition, significant expenses of the enterprise are allocated for the maintenance of microprocessor devices: it is necessary to have expensive equipment, software, as well as specialists with appropriate qualifications.

To select microprocessor protection, the following models are considered: SEPAM S40 - Schneider Electric, SIPROTEC 7SJ642 - Siemens, MRZS 05 - Kyivprylad.

Based on the aforementioned properties of microprocessor-based protections, it was decided to choose a microprocessor-based protection of the domestic model MRZS-05 Kyivprylad because of the relentless reliability and low cost compared to foreign counterparts (price / quality ratio), the proximity of the service and the personnel training center, and the simplicity of programming the device.

A relay protection and automation device based on MRZS-05 RSGI.466452.007 of the Kyivprylad production association is selected as a relay protection and automation device.

Figure 4.3 – Appearance of MRZS-05 [14]

The main functions of the MRZS-05 relay protection and automation device:

a) providing control and measurement of the following quantities:

1) line voltages of alternating current with a nominal value of Uн = 100 V with a frequency of 50 Hz;

2) phase currents with a frequency of 50 Hz with a nominal value of In = 5 A in the range from 0.05 to 30 In;

3) zero sequence current from 0.05 to 2 A;

4) frequency in the network in the range from 45 to 51 Hz;

5) active and reactive power.

b) relay protection functions:

1) three-stage maximum current protection (MCP) against phase-to-phase short circuits. MCP can be of three versions, at choice: three-stage MCP with a time delay independent of the current; three-stage overcurrent protection, where the first and third stages have a current-independent time delay, and the second – a current-dependent time delay and has two options for the ampere second characteristic of the dependent stage; three-stage overcurrent protection with the possibility of blocking each stage by voltage;

2) protection against earth faults on zero sequence current non-directional, reacting to zero sequence current, operates with or without delay for tripping or signal and has two stages;

3) overvoltage protection operates with a trip or signal delay. Ability to monitor voltages in three phases independently. The coefficient of return of starting elements of protection stages is not less than 0.95 and not more than 0.98. Triggers of voltage phases can be combined according to the "AND" or "OR" logic;

4) two-stage undervoltage protection with or without current monitoring operates with a trip or signal delay. Ability to monitor the voltage in all three phases, the return ratio is from 1.01 to 1.05. It is possible to disable the protection blocking at the level of 0.25 V. The starting elements of the voltage phases can be combined according to the "AND" or "OR" logic;

5) circuit breaker failure backup device (CBFB). The CBFB is started when the overcurrent protection tripping is triggered or through a discrete input. CBFB has two stages in response time.

c) automation functions:

1) switching on and off the switch. The switch is switched on and off both from the MRZS and through a discrete input (impulse). If there is a command to open the circuit breaker, the closing signal is blocked;

2) automatic acceleration of MCP when the switch is turned on. Acceleration is entered by the command to close the circuit breaker for the second or third stage of the overcurrent protection;

3) two or one-time automatic reclosing (AR). Automatic reclosing is started from MCP or external devices;

4) automatic frequency unloading (AFU), acts on shutdown and signaling when the frequency drops from 50 to 45 Hz.

d) emergency waveform recorder of currents and voltages

1) parameterizable recording duration;

2) total duration – 15 s.

e) registrar of discrete signals: 50 last alarms; up to 50 records in each accident.

Number of inputs, outputs:

a) discrete outputs (relays) in total – 7; programmable – 6;

b) discrete inputs – 8;

c) only 7 LEDs; programmable – 6;

d) defined functions – 16;

e) defined triggers – 3;

f) inertial functions – 3.

Configuration of inputs, outputs, indicators, time delays, recorders is performed using the "Sizif v4" free service software, which has the ability to record archives from a file, logging and ranging [14].

5 OCCUPATIONAL SAFETY

Since the theme of the thesis "10 kV, 1600 A distribution switchgear panel" involves calculations (works, research) in a premise (laboratory) equipped with personal computers with visual display terminals, so below we will consider measures to ensure safety, industrial sanitation, occupational health and safety. security for the premises (laboratories) equipped with personal computers, in accordance with the guidelines.

The work of a personal computer user is performed in a monotonous position in conditions of limitation of general muscular activity with mobility of the hands, high stress of visual functions and neuro-emotional stress under the influence of various physical factors: electrostatic field; electromagnetic radiation in the over low-frequency, low-frequency and medium-frequency ranges (5 Hz - 400 kHz); X-ray, ultraviolet, infrared radiation, visible radiation, acoustic noise; unsatisfactory level of illumination, unsatisfactory meteorological conditions [35].

It is established that the state of the body of PC users on subjective (complaint) and objective indicators (functional state of the body) depends on the type of work and conditions of its implementation. All PC users can be divided into users who work on a PC in accordance with their professional responsibilities, periodically (for example, students).

Intensive work on the PC is the cause of many diseases. The cause of deviations in the user's health are unsatisfactory ergonomic characteristics of the monitor, improper organization of the workplace, unsatisfactory sanitary and hygienic working conditions, which lead to a number of diseases: visual impairment; musculoskeletal disorders; skin diseases; disorders associated with stressful situations and nervous and emotional stress [35].

It is necessary to proceed from the fact that any PC is an electrical installation with a supply voltage of up to 1000 V and it and everything related to its operation are fully covered by the requirements of electrical safety. Therefore, in order to ensure the safety of both users and service personnel of the PC, when equipping laboratory equipped with visual display terminals of electronic computers, the requirements of electrical safety were applied in accordance with the " Rules for Arrangement of Electrical Installations " (ПУЕ) [36] and Normative Legal Act On Occupational Safety НПАОП 40.1-1.01-97 “Rules of safe operation of electrical installations” [37].

Based on the analysis of the existing equipment and technological processes in the room (laboratory) equipped with personal computers with visual display terminals, according to State Standard ГОСТ 12.0.003-74 “Occupational safety standards system. Dangerous and harmful production effects. Classification” [35], the following dangerous and harmful production factors that can lead to injury or damage to the health of workers were identified [35, 38]:

a) Visual impairment.

Irrational lighting, lighting specifics of workplaces with a PC and non-compliance with the mode of operation can lead to visual impairment.

Lighting specificity is due to the lighting diversity of objects of visual work of the PC user: screen, documentation and keyboard, located in different areas of observation, which requires multiple movement of the line of sight from one to another. The working documentation is most often placed on the table in a horizontal plane at a distance of the optimal line of sight (approximately 350 mm), the objects of distinction have a negative contrast - dark objects on a light background. Objects on the keyboard are larger and located in an inclined plane. Bright signs on a dark background of an almost vertically oriented screen are located at a distance of 450-600 mm, which requires an unusual horizontal orientation of the line of sight. This is unconsciously associated with looking into the distance when the muscular mechanisms of the eye are relaxed, although for qualitative discrimination of signs they must work hard to ensure high visual acuity. There is a constant readjustment from bright objects with positive contrast to dark with negative contrast. During the eight-hour working day on the monitor, the user gives approximately 30,000 views to the screen, the eye works with overload and cannot sufficiently adapt to this situation. Such features lead to tension of the muscular and light-perceiving apparatus of the eyes, which is one of the causes of asthenopic phenomena (tearing in the eyes, pain in the eyes, breaking in the superciliary area, blurred contours, blurred images).

Constant looking at the frosted glass of the monitor screen reduces the frequency of blinking, which leads to drying and curvature of the cornea, impairs vision (Sikka syndrome).

The user's work on the pulsating self-luminous screen of the monitor, which does not meet the regulatory requirements for limiting the pulsation (flicker), causes discomfort and fatigue (general and visual).

Working with the mirror reflective and non-flat outer surface of the monitor screen, on which numerous reflected glare appears, leads to the occurrence of asthenopic phenomena and functional changes in the eye.

In the workplace, the brightness in the field of view is often unfavorably distributed, as the illuminated surfaces of the periphery (ceiling, walls, furniture, etc.) are brighter than the center of the field of view - dark, dimly lit and sometimes poorly filled with monitor screen. This distribution of brightness in the field of view leads to a violation of the basic visual functions of the eye.

The dazzling effect of luminaires indoors, in the workplace with a PC is greater than in others, because the user's line of sight when working with the screen is almost horizontal, which reduces the protective angle of various blinding sources (luminaires, windows, etc.). This causes not only asthenopic phenomena, but also functional disorders of the user's eyes.

Color font increases the load on vision, because the components of colors have different wavelengths and are visible at different distances. The eye needs more precise adaptation than with a black and white image.

b) Musculoskeletal disorders.

Prolonged static tension of the muscles of the back, neck, arms and legs, which leads to fatigue and specific complaints. Spinal injuries are the result of insufficient ergonomics of the user's workplace, i.e. the chair incorrectly supports the flexion of the spine. The shoulders and neck become tense and swollen due to the unnatural position and there is pain in the neck, back and head.

Improper position of the hands when entering data using the keyboard (wrist when dialing up) leads to compression of the nerves in the narrow places of the wrist (Carpal tunnel).

Repetitive strain injury syndrome (chronic strain) is an injury that occurs as a result of constant tension in the muscles of the hands as a result of improperly equipped in terms of ergonomics of the workplace when using a PC. This chronic disease can develop unnoticed for several years. Such overloads lead to overstrain of all muscular system of the person.

The most dangerous is that due to the concentration of attention on the monitor screen dulls the timely warning of pain, which is an alarm signal to the body. Diseases of the hands and hands are observed in PC workers 7-12 times more often than in others, and are often misdiagnosed as tendonitis.

c) Disorders associated with stressful situations and nervous and emotional stress.

PC work is a job with a particularly noticeable monotony: more than 600 identical actions during 75% of working time in 1 hour. Monotony of work, non-ergonomic workplace, electromagnetic radiation lead to diseases of general neurotic nature in the form of increased general fatigue, headache, a feeling of heaviness of the head, poor sleep. Persistent neuropsychiatric disorders in the form of increased irritability, anxiety, restlessness (excited type), depression, general stiffness at work, decreased reaction rate (brake type), probably caused by electromagnetic waves emitted by the PC and monitor. The effect of ultra-low and low frequency electromagnetic radiation on the human body has not been studied enough, and research in this direction continues, but the effect of electromagnetic fields of these frequencies on biological objects, especially the brain, is already known - it can cause tumors.

d) Skin diseases.

The operation of a PC user near an electrified monitor screen, which attracts airborne dust particles and charges them, leads to skin irritation in people with sensitive skin, rashes and skin inflammation.

e) Poisoning of the body.

It is necessary to note such harmful factors of influence on the user, as poisons from material of the case and boards of the personal computer and the monitor (dioxins and furan) and release of ozone when working with the laser printer.

Dioxins and furans are odorless and carcinogenic gases that belong to the fire-fighting materials required for monitor and board enclosures. These poisons are formed during combustion, but there is evidence that these harmful substances are present in the atmosphere and at normal operating temperatures in small quantities.

Ozone is formed due to the influence of electric charges that occur in laser printers on the oxygen in the air. And although new laser printers filter ozone, there is a problem because over time the filter breaks down and needs to be replaced in a timely manner. Ozone severely irritates the mucous membranes of the nose, eyes and throat and can lead to cancer as a carcinogen.

5.1 Occupational safety measures

The laboratory under consideration is a room of 12 sq. m, located on the second floor. It has two windows on the opposite side of the entrance.

Equipment and organization of workplaces of PC users is provided in accordance with State Sanitary Rules and Regulations DSANPIN 3.3.2.007-98 "State sanitary rules and regulations for work with visual display terminals of electronic computers" [38].

Thus, floor covering is matte with a reflection coefficient of 0.3 – 0.5. The floor surface is smooth, non-slip, with antistatic properties. Diffuse-reflective materials with reflection coefficients for the ceiling 0.7 – 0.8 were used for the interior decoration of the laboratory; for walls 0,5 – 0,6.

The laboratory is equipped with:

a) 20 PCs with a total electrical power of 4.5 kW/h;
b) 20 monitor displays with a total electrical power up to 1.2 kW/h;
c) two inkjet printers with a total electrical power 0.05 kW/h during operation;

A different number of PCs and monitors are used to conduct a lesson using computer programs, and a projector is also used for these purposes. Printers are used to print university documents.

The laboratory equipped with the PCs represents the electric installation with a voltage of 220 V. Such electric installations are connected to the general grounding system. According to the “Rules for Arrangement of Electrical Installations” (ПУЕ) [36], the resistance of the grounding device of the electrical installation with a voltage of 220 V at any time of the year does not exceed 8 Ohms. The power cables of such an electrical installation was additionally calculated for peak load modes.

The monitor is a very important part of a computer system. It depends on the comfort, convenience and productivity of working on a computer, however, working on a "bad" monitor can have a negative impact on health.

EU Directive 90/270 EEC – display screen equipment [39] in the section "Minimum health and safety requirements" strictly regulates the safe working conditions and health protection requirements for people working with computers, making the following five requirements for working with the monitor:

a) the characters on the screen are clear and well distinguished;
b) the image is free of flicker;
c) brightness and / or contrast is easy to adjust;
d) screens are free from glare and reflection;
e) radiation is reduced to extremely low levels.

The monitors are positioned so that the top of the screen is at eye level. The screens of the PC monitors are located at the optimal distance from the user's eyes, which is 600-700 mm, but not closer than 600 mm, taking into account the size of alphanumeric characters and symbols.

Technical characteristics of monitors (screen size, resolution, image grain, values of vertical and horizontal scan frequencies, video bandwidth, controllability, microprocessor control, dynamic focusing, presence of invar mask and demagnetization, anti-glare coating, protection against electrostatic and electrostatic, power management system), if they are not taken into account when choosing a monitor or incorrectly installed, can adversely affect vision and health in general.

The main element of any monitor is a cathode ray tube (CRT). The principle of its operation is the same. The electron beam generated by the electron gun (cathode) hits the screen covered with a phosphor and causes it to glow. The modulator regulates the intensity of the beam, and hence the brightness of the phosphor. The deflection system scans the beam on the surface of the screen, that is, its movement in a zigzag trajectory from the upper left corner of the screen to the lower right and return to the starting position with a special reverse signal. In the process of scanning, the beam sequentially excites discrete phosphor points, called pixels (pixel - picture element), and forms closely spaced rows. The color monitor has three electronic guns with separate control circuits, and on the surface of the screen are applied phosphor elements of three types, giving the luminescence of red, green and blue spectral range. Each electron beam excites a phosphor of "its" color.

Optimal values of microclimate parameters have been provided in premises at permanent workplaces with computer equipment: temperature, relative humidity and wind speed, in accordance with the requirements of State Sanitary Norms ДСН 3.3.6.042-99 "Sanitary norms of microclimate of industrial premises" [40] and State Standard ГОСТ 12.1.005-88 "Occupational safety standards system. General sanitary requirements for working zone air" [41].

The levels of positive and negative ions in the air of rooms with computer equipment comply with sanitary and hygienic standards Sanitary and Hygienic Norms ГН 2152-80 "Sanitary and hygienic standards of permissible levels of air ionization of industrial and public premises" [42].

Considered laboratory premise with computer equipment has natural and artificial lighting. Fluorescent lamps are used as artificial light sources and incandescent lamps in local lighting fixtures.

Used lighting system meets the following requirements:

a) lighting in the workplace corresponds to the nature of visual work, which is determined by three parameters:
   1) object of distinction - the smallest size of the object considered on the monitor of the personal computer (PC) and workstation (PC);
   2) background, which is characterized by the reflection coefficient;
   3) contrast of object and background;

b) a sufficiently uniform distribution of brightness on the working surface of the monitor, as well as within the surrounding space is ensured;

Natural lighting in the laboratory with computer equipment meets the requirements of State construction regulations of Ukraine B.2.5-28:2018 "Engineering equipment of buildings and constructions. Natural and artificial lighting" [43]. Natural lighting carried out through light slots, oriented mainly to the north or northeast and provide a coefficient of natural light not less than 1.5%. To protect against direct sunlight, which creates direct and reflected glare on the surface of screens and keyboards, sun protection devices have been provided, and windows have blinds or curtains.

Artificial lighting in premises with workplaces equipped with PCs have been carried out by a system of general uniform lighting using ceiling linear fluorescent lamps of length 600 mm. In industrial and administrative-public premises, in case of predominant work with documents, the use of a combined lighting system is allowed (in addition to the general lighting system, local lighting fixtures are additionally installed).

The value of illumination on the surface of the desktop in the area of documents is 300-500 lux. If these illuminance values cannot be provided by a general lighting system, local table lighting with led lamps is used. In this case, the local lighting fixtures are installed in such a way as not to create glare on the screen surface, and the brightness of the screen do not exceed 300 lux.

When performing work with a PC, the values of the characteristics of noise and vibration in the workplace do not exceed the permissible in accordance with State Sanitary Rules and Regulations DSANPIN 3.3.2.007-98 “State sanitary rules and regulations for working with visual display terminals of electronic computers” [38], State Sanitary Norms ДСН 3.3.6-039-99 “State sanitary norms of industrial general and local vibration” [44] and ДСН 3.3.6.037-99 “Sanitary standards of production noise, ultrasound and infrasound” [45].

Sources of noise when working with a PC are:

a) hard drive;

b) fan of the power supply unit of the network;

c) fan located on the processor;

d) high-speed CD-ROM;

e) mechanical scanners;

f) mobile mechanical parts of the printer.

During the operation of dot matrix needle printers, noise occurs when moving the print head and in the process of hitting the needle heads on the paper. During the operation of the ventilation system of the PC, which provides the optimal temperature of the electronic units, aerodynamic noise is created. In addition, there are other external sources of noise not related to the operation of the PC. Noise generated by working PCs is broadband, constant with aperiodic amplification during printer operation. Therefore, the noise estimated by the total sound pressure level by frequency adjustment "A" and does not exceed 60 dBA.

Reducing the noise level in the premise was done as follows:

a) using PC power supplies with fans on rubber suspensions;

b) the use of PCs in which temperature sensors are mounted in the power supply and at critical points of the motherboard (processor, chipset chips), which allow you to programmatically adjust both the moments of turning on the fans and their speed;

c) put the hard drive into Standby mode if the computer does not run for a specified period of time. This time is set in the voltage management options on Windows operating systems. If you do not need it in Standby mode, you can disable it in the motherboard BIOS;

d) using PCs in which the fan on the processor is installed by the manufacturer (VOC processor);

e) the use of motherboards in the format of ATX cases, which allows you to adjust the autonomous speed and time of unlocking the fan of the power supply from the mains;

f) use 24-38x high-speed CD-ROMs for devices that make less noise than 48-50x high-speed CD-ROMs, or use a drive that reads multiple tracks of CDs or software at the same time to reduce speed.

g) replacement of dot matrix printers with inkjet and laser printers, which provide a much lower sound pressure level during operation;

h) the use of shared printers located at a considerable distance from most workstations of PC users;

j) reduction of noise on the way of its distribution through placement of a sound-proof fence in the form of walls, partitions, cabins;

k) acoustic treatment of premises - reduction of energy of reflected sound waves by increasing the area of sound absorption (placement on the surfaces of the room of sound-absorbing cladding, location in the premises of artificial sound absorbers).

Requirements to the modes of work and rest of PC users are determined by the work performed by the user in accordance with the requirements of State Sanitary Rules and Regulations DSANPIN 3.3.2.007-98 "State sanitary rules and regulations for work with visual display terminals of electronic computers" [38]. In all cases where circumstances do not allow the use of regulated breaks, the duration of continuous work with the PC should not exceed 4 hours. Adjustable breaks should be set regardless of the nature of the work - every hour for 15 minutes.

In order to reduce the negative impact of monotony it is advised to alternate some operations, such as entering text using the keyboard and editing text, and so on. To reduce nervous and emotional tension, fatigue of the visual analyzer, improve cerebral circulation, overcome the adverse effects of hypodynamics, prevent fatigue, it is advisable to use some breaks to perform a set of exercises.

5.2 Fire safety measures

The premises of the laboratory are equipped with computer cases, monitors, keyboards, computer mice, in the design of which there is a lot of plastic.

According to Fire Safety Regulations НАПБ В.03.002-2007 "Standards for determining the categories of premises, buildings and outdoor installations for explosion and fire safety", part of the description of В category - fire hazardous premise:

"Flammable gases, flammable and hardly flammable liquids, and also substances and / or materials that are capable of exploding and burning or only burning during contact with water, oxygen and / or each other; …"

Based on the description of В category, and based on the fact that PC circuits may cause a fire in contact with water, we can conclude that the laboratory premise belongs to В category.

The degree of fire resistance of the premise is set depending on its purpose, the category of explosion and fire hazard, height (storey), floor area within the fire compartment.

According to the category of production on fire danger and requirements of State Building Codes ДБН В.1.1.7-2002 "Fire safety of construction objects", the fire resistance of the room (laboratory) is the III degree.

When choosing fire detectors, the requirements of the National Standard of Ukraine ДСТУ-Н CEN/TS 54-14:2009 “Fire detection and fire alarm systems. Part 14: Guidelines for planning, design, installation, commissioning, use and maintenance” were used and these building codes:

a) the type of smoke detector meets the requirements of the standards of Ukraine EN 54-7:2019 IDT ДСТУ EN 54-7:2019 «Fire detection and fire alarm systems. Part 7: Smoke detectors. Point detectors using scattered light, transmitted light or ionization» and ДСТУ EN 54-12:2004 «Fire detection and fire alarm systems. Part 12: Smoke detectors. Line detectors using an optical light beam», taking into account the sensitivity to different types of smoke;

b) fire detectors are used in accordance with the National Standard of Ukraine ДСТУ EN 54-10:2004 “Fire detection and fire alarm systems. Part 10: Flame detectors. Point detectors”, if in the control area in case of fire at the initial stage there may be an open flame or overheated surface (usually more than 600 °C). Flame detectors can be used in controlled areas of overheated but non-emitting objects, such as drying chambers;

c) thermal fire detectors are used in accordance with National Standard of Ukraine ДСТУ EN 54-5:2019 “Fire detection and fire alarm systems. Part 5: Heat detectors. Point heat detectors”, if in the control zone in case of fire at its initial stage heat is provided, and the use of other types of detectors is impractical due to factors that lead to their malfunction;

d) when using thermal fire detectors, it is necessary to select them, taking into account the classes of detectors with the values of their normal temperature of use, maximum temperature of use; minimum and maximum static operating temperature in accordance with the requirements of the National Standard of Ukraine ДСТУ EN 54-5:2019 “Fire detection and fire alarm systems. Part 5: Heat detectors. Point heat detectors”;

e) if the dominant sign of fire detection at the initial stage is unknown in the controlled area, then in this case it is recommended to use a combination of fire detectors that respond to different signs of fire or combined fire detectors;

f) smoke alarms, which have a sound alarm in their design, may be used when there is smoke at the initial stage of the fire and controlled premises are used for short-term residence (stay) of people (hotels, hospitals, dormitories, etc.).

According to Fire Safety Regulations НАПБ В.03.001-2004 "Typical norms of fire extinguishers" for the laboratory equipped with personal computers with visual display terminals provided by primary means of fire extinguishing. Portable carbon dioxide fire extinguishers with a charge of fire extinguishing substance with weight of 3.5 kg were chosen. Minimum amount of fire extinguishers is 4 cylinders for premise with area less than 25 sq. m.

Measures for safety, industrial sanitation, occupational health and fire safety provided for the laboratory equipped with visual display terminals provide safe and comfortable working conditions for PC operators.

6 ECONOMIC GROUNDS FOR THE SWITCHGEAR PRODUCTION

The considered design of switchgear is developed on the basis of the complete switchgear like KM-1Ф on voltage of 10 kV and current of 1600 A.

The complete switchgear of the KM-1Ф type is manufactured at the "Zaporizhya High Voltage Aparatus" (ZZVA). It is one of the largest electrical engineering companies in Ukraine and well-known in many countries of the world. The company has been developing, manufacturing and supplying electrical equipment to almost all regions of the world.

The main consumers of this product are "Zaporizhstal", "Zaporizhya aluminum factory", "Mariupol" and other leading enterprises of Ukraine.

The developed design of the switchgear differs from the basic one due to the introduction of a relay protection and measurement device MRZS-05.

Microprocessor protection SEPAM, competing with the selected device, manufactured by "Schneider Electric", satisfy the customer in all technical parameters, however, they do not provide an optimal ratio of capabilities and price, which is not unimportant for domestic consumers. From this we can conclude that, from an economic point of view, the selected device is the most profitable.

Improvements in the design of the switchgear make it possible to increase the service life of the product, reduce the frequency of scheduled repairs, since the reliability of the structure increases, and the new design becomes more convenient in operation and safer in service.

To calculate the total cost of a complete switchgear type KM-1Ф for a voltage of 10 kV and a current of 1600A, it is necessary to take into account: material costs for raw materials and basic materials, purchased components, transport procurement costs, basic and additional wages of workers, expenses for social needs, expenses for the maintenance and operation of equipment, general business expenses, production costs, administrative expenses, consumption of a new product for marketing.

Table 6.1 – Technical and economic indicators of products

Indicator name	Basic product	Designed product
1	2	3
Rated voltage, kV	10	10
Rated current, A	1000	1600
Rated current of the main circuits of the switchgear cabinet, A	1000	1600
Rated breaking current of the circuit breaker built into the switchgear, kA	20	20
Thermal resistance current, kA	20	20
Rated current of electrodynamic resistance of the main circuits of the switchgear cabinet, kA	51.0	51.0
Thermal resistance current flow time, s	3	3
Planned production output, units	24	Calculated in this section

The calculation of material costs for the designed product is summarized in Table 6.2, which contains the name of the material used for the manufacture of KM-1Ф switchgear, consumption rates and cost for each unit. In this case, transport and procurement costs are taken into account, the realized income is deducted.

The calculation of the costs of packaging the product, after its assembly, for its further transportation to the place of operation, is given in Table 6.3. This table summarizes all costs of raw materials and supplies.

The calculation of purchased components, taking into account TOR and minus waste for switchgear, is given in Table 6.4.

Table 6.2 – Calculation of material costs

Material name	Norm	Price, UAH	Total, UAH
1	2	3	4
Steel corner 20·20 (small grade)	3.7	42.33	156.60
Steel corner 36·36, 63·40 (medium grade)	2.24	61.33	137.40
Plate steel Вст3сп20	5.83	79.15	461.50
Plate steel Вст3сп4-8	65.27	62.39	4 073.80
Steel sheet х/к В-5 ШН 10кп 1-3.9	82.3	43.41	3572.64
Structural plate steel Ст35ф9(calibr.)	6.1	50.30	306.83
Structural plate steel х/к 0.5-2.0	194.19	39.28	7 627.78
Aluminum busbar ШАТ	13.60	14.70	199.92
Wire ПВ-1 1.5	166.69	5.00	83.35
Wire ПВ-1 2.5	20.87	7.60	15.86
Wire ПВ-1 4.0	2.45	11.70	2.87
Wire ПВ-1 6.0	3.72	16.70	6.21
Plastic white	0.25	194.84	48.71
Lockwasher	3.15	11.6	36.54
Ordinary wire св-08-кп 1.2	3.10	45.20	140.12
Ordinary wire св-08-кп 1.6	0.76	56.70	43.10
Carbon dioxide	2.10	93.25	187.23
Spring wire 0.8	0.136	16.25	2.21
Cotter pin	0.004	4.90	0.02
Tin 01	0.079	70.00	12.23
Round copper wire ММ-8	0.076	126.62	9.62
Enamel ПФ-133 yellow	0.01	89.50	0.86
Enamel ПФ-133 green	0.018	85.90	0.14
Enamel ПФ-115 red	0.017	94.40	1.60

Continuation of Table 6.2

1	2	3	4
Enamel ПФ-115 black	0.001	75.30	0.07
Primer ФЛ-03к	0.018	51.48	0.92
Primer ГФ-021	0.24	56.37	13.52
Putty ЭП-0010	0.02	68.80	1.37
Xylene	0.303	14.60	4.42
Tsiatim grease	0.22	18.48	4.07
Solvent white-spirit	1.296	65.3	84.63
Glue БФ-4	0.05	47.50	2.37
Paper ДБ waterproof	0.056	12.50	0.7
Gauze	0.111	7.00	0.77
Napkins	0.997	4.25	4.24
Rags	0.444	4.50	1.98
Detergent ПТС-5	0.002	6.30	0.01
Knitted gloves	0.011	4.25	0.05
Surgical gloves	0.011	2.50	0.02
Other materials	14.20	3.80	53.96
Total for the product			17 300.24

Table 6.3 – Calculation of costs for product packaging, raw materials and materials

Material name	Norm	Price, UAH	Total, UAH
1	2	3	4
Enamel ПФ-115 т/ green	0.069	89.94	6.20
Plate steel Вст3сп 4-8	6.65	48.00	319.20
Nails	1.38	40.00	55.2

Continuation of Table 6.3

1	2	3	4
Larch lumber	0.16	1 800.00	288.00
Steel channel8	22.90	37.85	866.76
Fiberboard	16.03	48.00	769.44
Wrapping paper	0.42	7.80	3.27
Roofing glassine П350	2.53	12.10	30.6
Total packing	2 338.67		
Total for product and packaging	19 638.91		

Table 6.4 – Calculation of costs for purchased components

Material name	Quantity, unit	Price for one, UAH	Total, UAH
1	2	3	4
Circuit breaker BB/TEL –10-20/1000	1	61 700.00	61 700.00
Current transformer ТЛШ- 10-200/5	3	3 850.00	12 550.00
Insulator ИОР-10-750 УХЛ2	9	115.00	1 035.00
Armature СКЛ 12А- Б-2-220 gr., red, yell.	3	45.00	135.00
Block lock ЭМБ ЗУЗ	2	316.00	632.00
Ammeter Э-365	1	480.00	480.00
Switch ПКУ 3-12 С	1	200.00	200.00
Key ЭМК	1	650.00	650.00
Block APP 5 282 104	1	500.00	500.00
Surge arrester ОПН-КР/TEL-10	3	1 800.00	5 400.00
СШР48П20ЭГ2 (plug-socket) 20 cond. (XP1)L2.7	2	490.00	490.00
Arc fault signaling device	1	700.00	700.00

Continuation of Table 6.4

1	2	3	4
Insulator ИПК-10-1600-5 УЗ	6	270.50	1 623.00
Transformer ТЗЛМ-10	2	1 300.00	2 600.00
Protection МРЗС -05	1	12 800.00	12 800.00
Automatic Switch S262 C25	1	230.00	230.00
Relay РЭУ 11-20-5-40	4	480.00	1 920.00
Lock ЗБ1 УЗ	2	250.00	500.00
Limit switch ВП 19	2	250.00	500.00
Block lock ЭМБ ЗУЗ	2	620.00	1 240.00
Bearing 304	4	45.00	180.00
Cutout P-16	1	83.00	83.00
Plug and socket РШ-30	3	47.00	111.00
Total	—	—	105 914.00

Table 6.5 – Calculation of basic wages

Operation	Rank	Number of norm / hour	The cost 1n/hour, UAH	Total main salary, UAH
1	2	3	4	5
Procurement	2	22.5	12.68	285.22
Installing parts	4	16.0	14.08	225.22
Adjustment	3	14.5	12.60	182.70
Selection of EA	4	15.4	18.61	286.55
Fastening busbars and contact connections	3	28.3	12.73	360.18
Cabinet assembly	4	55.7	13.49	751.44
Normocontrol	5	16.4	20.19	331.04

Continuation of Table 6.3

1	2	3	4	5
Engineering Technical Workers	5	57.9	34.27	1 985.33
Total				4 407.69

Wages are calculated on the basis of the labor intensity of parts manufacturing, hourly tariff rates. The calculation of the basic wages for the product is given in Table 6.5.

Based on production costs, the calculation of the cost of the product is determined, that is, the costs of manufacturing a unit of production are determined.

The decrease in the cost of the designed product in comparison with the base one occurs due to the installation of a domestic component - a relay protection and automation device MRZS-05 of the Kyivprylad software; comparison is given below.

The difference in the price of purchased components for the basic and designed switchgear devices: for basic product equals 156 320.50 UAH; for designed product equal 105 914.24 UAH.

A decrease in general production (EMC, WC, GPC) and administrative costs occurs due to a decrease in workshop costs (decrease from 300% to 180%), since these items are a percentage of the basic salary. These data are shown in Table 6.6.

General production costs are:

a) costs for the maintenance and operation of equipment (EMC) – 250%;

b) workshop costs (WC) – 300%;

c) general plant costs (GPC) – 120%;

According to the company, the percentage of sales expenses is 2.3%.

Difference in sales expenses (SE) (2.3% from components expenses): for basic product equals 3 595.36 UAH; for designed product equal 2 436.02 UAH.

The full cost of production is an economic and financial indicator of an enterprise's activities, which characterizes the efficiency of management and is the basis for calculating prices. We determine the price of the switchgear according to the formula (6.1):

$$P_{wholesale} = FC + Pr\,, \tag{6.1}$$

where $P_{wholesale}$ - wholesale price of the product, UAH

FC – full cost of the product, UAH;

Pr – profit, UAH.

Table 6.6 - The difference in expenses for organizational measures, general production and administrative costs of the basic and designed product

Name of articles	Percent	Basic product, UAH	Designed product, UAH
General production costs (ConsF), including:			24 242.28
a) Equipment maintenance costs (EMC)	250	11 383.99	11 019.22
b) Workshop costs (WC)	300 180	13 223.06	7 933.84
c) General plant costs (GPC)	120	5 464.327	5 289.22
Administrative expenses (AE)	200	9 107.178	8 815.37

The cost of production can be determined by the formula (6.2):

$$PC = M + C + Wb + Wa + ConsIns + ConsF\,, \tag{6.2}$$

where PC – production cost of the product, UAH;

M – cost of raw materials and basic materials, equal 19 638.91 UAH

C – the cost of purchased and completing products, equal 125 914.00 UAH;

Wb – basic wages of production workers, equal 4 407.69 UAH;

Wa – additional wages of production workers, equal 2 776.84 UAH;

ConsIns – single social contribution (ESV) from the wages of production workers, equal 1 580.6 UAH;

ConsF – general production costs, equal 24 242.28 UAH.

With a decrease in all of the above items, the production cost of the designed product also decreases, these data are given in below;

The difference between the production cost (PC) of the basic and designed product: for basic product equals 215 085.57 UAH; for designed product equal 158 560.23 UAH.

Reducing the total cost, which consists of the following items: production cost (PC), sales expenses (SE), transport and procurement costs, administrative expenses (AE), these data are shown below.

The difference in the total cost of the base and designed product: for basic product 232 578.29 UAH; for designed product equal 174 601.89 UAH.

Decrease in profit and value added tax (hereinafter VAT), because profit is 25% of the total cost and VAT is 20% of the wholesale price. These data are shown below.

The difference between profit and VAT of the base and designed product: for basic product equals 58 144.57 UAH; for designed product equals 43 650.47 UAH.

Table 6.7 shows the total cost of the product, profit, wholesale price, VAT, and the free-selling price for the product.

Social security contributions are charged at 22% of wages (ESV).

Additional capital investments include:

a) the cost of creating, or purchasing new fixed assets for the production of products, their installation, setting up for the organization of production;

b) costs associated with the development of technical documentation, research, production of test samples, etc.

Specific overhaul costs (SOC) can be up to 20% of the wholesale price:

$$SOC = 43\ 650.47\ \text{UAH}$$

Table 6.7 - Price calculation for switchgear

Name of articles	Percent	Total, UAH
Raw materials and basic materials (M)		19 638.91
Purchased components (C)		105 914.00
Transportation and procurement costs		4 330.18
Basic wage (Wb)		4 407.69
Additional wage (Wa)	63	2 776.84
Single social contribution (ESV) from the wages of production workers (ConsIns)	22	1 580.60
General production costs (ConsF) including:		24 242.28
a) Equipment maintenance costs (EMC)	250	11 019.22
б) Workshop costs (WC)	180	7 933.84
в) General plant costs (GPC)	120	5 289.22
Production cost (PC)		158 560.32
Administrative expenses (AE)	200	8 815.37
Sales expenses (SE)	2.3	2 896.02
Full cost (FC)		174 601.89
Profit (Pr)	25	43 650.47
Wholesale price ($P_{wholesale}$)		218 252.37
VAT	20	43 650.47
Freely released price		261 902.84

The associated capital expenditures for switchgear consist of the following costs: overhaul costs, foundation costs, production area costs.

Overhaul costs account for 50% of the product cost, for foundations - 15%, production area costs can be determined from the following relationship (6.3):

$$\text{ConsArea} = \text{AreaCost} \cdot \text{S} \cdot \text{Karea}\,, \qquad (6.3)$$

where AreaCost – price of 1 m^2 of area equal to 1 800 UAH;

S – production area occupied by the product 0.975 m^2;

Karea – coefficient taking into account additional area (Karea = 1.15).

The calculation results are shown in table. 6.8

Table 6.8 - Associated Capital Expenditures

Related expenses	Cost, UAH
Overhaul	87 300.95
Foundation and installation	26 190.28
Production area	2 018.25
Total	115 509.48

Annual operating costs are calculated based on the type of electrical equipment. For switchgear, they will accommodate:

a) expenses for current repairs and materials required for maintenance;

b) depreciation expenses.

Maintenance costs are determined by the following relationship:

$$\text{ConsMaint} = \text{ConsRepair} \cdot \text{Nrepair}\,, \qquad (6.4)$$

where ConsRepair – cost of one current repair, ConsRepair = 8 700 UAH;

Nrepair – number of repairs per year.

Depreciation expenses are 15% of the cost of installation and installation of switchgear, production area and overhaul.

Operating costs are shown in Table 6.9

Table 6.9 - Operating costs

The composition of the current costs of the consumer	Cost, UAH
Maintenance costs	26 100.00
Depreciation expenses	17 326.42
Total	43 426.42

As a result of the improvement of the basic product, the number of used products will decrease by 1.5 times, i.e. over a service life of 20 years, 1 switchgear structure will be excluded from operation.

Break-even production is characterized by a critical volume of production and sales of products, at which profit is zero (the point of critical volume).

Let's calculate the critical volume of production using the following dependencies (6.5):

$$\mathrm{Ncr} = \frac{\mathrm{ConsFixed}}{(\mathrm{P_{wholesale}} - \mathrm{ConsVar})}, \qquad (6.5)$$

where ConsFixed – fixed costs for the entire volume of production, UAH;

Pwholesale – wholesale price, UAH;

ConsVar – variable costs per unit of production, UAH.

Fixed costs per unit of production are determined by the formula (6.6):

$$\text{ConsFixed} = (\text{ConsF} + \text{AE} + \text{SE}) \cdot \text{Nyear}\,, \qquad (6.6)$$

where ConsF – – general production costs, equal 24 242.28 UAH;

AE – administrative expenses, equal 8 815.37 UAH;

SE – sales expenses, equal 2 896.02 UAH;

$$\text{ConsFixed} = (24\ 242.28 + 8\ 815.37 + 2\ 896.02) \cdot 40 = 1\ 438\ 146.88\ \text{UAH}$$

Variable costs per unit of production are determined by the formula (6.7):

$$\text{ConsVar} = \text{M} + \text{C} + \text{Wb} + \text{Wa}\,, \qquad (6.7)$$

$$\text{ConsVar} = 19\ 638.91 + 105\ 914.00 + 4\ 407.69 + 2\ 776.84$$
$$= 137\ 737.44\ \text{UAH}$$

Therefore, substituting to the formula (6.5):

$$\text{Ncr} = \frac{1\ 438\ 146.88}{218\ 252.37 - 132\ 737.44} = 17\ \text{units}$$

The efficiency (E) of using a new (designed) product is found by the formula (6.8):

$$\text{E} \ = \ \text{N base units} \ \cdot \ \text{FPb} \ - \ \text{N project products} \ \cdot \ \text{FPpr}\,, \qquad (6.8)$$

$$\text{E} = 2 \cdot 232\ 578.29 - 1 \cdot 174\ 601.89 = 290\ 554.68\ \text{UAH}$$

where FPb – full price of base product;

FPpr – full price of project products.

The graph of the point image is shown in Figure 6.1.

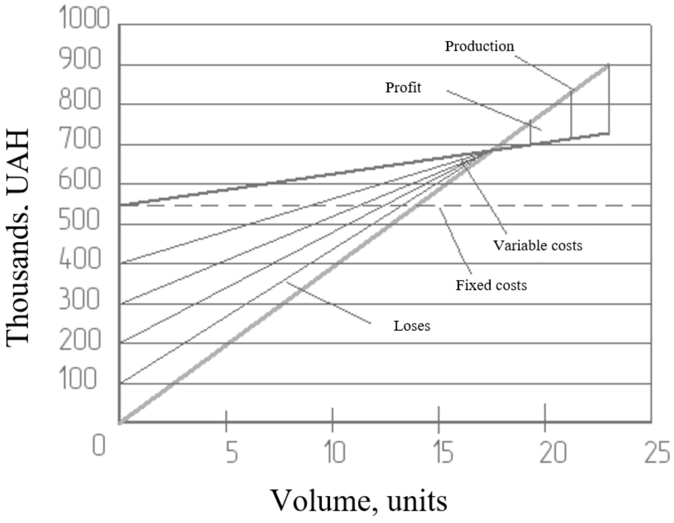

Figure 6.1 - Production break-even schedule

Consequently, when using a new switchgear product, savings of 290 554.68 UAH occur. over a service life of 20 years.

The value of the economic effect is commensurate with the cost of the basic switchgear product during the operational period.

CONCLUSIONS

In the diploma project, based on a review of existing designs of complete switchgears, as well as their protection, automation and control devices, a switchgear of 10 kV, 1600 A was developed. The switchgear device manufactured by ZZVA JSC was chosen as the basic design.

The calculation of the current-carrying circuit of the complete switchgear has been performed. Three-pole aluminum busbars with a total cross-sectional area of $1080 \cdot 10^{-6}$ m^2 were chosen as a conductive element, due to the introduction of which heat removal from the busbar surface is improved. To check the dynamic resistance, the bending stress of the material was calculated and the busbar stability condition was checked, $0.54 \cdot 10^7 < 10.8 \cdot 10^7$. To check the busbars for thermal resistance, the temperature of heating the busbars by the short-circuit current was determined and compared with the permissible one, 150 ℃ < 200 ℃, which means that the bus is thermally resistant.

The equipment of the main circuits was selected: a vacuum circuit breaker – BB/TEL-10-25/2000 (Tavrida Electric Ukraine), a ТЛШ-10 current transformer, ИОР-10-3.75 support insulators and ИПК-10-1600-5 bushing insulator, a relay device was chosen as a device for relay protection and automation for the designed switchgear protection made on the microprocessor element base MRZS-05 "Kyivprylad" with programing software "Sizif v4".

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Формат	Зона	Поз.	Позначення	Найменування	Кіл.	Примітка
				<u>Документація</u>		
A1			GKIU.674691.012 AD	Складальне креслення		
				<u>Складальні одиниці</u>		
		1		Шкаф релейний	1	
A1		2	GKIU.305362.012 AD	Механізм шторочний	1	
		3		Викатний елемент	1	
A1		4	GKIU.685543.012 AD	Заземлювач	1	
A1		5	GKIU.304551.012 AD	Привід заземлювача	1	
				<u>Деталі</u>		
		7		Пластина	1	
		8		Шина	3	
		9		Перегородка	1	
		10		Ламель	12	
		11		Двері	1	
		12		Ручка	1	
		13		Важіль нажимний	2	
		14		Колесо	2	
		15		Скоба	2	

Зм.	Арк.	№ докум.	Підпис	Дата	GKIU.674691.012			
Розроб.		Лапшинов Є.Д			Complete switchgear КМ-1Ф	Літ.	Арк.	Арк-в
Перев.		Жорняк Л.Б.				У	1	2
Т.контр.						НУ "Запорізька Політехніка" Е-417а		
Н.контр.								
Затв.		Андрієнко П. Д.						

Формат	Зона	Поз.	Позначення	Найменування	Кіл.	Приміт-ка
				<u>Стандартні вироби</u>		
		20		Болти М10-6g×12.58.019	16	
				ГОСТ 7796-70		
		21		Гайки М10.5-7Н.5.019	16	
				ГОСТ 5915-70		
		22		Шайби 10. 65Г. 019	16	
				ГОСТ 6402-70		
				<u>Інші вироби</u>		
		25		Трансформатор струму	3	
				ТШЛ-10-2000/5-0.5/10Р		
		26		Прохідний ізолятор	9	
				ИПК-10-1600-5 У3		
		27		Ізолятор опорний	9	
				ИОР – 10 – 3,75		
		28		Вакуумний вимикач	1	
				ВВ/TEL-10-25/2000 УХЛ2		
				ІТЕА.674152.003 ТУ		
				<u>Матеріали</u>		
				Провід ПВЗ 0.75Б		
				ГОСТ 6323-79		

Зм.	Арк.	№ докум.	Підпис	Дата	GKIU.674691.012

Формат	Зона	Поз.	Позначення	Найменування	Кіл.	Примітка
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A1			GKIU.685543.012 AD	Складальне креслення		
				<u>Складальні одиниці</u>		
		1		Кронштейн	1	
		2		Зв'язок гнучкий	1	
		3		Тяга	1	
		4		Ніж контактний	1	
				<u>Деталі</u>		
		7		Ламель	2	
		8		Планка	1	
		9		Пружина	1	
		10		Вал	1	
				<u>Стандартні вироби</u>		
		12		Болт М16-6gх60.58	4	
				ГОСТ 7796-70		

Зм.	Арк.	№ докум.	Підпис	Дата	GKIU.685543.012		
Розроб.	Лапшинов Е.Д				Grounding switch Assembly drawing	Літ.: У	Арк.: 1 / Арк-в: 2
Перев.	Жорняк Л.Б.						
Т.контр.						НУ "Запорізька Політехніка" Е-417а	
Н.контр.							
Затв.	Андрієнко П. Д.						

Формат	Зона	Поз.	Позначення	Найменування	Кіл.	Примі-ка
		13		Болт М10-6g×25.66.019	4	
				ГОСТ 7875-70		
		14		Гайка М12-6Н.5.019	12	
				ГОСТ 5927-70		
				<u>Інші</u>		
		16		Ізолятор	1	

Зм.	Арк.	№ докум.	Підпис	Дата	GKIU.685543.012

Формат	Зона	Поз.	Позначення	Найменування	Кіл.	Примі-ка
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				Складальні одиниці		
		1		Блок замок	1	
		2		Блокувальна тяга	1	
		3		Тяга	1	
		4		Знімна рукоятка	1	
				Деталі		
		6		Кронштейн	1	
		7		Полувісь	1	
		8		Упор	1	
		9		Тяга	1	
		10		Косинець для блокування	1	
		11		Рычаг	1	
				Стандартні вироби		
		13		Болт М12х60.36.016	2	
				ГОСТ 7786-81		

Зм.	Лист	№ докум.	Підпис	Дата	GKIU.304551.012			
Разраб.		Лапшинов Є.Д			Grounding switch drive Assembly drawing	Літ.	Лист	Листів
Перев.		Жорняк Л.Б.				У	1	2
Т.контр.						НУ "Запорізька Політехніка" Е-417а		
Н.контр.								
Затв.		Андрієнко П. Д.						

Формат	Зона	Поз.	Позначення	Найменування	Кіл.	Примі-ка
		14		Болт М10-6g×25.66.019	6	
				ГОСТ 7875-70		

Зм.	Арк.	№ докум.	Підпис	Дата	GKIU.304551.012

Формат	Зона	Поз.	Позначення	Найменування	Кіл.	Примі-ка
				<u>Документація</u>		
A1			GKIU.305362.012 AD	Складальне креслення		
				<u>Складальні одиниці</u>		
		1		Ролик	1	
				<u>Деталі</u>		
		3		Направляючий стрижень	1	
		4		Тяга	1	
		5		Важіль	1	
		6		Вісь	1	
		7		Верхня шторка	1	
		8		Скоба	1	
		9		Косинець	1	
		10		Нижня висувна шторка	1	
				<u>Стандартні вироби</u>		
		13		Болт М12x60.36.016	2	
				ГОСТ 7786-81		

Зм.	Арк.	№ докум.	Підпис	Дата	GKIU.305362.012		
Розроб.		Лапшинов Є.Д			Shutter mechanism Assembly drawing	Літ.	Арк.	Арк-в
Перев.		Жорняк Л.Б.				У	1	1
Т.контр.						НУ "Запорізька Політехніка" E-417a		
Н.контр.								
Затв.		Андрієнко П. Д.						