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: Комутаційний апарат для керування електродвигуном рухомого транспорту 220 В, 160 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
Попов Є.Д.
(прізвище та ініціали)

Керівник Жорняк Л.Б.
(прізвище та ініціали)

Рецензент Сергієнко В.С.
(прізвище та ініціали)

2021

Форма № 25

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

Інститут, факультет___Фізико-технічний інститут, Електротехнічний факультет__
Кафедра______________Електричних та електронних апаратів_______________
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 __Андрієнко П.Д.__
____
«______» ________________20___року

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

________________________Попова Євгена Денисовича______________________
(прізвище, ім'я, по батькові)

1. Тема проєкту (роботи)__Комутаційний апарат для керування електродвигуном_ рухомого транспорту 220 В, 160 А_____________________________________
керівник проєкту (роботи)______ Жорняк Людмила Борисівна кандидат технічних наук, доцент____
(прізвище, ім'я, по батькові, науковий ступінь, вчене звання)
затверджені наказом закладу вищої освіти від «_11_»___березня__2021року №___
2. Строк подання студентом проєкту (роботи)__________________________________
3. Вихідні дані до проєкту (роботи)_Uном = 220 В, Іном = 160 А_________________
____
____
4. Зміст розрахунково-пояснювальної записки (перелік питань, які потрібно розробити)_Огляд конструкції, Розрахунок контактора постійного струму, Охорона праці, Економічний розділ, Висновки___________________________
____
____
5. Перелік графічного матеріалу (з точним зазначенням обов'язкових креслень)
ГКІЮ.644413.016СК Контактор постійного струму Складальне креслення — А1, 1 лист; ГКІЮ.731258.016.СК Дугогасна камера — А1, 1 лист;_ГКІЮ.685442.016.СК Електромагніт — А3, 1 лист;_ ГКІЮ.685121.016.01 Нерухомий контакт — А3, 1 лист; ГКІЮ.685121.016.02 Рухомий контакт — А3, 1

лист; ГКІЮ.734541.016.03 Скоба — А3, 1 лист, Плакат Тягова та протидіюча характеристика електромагніта — А2, 1 лист; Плакат Вольт-амперна характеристика дуги — А2, 1 лист.

6. Консультанти розділів проєкту (роботи)

Розділ	Прізвище, ініціали та посада Консультанта	Підпис, дата	
		завдання видав	Прийняв виконане завдання
Економіка	Пожуєва Т.О., професор		
Охорона праці	Скуйбіда О.Л., доцент		

7. Дата видачі завдання «_______» ________________20___року.

КАЛЕНДАРНИЙ ПЛАН

№ з/п	Назва етапів дипломного проєкту (роботи)	Строк виконання етапів проєкту (роботи)	Примітка
1	Техніко-економічне обгрунтування проєкту	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 проєкту	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 проєкту	14.05.2021	
8	Узгодження проєкту з керівником проєкту та консультантами з економіки та з охорони праці	17.05.2021	
9	Нормоконтроль та затвердження завідувачем кафедри	19.05.2021	
10	Рецензування проєкту	21.05.2021	
11	Захист проєкту	25.05.2021	

Студент(ка) _____________ **Попов Є.Д.**
(підпис) (прізвище та ініціали)

Керівник проєкту (роботи) _____________ **Жорняк Л.Б.**

(підпис)   (прізвище та ініціали)

ABSTRACT

EN: 116 p, 10 fig., 17 tables, 53 sources.

CONTACTOR, CURRENT, VOLTAGE, RESISTANCE, CORE, COIL, ARMATURE, ELECTROMAGNETIC DRIVE.

Design object is electromagnetic direct current contactor with parameters 220V, 160A.

Purpose is to calculate and design of the DC contactor with the new parameters.

Research method is technique for calculation of the contactor proposed in specialized literature [4,5,6,9,11,12,13].

Calculation of the electromagnetic DC contactor contains the following sections: calculation of current carrying contour, calculation of contact connections, calculation of switching contacts, calculation of arc extinguishing system, calculation of additional contacts, kinematic calculation of the electromagnetic drive and calculation of the drive electromagnet.

In the result of calculation electromagnetic DC contactor was designed with parameters: $U_{rat} = 220\ V$, $I_{rat} = 160\ A$, $U_c = 48\ V$, $I_{ac} = 10\ A$, $n_{tr} = 3$, $z = 1200$, N = 1000000.

INTRODUCTION

Chosen topic is relevant due to worldwide trends regarding the abandonment of the use of vehicles with internal combustion engines and the transition to environmental-friendly substitutes, including electric motors.

The aim of the diploma project is to design a DC electromagnetic contactor with parameters 220 V, 160 A taking into account the peculiarities of its use in control circuits of the moving vehicle electric motors (the main difference in use of contactors in the moving vehicles is the difficult operating conditions: vibration, polluted air, temperature changes in a wide range).

To achieve this goal, it is necessary to solve the following tasks:

- to review the existing designs of contactors and choose the optimal design for the use of the contactor in moving vehicles.
- to analyze possible directions of design improvement
- to carry out design calculation of the contactor on the basis of the chosen design
- to provide an economic justification for the introduction of the contactor in production

Research methods: analysis of technical documentation, mathematical modeling (calculation), method of budgeting-forecasting of production volumes and sales

The theoretical basis is textbooks, handbooks and manuals for the design, calculation and construction of electrical appliances. Legislative and normative acts of Ukraine, instructive departmental materials are used in the work.

Practical significance. the contactor designed in the diploma project can find application in control circuits of the moving vehicle electric motor .

CONTENT

1 DESIGN OVERVIEW

1.1 Classification and features of electromagnetic contactors [2,5,12]

Electromagnetic contactors are electromechanical systems that are used for frequent switching of power supply circuits. The main application of these devices is the use in control systems for the operation of electric drives, which are installed on various industrial plants and electrical machines. The electromagnetic system available in the contactors, allows to remotely carry out the closing / opening processes of the main contacts.

The selection of structural forms, including the selection of the structural scheme and the general layout of the structure, is the main and most difficult design stage. In a specific design of the apparatus, there may be factors that cannot be satisfied at the same time and even contradict each other. It is necessary to find the optimal combination of several factors, giving priority to the most important.

Design features of contactor systems

The electromagnetic contactor includes the following key components:

- a group of main contacts;
- electromagnetic subsystem;
- subsystem for arc extinguishing;
- an auxiliary contact group.

The main contact group is a set of switching contacts, with the help of which the current-supplying power circuits are closed/opened. The contacts must withstand a large number of switching cycles and withstand a long period of carrying currents of a sufficiently large magnitude. There are two types of main contacts: bridge and lever.

The electromagnetic subsystem is used to remotely control the operation of the contactor mechanism. The main elements of the electromagnetic subsystem are the core, the armature, the take-up coil, and the fasteners.

This system can be configured to turn on and hold the armature in the power-on state, or only to turn it on without further holding – in this case, holding is realized by means of a latch. When the flow of current through the control coil stops, the contact group mechanism is also disconnected – this happens under the action of the return spring.

Arc extinguishing system is used to extinguish the electric arc that is generated during the opening of the main contacts. The presence of an arc discharge affects the contacts negatively and after a certain time can lead to their failure. In DC contactors, the arc is extinguished by using a magnetic field.

Auxiliary contacts are used for switching control circuits of contactor systems, as well as interlocking and signaling circuits. This contact group is intended for continuous conduction of currents with a value of more than 20A, as well as for disconnecting circuits with a current value of not more than 5A. The auxiliary group of contacts is produced in two types – closing and opening, mainly of the bridge type.

Despite the fact that DC contactors are used less often than AC contactors and there is practically no modernization of their design, there are many different series and models of contactors, in the design of which various technical solutions and materials are used.

There is a task to design 220 V, 160 A switching device to control the moving vehicle electric motor, so it is necessary to select the optimal design of the contactor to control the moving vehicle electric motor.

Here are examples of electromagnetic DC contactors from different manufacturers with technical characteristics similar to those specified in the project task:

1.2 Electromagnetic contactors, MK series [41,42,43,44,45]

Electromagnetic contactors of the MK series are designed for switching power electrical circuits and control circuits of direct and alternating current. MK series contactors are used on the rolling stock of rail transport, trolleybuses and in general industrial stationary installations. Technical characteristics of the MK 4-10 160A contactor is presented in Table 1.1.

Table 1.1 [45]

Type of current	DC
Rated current	160A
Rated voltage	DC — Up to 220V AC — Up to 380V
Rated voltage of retracting coil	24, 48, 75, 110, 220V
Rated long-term current flowing through auxiliary contacts	10A
Rated voltage of auxiliary contacts	DC — from 110 up to 220V AC — from 110 up to 660V
Switching frequency under the load	1200 cycles per hour
Protection	IP00
Operation mode	Continuous, intermittent continuous, recursive short-time, short-time
Power consumption	45W
Climatic performance	Temperate 3, tropical 3, cold-temperate
Wear resistance	More than 10000000 cycles
Weight	5 kg

Design features of the MK4-10 160A 220V DC contactor (Fig 1.1, 1.2)

Contactors have a monoblock structure. All elements of the contactor are assembled on a U-shaped bracket. The valve-type solenoid contains a bracket, cores with coils mounted on them and an armature. The contact system of the main and auxiliary circuits is of the bridge type. The main contacts have arc chutes with series coils. The retractor coils of the contactors are suitable for DC power supply only and are designed for rated control circuit voltages of 24 (27), 48 (50), 75, 110 and 220 V.

Contactors can be manufactured with AC retractor coils with a rectifier unit. The design of the auxiliary circuit contacts allows the conversion of NO contacts to NC contacts and vice versa. In this case, the number of NC contacts should be no more than 50% of the total number of contacts of the auxiliary circuit. Contacts are made of electrical copper with cermet solders based on copper or silver. Two contactors of the same type with NO contacts, located side by side, allow the installation of a mechanical interlock, in which two contactors should not be switched on simultaneously.

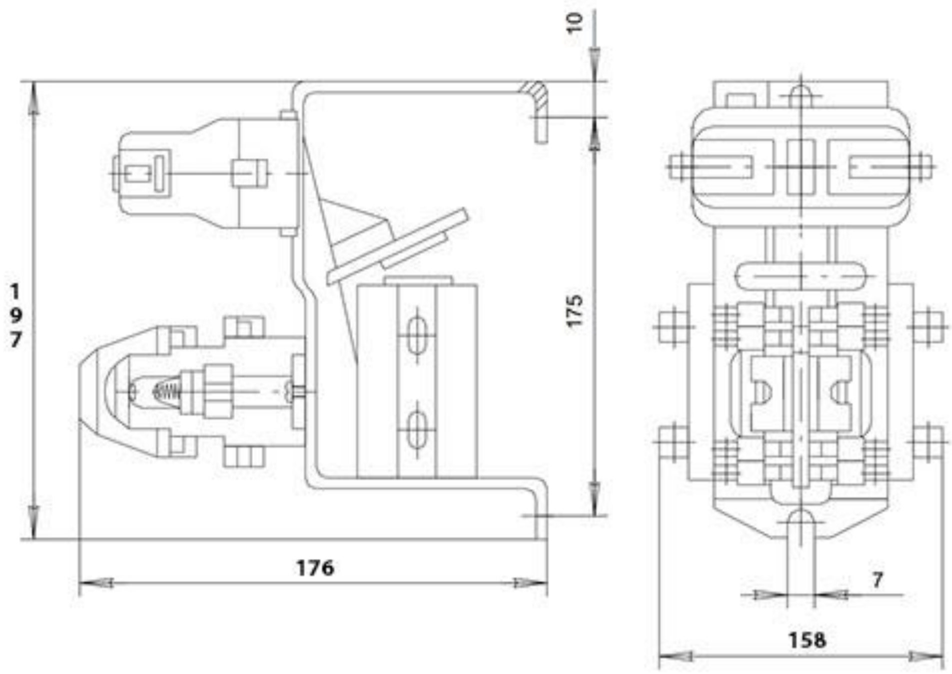

Figure 1.1 — Assembly drawing of the electromagnetic MK4-10 160A 220V DC contactor [45]

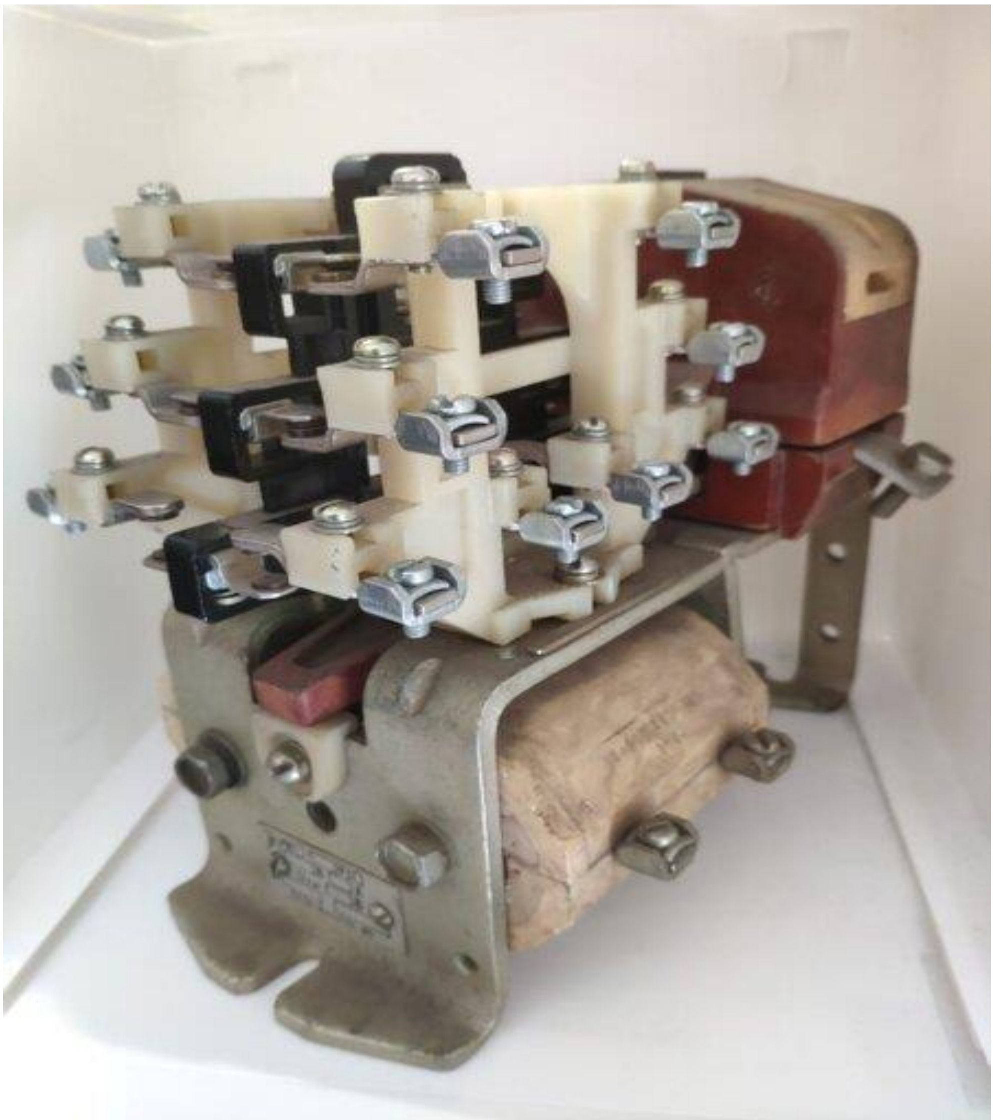

Figure 1.2 — Electromagnetic МК4-10 160A 220V DC contactor [45]

1.3 Electromagnetic contactors, КПВ-600 series [46, 47, 48,49]

КПВ-603 160A contactor with one closing main contact for DC circuits, designed to turn on and off electrical circuits in stationary installations and to control electric motors, can be used as a line contactor, reversing contactor, acceleration contactor, etc.

Technical characteristics of the КПВ-603 160A contactor is presented in Table 1.2.

Table 1.2 [49]

Type of current	Direct
Rated current	160A
Rated voltage	Up to 220V
Rated voltage of DC coil	110, 220V
Long-term current flowing through auxiliary contacts	10A
Rated voltage of auxiliary contacts	220B
Parameters of the main circuit	Number of contacts – 1 NO;
Parameters of the auxiliary circuit	Number of NO contacts – 2; Number of NC contacts – 2
Protection	IP00
Operation mode	Continuous, intermittent continuous, recursive short-time, short-time
Power consumption	40 W
Climatic performance	Temperate 3, tropical 3, cold-temperate
Mechanical wear resistance	2 000 000 cycles
Wear resistance	200 000 cycles
Weight	9 kg

Design features of the КПВ-603 160A DC contactor (Fig. 1.3,1.4):

Contactors have a monoblock structure. All elements of the contactor are assembled on a Z-shaped bracket. Magnetic system is a valve type. The armature rotates on prisms. Arc extinguishing occurs in a chamber with a wide gap. An L-shaped armature is inserted into the slot of the main bracket of the magnetic circuit, to which there is attached bracket, carrying a movable contact with a contact spring.

Two contactors of the same type with NO contacts installed side by side can be mechanically interlocked. In this case, the right contactor, to which a mechanical interlock is attached on the left side, allows the installation of block contacts only on the right side.

Contactors can be made with 2 NO and 2 NC block contacts, 2 NO and 1 NC block contacts or without them. The design of block contacts used on contactors allows, during installation or under operating conditions, to reassemble the elements by changing the position of NO and NC contacts within the specified number, while the number of NC contacts should be no more than 2 of the total the number of contacts in the auxiliary circuit.

For operation in continuous mode, the contacts of КПВ-603 contactor must have contact pads made from silver.

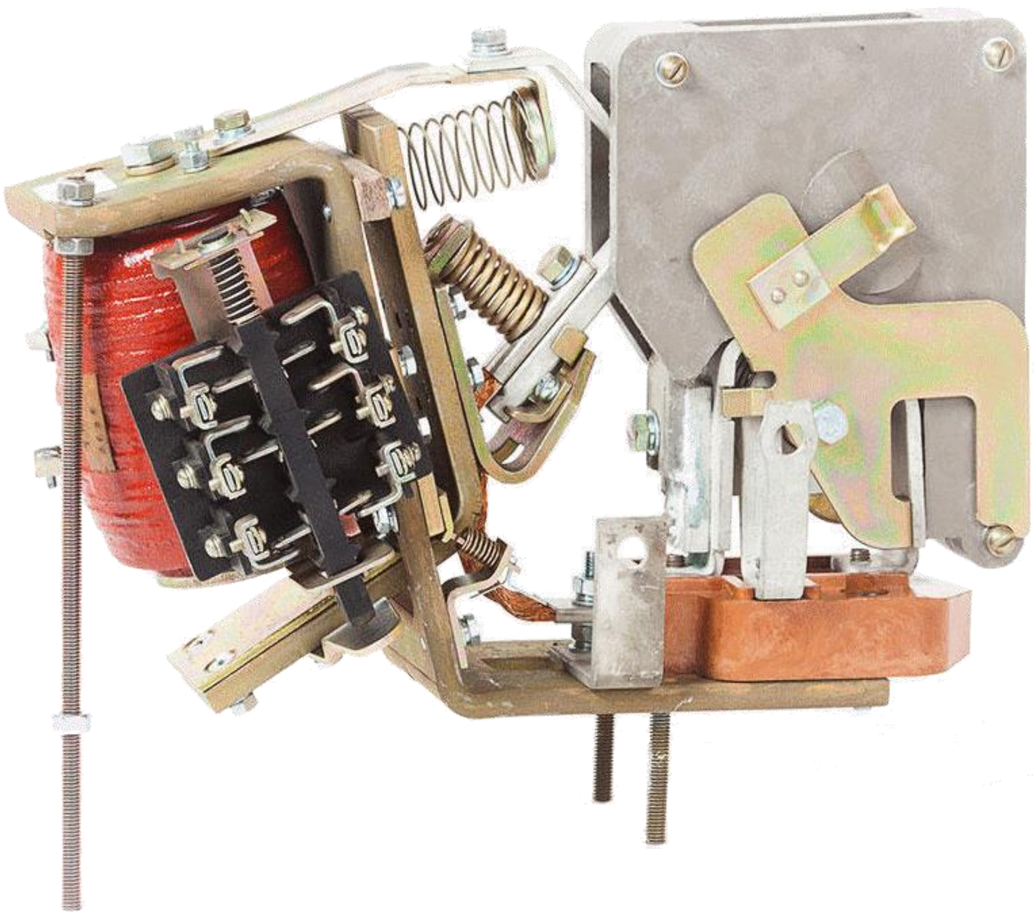

Figure 1.3 — КПВ-600 electromagnetic DC contactor [49]

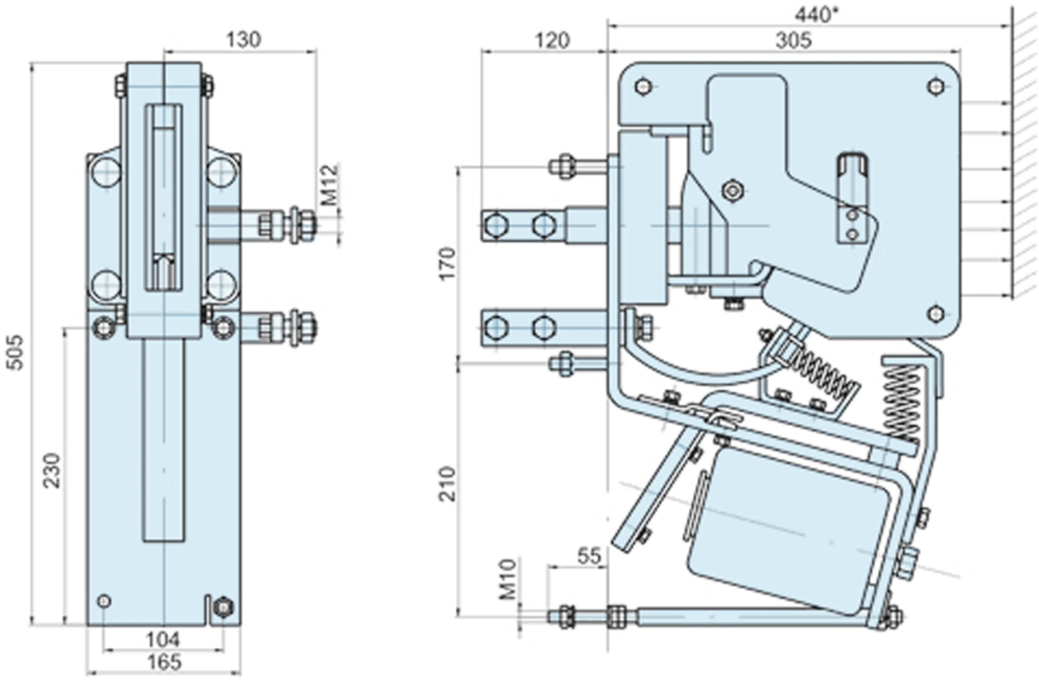

Figure 1.4 — Assembly drawing of КПВ-600 electromagnetic DC contactor [49]

1.4 Electromagnetic contactors, КН, КНУ series [50, 51, 52, 53]

КН and КНУ DC electromagnetic contactors are designed for switching DC electric circuits and automatic control of ship's electric drives; allow installation in shells of complete devices.

Design features of the of the КН 471 electromagnetic DC contactor (Figure 1.5):

The electromagnetic system of the contactor consists of an armature and a magnetic circuit, including coils with a steel core. The U-shaped magnetic core is made of sheet steel. Its ends are bent for attaching to the contactor.

The base with the coils and the armature are mounted on the frame. The windings of the closing coil are wound on an insulated core. The upper part of the core is fixed with a clamp, which is also a short-circuited turn, increasing the release time of the contactor.

The closing coil is made with two windings (holding and starting). The starting winding of the closing coil is supplied through the opening auxiliary contacts and is disconnected at the end of the armature stroke (when the contactor is switched on).

Technical characteristics of the КН 471 DC contactor is presented in Table 1.3.

Table 1.3 [53]

Type of current	Direct
Rated current	160A
Rated voltage	Up to 220V
Rated voltage of DC coil	40V
Long-term current flowing through auxiliary contacts	7A
Rated voltage of auxiliary contacts	220 V
Parameters of the main circuit	Number of contacts – 2 NO
Parameters of the auxiliary circuit	Number of NO contacts – 2; Number of NC contacts – 1
Switching frequency under the load	Up to 600 per hour
Protection	IP00
Operation mode	Continuous, intermittent continuous, recursive short-time, short-time
Power consumption	55 W
Climatic performance	Temperate 3, tropical 3, cold-temperate
Mechanical wear resistance	1 500 000 cycles
Wear resistance	150 000 cycles
Weight	8 kg

The closing coil is made with two windings (holding and starting). The starting winding of the closing coil is supplied through the opening auxiliary contacts and is disconnected at the end of the armature stroke (when the contactor is switched on).

The moving system of the contactor in the open position is fixed by another retaining clip with a return spring. A bronze plate is attached to the armature, which protects the armature from sticking when the closing coil is turned off. The fixing bracket is fixed on a fixed axis and rests on the armature.

Auxiliary contact system is a bridge type. Bridges are made from silver. Fixed auxiliary contacts are made on squares, on which spring lamellas with silver overlays are fixed. The auxiliary contact system is designed to ensure reliable operation of the contactors under vibration and shock conditions.

In the on and off positions, the lamellas lie on the stops of the squares. Fixed main contactors and fixed auxiliary contacts (squares with lamellas) are mounted on heat-resistant plastic panels. Both panels are covered with plastic covers. A magnetic blowing coil with a steel core is connected in series to the fixed main contacts. Coil winding is made of copper tape.

The magnetic blowing coil has inter-turn insulation made of sheet fiber and is covered with heat-resistant enamel. One end of the magnetic blowing coil serves as a terminal for external connection, the other is connected to a fixed main contact. The free end of this contact is the arcing horn.

The steel plates of the arc chute are attached to the core of the magnetic blowing coil. The plates are supplied to the area of the main contacts (moving and stationary) by the magnetic flux arising from the passage of current through the coil. The electric arc arising from the opening of the main contacts is blown off from them by the magnetic field, passes to the arc-extinguishing horn, stretches, cools and extinguishes in a narrow-slot de-ion grid.

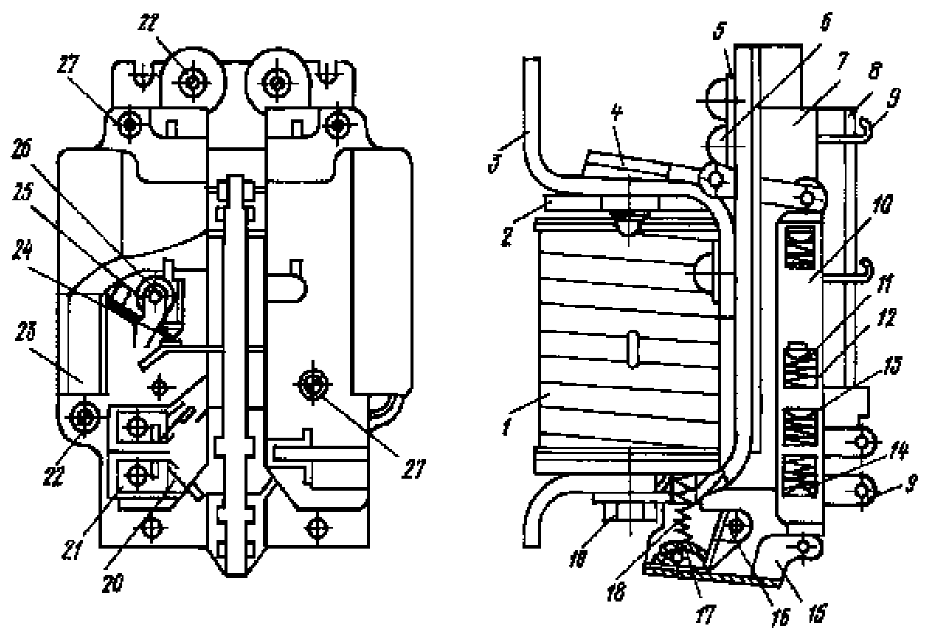

Figure 1.5 — Assembly drawing of the КН 471 electromagnetic DC contactor [53]

1.5 Conclusion

The main difference in use of contactors in the moving vehicles is the difficult operating conditions: vibration, polluted air, temperature changes in a wide range. Because of this, design of the contactor should guarantee high reliability and uninterrupted operation.

Design of electromagnetic contactors, MK series was selected as the basis for the project due to its high mechanical wear resistance and switching wear resistance, maintainability and ease of exploitation.

2 CALCULATION OF DIRECT CURRENT CONTACTOR

2.1 Calculation of current carrying contour

Current carrying contour usually consists from parts of various configurations, sizes and designs. These include clamps of contact leads, wires, cables, bus, rods, coils, contact holders, switching contacts, flexible conductors of hinge contact connections, etc.

Task of its calculation is to determine cross-sections of parts in current carrying conductor. Cross-section of these parts significantly affects their dimensions, consequently affects dimensions of the apparatus. Cross-section is an initial value for a number of subsequent calculations of the above parts of electrical apparatus.

It is necessary to select constructive forms of conductors of a current-carrying contour and approximately determine their length at the initial stage of designing the apparatus.

At the same time, constructive forms of contact connections of conductors should be selected. In this case, one should strive to apply possibly fewer contact connections. Because each contact connection creates a transition resistance, which leads to electrical losses and heating of elements. In addition, each connection can cause malfunction of the device during operation.

2.1.1 Calculation of equivalent current

If the operating mode of the contactor is intermittent, the calculation of its current-carrying parts in the nominal operating mode is carried out taking into account the equivalent current. Equivalent current I_{eq} is a current that would cause the same heating of current carrying parts as the breaking real rated current I_{rat} during continuous operation, in conjunction with additional heating of the contacts by an electric arc.

Equivalent current I_{eq} is calculated by empirical formula:

$$I_{eq} = I_{rat} \cdot \sqrt{\frac{DC}{100} + \frac{z}{600} \cdot \sqrt{\frac{DC}{100}}}, \tag{2.1.1}$$

where I_{eq} — equivalent current, A;

I_{rat} — rated current, which is equal 160 A;

DC — duty cycle, which is equal 40%;

z — permissible number of switching cycles per hour, which is equal 1200.

$$I_{eq} = 160 \cdot \sqrt{\frac{40}{100} + \frac{1200}{600} \cdot \sqrt{\frac{40}{100}}} = 206.45 \text{ A.}$$

Further calculation of the electromagnetic contactor is carried out according to the larger of the values I_{eq} or I_{rat}.

According to the calculated value of the current I_{eq}, it is necessary to determine the preliminary technical parameters of the current-carrying buses.

Preliminary technical parameters of the current-carrying buses are following:

copper (Cu) is material of current-carrying buses;

a_{pr} equaled to 3 mm is preliminarily value of bus thickness;

b_{pr} — preliminarily value of bus width, which is equal 12.5 mm;

$k_{g.pr}$ — preliminarily value of bus geometry factor, which is equal 4.2;

$I_{load.pr}$ — preliminarily value of bus current load, which is equal 223 A.

The current density of copper bus j_{Cu} must be in range (4-6) A/мм2; for aluminum bus — j_{Al} = (2-4) A/мм2.

Current-carrying buses having a high value of the bus geometry factor for further calculations are preferable.

2.1.2 Calculation of technical parameters of current-carrying buses

Dimensions of current carrying buses with rectangular section are calculated by value of equivalent current. Calculated thickness of current carrying bus a_{calc}:

$$a_{calc} = 10^3 \cdot \sqrt[3]{\frac{I_{eq}^2 \cdot \rho_0 \cdot \left(1 + \alpha \cdot \Theta_{perm}\right)}{2 \cdot k_{ht} \cdot \left(1 + k_{g.pr}\right) \cdot k_{g.pr} \cdot \left(\Theta_{perm} - \Theta_{env}\right)}}, \qquad (2.1.2)$$

where ρ_0 — specific electrical resistance of bus metal, which is equal $1.62 * 10^{-8}$ Ohm×m;

a — temperature factor of metal resistance, which is equal $4.3 * 10^{-3}$ 1/°C;

Θ_{perm} — permissible heating temperature of bolt connection, which is equal 95 °C;

Θ_{env} — temperature of environment, which is equal 40°C;

k_{ht} — heating transfer coefficient, which is equal 9 $\frac{\text{W}}{\text{m}^2 \cdot {}^\circ\text{C}}$;

$k_{g.pr}$ — preliminarily value of bus geometry coefficient, which is equal 4.2.

$$a_{calc} = 10^3 \cdot \sqrt[3]{\frac{206.45^2 \cdot 1.62 \cdot 10^{-8} \cdot (1 + 4.3 \cdot 10^{-3} \cdot 95)}{2 \cdot 9 \cdot (1 + 4.2) \cdot 4.2 \cdot (95 - 40)}} = 3.556\, mm.$$

Calculated width b_{calc} of current carrying bus is calculated by formula:

$$b_{calc} = a_{calc} \cdot k_{g.pr}, \qquad (2.1.3)$$

$$b_{calc} = 3.556 \cdot 4.2 = 14.937 \text{ mm.}$$

According to the reference data we take actual technical parameters of the standard current carrying bus of the calculated or nearest larger section for current I_{eq}.

Actual technical parameters of the current carrying bus:

a — actual thickness of current carrying bus, which is equal 4 mm;

b — actual width of current carrying bus, which is equal 16 mm;

k_g — actual bus geometry coefficient, which is equal 4;

I_{perm} — permissible current load of bus, which is equal 330 A.

Calculation of calculated current density in the current carrying bus:

$$j_{calc} = \frac{I_{eq}}{a_{calc} \cdot b_{calc}}, \tag{2.1.4}$$

$$j_{calc} = \frac{206.45}{3.556 \cdot 14.937} = 3.886\ A/mm^2.$$

Calculation of actual current density in the current carrying bus:

$$j_{act} = \frac{I_{eq}}{a \cdot b}, \tag{2.1.5}$$

$$j_{act} = \frac{206.45}{4 \cdot 16} = 3.226\ A/mm^2.$$

2.1.3 Calculation of the temperature of the current carrying buses in the rated mode

$$\Theta_b = \Theta_{env} + \frac{\rho_0 \cdot (1 + a \cdot \Theta_{perm}) \cdot I_{eq}^2}{k_{ht} \cdot P_b \cdot S_{b.cr.s}}, \tag{2.1.6}$$

where P_b — perimeter of the current carrying bus, which is equal $40 \cdot 10^{-3}$ m;

$S_{b.cr.s}$ — cross-sectional area of the current carrying bus, which is equal $64 \cdot 10^{-6}$ m^2;

$$\Theta_b = 40 + \frac{1.62 \cdot 10^{-8} \cdot (1+4.3 \cdot 10^{-3} \cdot 95) \cdot 206.45^2}{9 \cdot 40 \cdot 10^{-3} \cdot 64 \cdot 10^{-6}} = 82.21°C.$$

To eliminate the possibility of overheating of the current carrying buses and disruption of current transmission in the rated mode, the condition $\Theta_b < \Theta_{adm}$ must be met.

In the result of calculation, the next of the temperature of the current carrying buses in the rated value has been got:

$\Theta_b = 82.21°C$, that less then $\Theta_{adm} = 95°C$ for non-release bolt connections from copper and its alloys, for aluminum and its alloys.

2.1.4 Calculation of current carrying buses thermal resistance

The short circuit mode is considered as a short-term operating mode, in which the temperature of parts of an electrical apparatus can reach values exceeding the maximum permissible temperature in continuous mode. The duration of the short circuit is short, so there is no significant change in the physicochemical properties of the insulation and other elements of the apparatus.

Nevertheless, in this case, there are limitations that are determined by the temperature of recrystallization (softening) of the material of the current carrying parts. In electrical devices, the following maximum temperature values are adopted for short-term operation:

- non-insulated current carrying parts made of copper or its alloys – 300 °C;
- aluminum current carrying parts – 200 °C;
- current carrying parts (except aluminum) in contact with organic insulation or oil – 250 °C.

If the current-carrying contour is made of dissimilar materials, the value of the maximum temperature is taken equal to the lowest value among the materials used.

Having carried out the thermal calculation in relation to the continuous mode, it is necessary to evaluate the thermal resistance of the apparatus, i.e. its ability to withstand the heating of current carrying parts without their thermal destruction by a short-circuit current flowing through them for a time called time of thermal stability. Typically, the thermal resistance time is taken equal to 1, 5 and 10 s. Short-circuit current, which during this time heats the device to the permissible temperature in this mode, called thermal current.

Calculation of the thermal impulse A_{sc}:

$$A_{sc} = I_{sc}^2 \cdot t_{sc}, A^2 \cdot s. \quad (2.1.7)$$

Permissible heating temperature in short circuit mode for copper is taken equal 200 ÷ 300 ºC.

Calculation of thermal impulse $A_{sc}(\Theta_{adm})$ taking into account permissible temperature (Θ_{adm}) in the rated mode (Θ_{sc} is taken equal to 300 ºC):

$$A_{sc}(\Theta_{perm}) = \frac{\gamma \cdot C \cdot S_{b.cr.s}{}^2}{\rho_0 \cdot \alpha} \cdot ln\frac{1 + \alpha \cdot \Theta_{sc}}{1 + \alpha \cdot \Theta_{perm}}, \quad (2.1.8)$$

where γ — density of bus material, which is equal $8.9 \cdot 10^3$ kg/m^3;

C — heat capacity of bus material, which is equal 390 J/kg·ºC;

Θ_{adm} — permissible temperature of heating of bus bolt connection, which is equal 95 ºC.

$$A_{sc}(\Theta_{perm}) = \frac{8.9 \cdot 10^3 \cdot 390 \cdot 64^2}{1.62 \cdot 10^{-8} \cdot 4.3 \cdot 10^{-3}} \cdot \ln\frac{1+4.3 \cdot 10^{-3} \cdot 250}{1+4.3 \cdot 10^{-3} \cdot 90} = 7.907 \cdot 10^7 \text{ A}^2 \cdot \text{c}.$$

Calculation of thermal stability current value $I_{sc}(\Theta_{perm})$ in the dependence of the value of calculated time of short circuit 1 s, 5 s and 10 s taking into account temperature Θ_{perm}:

$$I_{sc}(\Theta_{perm}) = \sqrt{\frac{A_{sc}(\Theta_{perm})}{t_{sc}}}, A. \quad (2.1.9)$$

$$I_{sc}^{1s}(\Theta_{perm}) = 8.892 \cdot 10^3 \text{ A},$$

$$I_{sc}^{5s}(\Theta_{perm}) = 3.977 \cdot 10^3 \text{ A},$$

$$I_{sc}^{10s}(\Theta_{perm}) = 2.812 \cdot 10^3 \text{ A.}$$

Calculation of the current density j_{sc} for thermal stability current depending on the value of the estimated short circuit time 1 s, 5 s and 10 s and taking into account permissible temperature Θ_{perm}:

$$j_{sc}(\Theta_{perm}) = \frac{I_{sc}(\Theta_{perm})}{a \cdot b}, A/mm^2. \quad (2.1.10)$$

$$j_{sc}^{1s}(\Theta_{perm}) = 139 \text{ A/mm}^2,$$

$$j_{sc}^{5s}(\Theta_{perm}) = 62.1 \text{ A/mm}^2,$$

$$j_{sc}^{10s}(\Theta_{perm}) = 44 \text{ A/mm}^2.$$

Values of the current density j_{sc}.

$$j_{sc.table}^{1s}(\Theta_{perm}) = 152 \text{ A/mm}^2,$$

$$j_{sc.table}^{5s}(\Theta_{perm}) = 68 \text{ A/mm}^2,$$

$$j_{sc.table}^{10s}(\Theta_{perm}) = 48 \text{ A/mm}^2.$$

Calculation of thermal impulse A_{sc} taking into account temperature Θ_b in the rated mode:

$$A_{sc}(\Theta_b) = \frac{\gamma \cdot C \cdot S^2}{\rho_0 \cdot \alpha} \cdot ln \frac{1 + \alpha \cdot \Theta_{sc}}{1 + \alpha \cdot \Theta_b}, \quad (2.1.11)$$

where γ — density of bus material, which is equal $8.9 \cdot 10^3$ kg/m^3;

C — heat capacity of bus material, which is equal 390 J/kg·ºC;

Θ_b — temperature of buses in the rated mode, which is equal 82.21 ºC.

$$A_{sc}(\Theta_b) = \frac{8.9 \cdot 10^3 \cdot 390 \cdot 64^2}{1.62 \cdot 10^{-8} \cdot 4.3 \cdot 10^{-3}} \cdot \ln \frac{1 + 4.3 \cdot 10^{-3} \cdot 250}{1 + 4.3 \cdot 10^{-3} \cdot 82.21} = 8.72 \cdot 10^7 \text{ A}^2 \cdot \text{c}.$$

Calculation of value of thermal stability current $I_{sc}(\Theta_{perm})$ in the dependence of the value of estimated time of short circuit 1 s, 5 s and 10 s:

$$I_{sc}(\Theta_b) = \sqrt{\frac{A_{sc}(\Theta_b)}{t_{sc}}}, A. \quad (2.1.12)$$

$$I_{sc}^{1s}(\Theta_b) = 9.338 \cdot 10^3 \text{ A},$$

$$I_{sc}^{5s}(\Theta_b) = 4.176 \cdot 10^3 \text{ A},$$

$$I_{sc}^{10s}(\Theta_b) = 2.953 \cdot 10^3 \text{ A}.$$

Calculation of the current density j_{sc} for thermal stability current depending on the value of the estimated short circuit time 1 s, 5 s and 10 s:

$$j_{sc}(\Theta_b) = \frac{I_{sc}(\Theta_b)}{a \cdot b}, A/mm^2. \quad (2.1.13)$$

$$j_{sc}^{1s}(\Theta_{perm}) = 145.909 \text{ A/mm}^2,$$

$$j_{sc}^{5s}(\Theta_{perm}) = 65.253 \text{ A/mm}^2,$$

$$j_{sc}^{10s}(\Theta_{perm}) = 46.141 \text{ A/mm}^2.$$

2.1.5 Calculation of technical parameters of flexible connection

Thickness of flexible connection is calculated by formula:

$$a_{fc} = \frac{S_{fc}}{b_{fc} \cdot k_f}, \quad (2.1.14)$$

where S_{fc} — cross-sectional area of flexible connection, which is equal $64 \cdot 10^{-6} m^2$;

$b_{fc} = b$ — width of flexible connection, which is equal $16 \cdot 10^{-3}$m;

$k_f = 0.785$ — the fill factor, the ratio of the cross-sectional area of the stranded wire to the area bounded by the contour described around it, which is equal 0.785.

Using the reference data, we select the dimensions of the flat copper wire that are closest to the calculated cross-section and permissible continuous current. If flat wire of a larger cross section is required, 2, 3 or 4 flat wires of a smaller cross section connected in parallel are used.

Actual technical parameters of the flexible connection:

a_{fc} — thickness of flexible connection, which is equal $4.6 \cdot 10^{-3}$ mm;

b_{fc} — width of flexible connection, which is equal $25 \cdot 10^{-3}$ mm;

n_{fc} — number of wires connected in parallel, which is equal 3;

$I_{perm.1.fc}$ – permissible continuous current through one flexible connection, which is equal 105 A.

2.2 Calculation of contact connections

Dismountable bolted connections of flat current-carrying buses are used as contact connections in the contactor.

During the calculation of conductors in DC contactor current carrying contour it is necessary to solve tasks:

– to determine area and dimensions of cross-section in rated mode;

– to test selected cross section in short-term mode:

a) for maximum inrush currents;

b) for emergency currents.

External appearance of non-detachable bolt joint of two current carrying buses with cross-section $S = a \times b$ with overlap $l_{b.o}$ is presented on figure 2.1. Force of contact pressure is created by pair bolt – nut. Washer is used to increase contact area and to stabilize parameters. It is permissible to use several bolt connections.

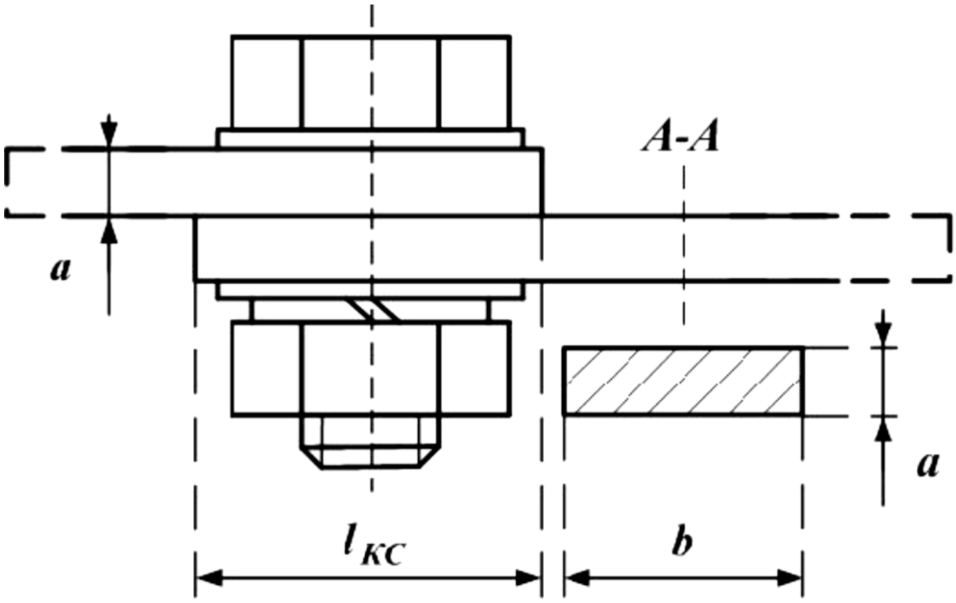

Figure 2.1 - Contact connection of flat current carrying buses

Overlap length of flat buses ends or flat surfaces of connected current carrying parts is usually sufficient to take equal to the bus width or width of the part contact plane, if it is possible to place required number of bolts.

2.2.1 Calculation of transition resistance of non-releasable bolted connection "bus-bus"

From the reference data in accordance with the individual task, the recommended value of the current density *j* for a non-releasable connection is selected:

j — recommended value of current density, which is equal 0.54 A/mm^2.

2.2.2 Calculation of the force of contact pressure

Calculation formula of required contact surface area S_1 is:

$$S_1 = \frac{I_{eq}}{j}, \tag{2.2.1}$$

where S_1 contact surface area of buses;

I_{eq} — equivalent current in the main contour of contactor;

j — recommended value of current density.

$$S_1 = \frac{206.45}{0.54} = 382.315\ mm^2.$$

Length of buses overlap $l_{b.o}$ is calculated by formula:

$$l_{b.o} = \frac{S_1}{b}, \tag{2.2.2}$$

where $l_{b.o}$ — length of buses overlap;

b — width of current carrying bus.

To get permissible values of transition resistance and voltage drop in contact connection, it is necessary to put contact pressure f_c on buses in accordance with recommendations.

Selection of recommended values f_c:

Not tinned copper – material of current carrying buses;

$f_{c.rec}$ — recommended contact pressure, which is equal 7 $\mathrm{H/mm^2}$.

Contact force F_c^b "bus – bus" is calculated by formula:

$$F_c^b = f_c \cdot S_1, \tag{2.2.3}$$

$$F_c^b = 7 \cdot 382.315 = 2.676 \cdot 10^3\ H.$$

By the value of contact force F_c^b from the reference data, we select required number of bolts n with estimated tightening force $F_{bolt}^1 \geq F_c^b$. During this process, it is necessary to consider that total area of contact sideslips $S_{c.s}$ shoudn't be less then calculated area S_1 of buses contact surface.

Besides, diameter d of holes in the bus for installing the bolt should be no more than 1/2 ÷ 1/3 of current carrying bus width *b*. Bolt hole can be selected just 0.1 mm over bolt diameter *d*. It is impermissible to exceed value of nominal current per one bolt.

Distance between bolts centers is chosen not less than (2.2 ÷ 2.4) *d*. This requirement limits number of bolts in non-detachable bolt joint. It is not recommended to use more than 4 bolts.

Actual length of buses overlap $l_{b.o}^{act}$ should be clarified by formula:

$$l_{b.o}^{act} = 2.2 \cdot d_{bolt} \cdot n, \tag{2.2.4}$$

where $l_{b.o}^{act}$ — actual length of buses overlap;

d_{bolt} — diameter of bolt, which is equal 6 mm;

n — number of bolts in contact connection, which is equal 4.

$$l_{b.o}^{act} = 2.2 \cdot 6 \cdot 4 = 53 \text{ mm}.$$

In subsequent calculations clarified value of actual length of buses $l_{b.o}^{act}$ should be used.

In the result of performed calculations the following parameters are accepted:

St.3 – bolt steel grade;

d – diameter of bolt, which is equal 5 mm;

n – number of bolts in contact connection, which is equal 3;

$S_{c.s}$ – area of contact sideslip of one bolt, which is equal 115 mm^2;

$S_{c.s}^{n}$ – area of contact sideslip of n bolts, which is equal 210 mm^2;

S_1 – area of buses contact surface, which is equal 382.315 mm^2;

F_c^b – calculated contact force, which is equal 2676 H;

F^{l}_{bolt} – tightening force of one bolt, which is equal 1400 H;

$I^{\text{bolt}}_{\text{rat}}$ – rated current through the one bolt, which is equal 40 A.

2.2.3 Calculation of contact connection total resistance

Total resistance of electrical contact connection $R_{c.tot}$ consists from transition resistance of contact surfaces R_c and ohmic resistance of contact R_{c1}. Resistance R_{c1} differs from resistance of the straight section of the bus due to the distortion of the current lines at the point of contact. This leads to an increase of resistance, which is taken into account by the correction factor.

2.2.4 Calculation of transition resistance of contact surfaces

$$R_c = \frac{k_s \cdot (1 + \frac{2}{3} \cdot \alpha \cdot \theta_{perm})}{n \cdot (0.102 \cdot F_c^b)^m}, \qquad (2.2.5)$$

where k_s — factor, that depends on material and condition of surface, which is equal $0.14 \cdot 10^{-3}$;

α — temperature factor of resistance, which is equal $4.3 \cdot 10^{-3}$ 1/°C;

θ_{perm} — permissible heating temperature of bolt connection, which is equal 95°C;

n — number of bolts in contact connection, which is equal 4;

F_c^b — calculated force of contact pressure, which is equal 2676 H;

m — factor of contact surface form, which is equal 0.8.

$$R_c = \frac{0.14 \cdot 10^{-3} \cdot (1 + \frac{2}{3} \cdot 4.3 \cdot 10^{-3} \cdot 95)}{4 \cdot (0.102 \cdot 2676)^{0.8}} = 5.009 \cdot 10^{-7} \text{Ohm}.$$

2.2.5 Calculation of ohmic contact resistance

$$R_{c1} = k_{cor} \cdot \frac{\rho_0 \cdot l_{cc}^{act}}{S}, \tag{2.2.6}$$

where k_{cor} — correction factor, which is equal (0.3 ÷ 0.6);

ρ_0 — electrical resistivity, which is equal $1.62 \cdot 10^{-8}$ Ohm×m;

$l_{b.o}^{act}$ — actual length of contact connection, which is equal $53 \cdot 10^{-3}$ m;

S — cross-sectional area of the current carrying bus, which is equal $64 \cdot 10^{-6}$ m^2.

$$R_{c1} = 0.3 \cdot \frac{1.62 \cdot 10^{-8} \cdot 53 \cdot 10^{-3}}{64 \cdot 10^{-6}} = 4.01 \cdot 10^{-6}\ Ohm.$$

Contact connection total resistance is calculated by formula:

$$R_{c.tot} = R_c + R_{c1}, \tag{2.2.7}$$

$$R_{c.tot} = 5.009 \cdot 10^{-7} + 4.01 \cdot 10^{-6} = 4.51 \cdot 10^{-6}\ Ohm.$$

2.2.6 Calculation of temperature exceeding of contact connection

In the rated mode temperature of contact connection τ_c should not exceed the heating temperature θ_b of buses adjoined to it more than 10°C and combined with θ_b should not be higher than permissible temperature θ_{perm} .

Temperature exceeding of contact connection is calculated by the formula:

$$\tau_c = \frac{I_{eq}^2 \cdot R_{c.tot}}{k_{ht} \cdot S_{ext.surf}}, \tag{2.2.8}$$

where $S_{ext.surf}$ — total area of connection external surface, which is equal

$$2 \cdot (2a + b) \cdot l_{b.o}^{act} = 2 \cdot (2 \cdot 4 \cdot 10^{-3} + 16 \cdot 10^{-3}) \cdot 53 \cdot 10^{-3} =$$
$$= 2.534 \cdot 10^{-3} m^2;$$

k_{ht} — heat transition factor, which is equal $9 \frac{\text{W}}{\text{m}^2 \times {}^\circ\text{C}}$.

$$\tau_c = \frac{206.45^2 \cdot 4.51 \cdot 10^{-6}}{9 \cdot 2.534 \cdot 10^{-3}} = 8.428°C.$$

Thermal parameters of contact connection:

τ_c — exceeding of contact connection temperature, which is equal 8.428°C ;

θ_b — heating temperature of the current carrying buses in the rated mode, which is equal 82.21°C;

$\theta_b + \tau_c$ — temperature of bus contact connection, which is equal 90.638°C;

θ_{perm} — permissible heating temperature of bus connection, which is equal 95°C.

2.3 Calculation of switching contacts

2.3.1 Calculation of dimensions of switching contacts

Calculation of dimensions of movable contact cross-section is performed by electrical density of current j_c. If I_{eq} in range from 20 A up to 1000 A, density of current is in the range:

$$j_c = (2.0 \div 7.5),\ \text{A/mm}^2.$$

Smaller values of j_c are applied in continuous operation mode at high currents, and a greater value - for intermittent or short-term operation mode.

General view of the main copper contact without facing and with silver or cermet facing is shown on the figure 2.2.

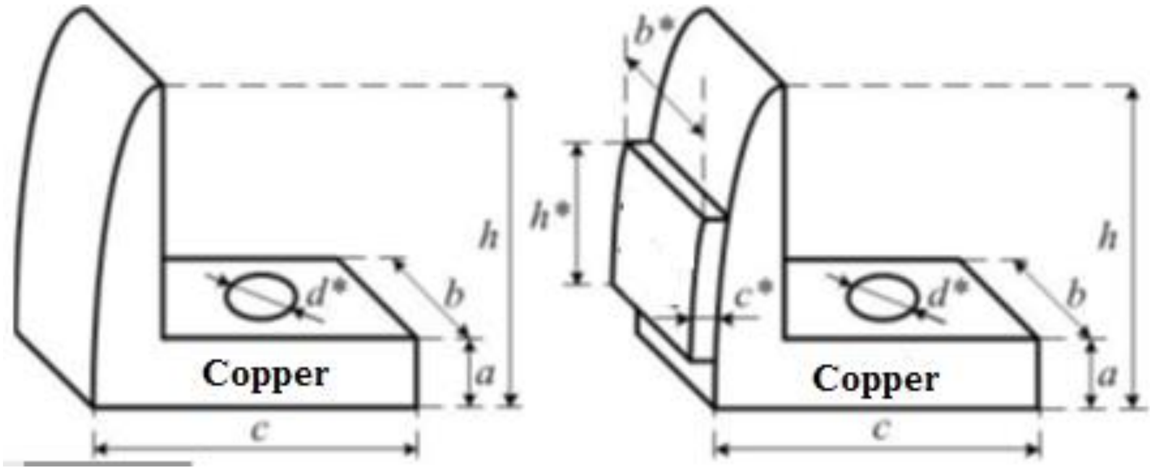

Figure 2.2 - General view of the main copper contact without facing and with silver or cermet facing

Calculation of area of movable contact cross-section S_{mc}:

$$S_{mc} = \frac{I_{eq}}{j_c}, \quad (2.3.1)$$

$$S_{mc} = \frac{206.45}{5} = 41.29\ mm^2.$$

Width of movable contact b_{mc} is calculated by formula:

$$b_{mc} = k_1 \cdot \sqrt{I_{eq}}, \quad (2.3.2)$$

where b_{mc} — width of movable contact;

k_1 — characteristic coefficient, which is equal $(1.1 \div 2.1)\ mm * A^{0.5}$.

$$b_{mc} = 1.4 \cdot \sqrt{206.45} = 20.116\ mm.$$

Thickness a of movable and fixed contact is chosen the same and calculated by formula:

$$a = \frac{S_{mc}}{b_{mc}}, \qquad (2.3.3)$$

$$a = \frac{41.29}{20.116} = 2.053\,mm.$$

a — refined technological value of thickness a, which is equal 3 mm.

Width of fixed contact b_{fc} is selected with taking into account permissible offset of movable contact from estimated position. Width of fixed contact b_{fc} should be $20 \div 25\%$ greater than width of movable contact b_{mc}.

$$b_{fc} = 1.2 \cdot b_{mc} \qquad (2.3.4)$$

$$b_{fc} = 1.2 \cdot 20.116 = 24.139\,mm.$$

To increase erosion resistance of the main contacts, their working surface can be faced with cermet or silver plates. Plate is soldered with refractory solder to the working surface of the main contact. Height h^* is selected in the range 1/2 ÷ 2/3 of contact height h.

Pads for facing of the main contacts are selected. Their width should be equal or wider than calculated values b_{mc} and b_{fc}. Dimensions h^* and c^* for movable and fixed contacts should be equal. Value c^* is selected depending on the values I_{eq}, z and N.

Dimensions of facing plate for moving contact:

$$b_{mc}^* = 20\,mm;\ h^* = 14\ mm;\ c^* = 3\,mm;$$

Dimensions of facing plate for fixed contact:

$$b_{fc}^* = 25\,mm;\ h^* = 14\ mm;\ c^* = 3\,mm;$$

Calculation of actual linear current density $j_{l.act}$ in switching contact:

$$j_{l.act} = \frac{I_{eq}}{b_{mc}^{*}}, \tag{2.3.5}$$

$$j_{l.act} = \frac{206.45}{20} = 10.323\, A/mm.$$

Calculation of actual current density $j_{l.act}$ in switching contact:

$$j_{s.act} = \frac{I_{eq}}{a \cdot b_{mc}^{\cdot}}, \tag{2.3.6}$$

$$j_{s.act} = \frac{206.45}{3 \cdot 20} = 3.441\ A/mm..$$

Actual dimensions of the main movable contact:

$$a_{mc}^{act} = a_{mc} = 3\, mm \text{ — thickness;}$$
$$b_{mc}^{act} = b_{mc} = 20\, mm \text{ — width;}$$
$$c_{mc}^{act} = a_{mc}^{act} + b_{mc}^{act} = 23\, mm \text{ — length;}$$
$$h_{mc}^{act} = c_{mc}^{act} = 23\, mm \text{ — height;}$$

Actual dimensions of the main fixed contact:

$$a_{fc}^{act} = a_{mc} = 3\, mm \text{ — thickness;}$$
$$b_{fc}^{act} = b_{fc} = 25\, mm \text{ — width;}$$
$$c_{fc}^{act} = a_{fc}^{act} + b_{fc}^{act} = 28\, mm \text{ — length;}$$
$$h_{fc}^{act} = c_{fc}^{act} = C \text{ — height;}$$

2.3.2 Selection of bolts, which attach contacts to the contact holder and lead of arc extinguishing current coil

Movable and fixed contact are attached to the contact holder with bolts. Contact holder and arc extinguishing coil are made from copper. Reliability of construction depends on parameters of bolts and tightening torque.

2.3.3 Calculation of force of contact pressure “contact-contact holder”

Required calculated contact surface area of movable contact is calculated by formula:

$$S_{mc}^{calc} = \frac{I_{eq}}{j}, \tag{2.3.7}$$

where S_{mc}^{calc} — calculated contact area of movable contact and contact holder;

I_{eq} — equivalent current in the main contour of contactor, which is equal 206.45 A;

j — recommended value of current density, which is equal $0.54\ A/mm^2$;

$$S_{mc}^{calc} = \frac{206.45}{0.54} = 382.315\ mm^2.$$

Calculation of actual contact surface area of movable contact and contact holder:

$$S_{mc}^{act} = b_{mc}^{act} \cdot c_{mc}^{act}; \tag{2.3.8}$$

$$S_{mc}^{act} = 20 \cdot 23 = 460\ mm^2.$$

From two values S_{mc}^{calc} and S_{mc}^{act} smallest value is selected for further calculation.

It is necessary to create contact pressure f_c according to the reference data to obtain the permissible values of the transient resistance and voltage drop in the contact connection "contact - contact holder".

The following recommended values f_c are selected:

Not tinned copper — material of contact connection;

f_c — recommended contact pressure, which is equal $12\ H/mm^2$.

Force of contact pressure $F_{cont}^{cont.hold}$ is calculated by formula:

$$F_{cont}^{cont.hold} = f_c \cdot S_{mc}^{calc}, \tag{2.3.9}$$

where f_c— specific pressure in contacting parts, which is equal $12\ H/mm^2$;

S_{mc}^{calc} — calculated contact area of movable contact and contact holder, which is equal $382.315\ mm^2$.

$$F_{cont}^{cont.hold} = 12 \cdot 382.315 = 4588\ H.$$

One bolt with calculated tightening force $F_b^1 \geq F_{cont}^{cont.hold}$ is selected by the value of required contact force $F_{cont}^{cont.hold}$. In the process of bolt selection, it is necessary to take into account that contact spot area S_{cs} shouldn't be less than S_{mc}^{calc}.

Bolt similar to that calculated above is used to attach fixed contact to the lead of arc extinguishing coil.

As a result of calculation the next technical parameters of bolt connection "contact — contact holder" are taken:

Steel 3 — bolt steel grade;

d — diameter of bolt, which is equal 12 mm;

S_{mc}^{calc} — calculated contact area of movable contact and contact holder, which is equal $382.315\ mm^2$;

$I_{nom.1.b} = 250\ A$.

2.3.4 Calculation of force of switching contacts contact pressure "moving contact - fixed contact"

All electrical apparatuses are designed with taking into account permissible overloads. Calculated force of contact pressure F_c should ensure the operation of the contact unit in all modes. In particular, it is necessary to exclude contact welding, discarding of contacts due to the action of electrodynamic forces in the contact pads and significant vibration.

Calculation of force of contact pressure F_c is performed by formula:

$$F_c = k \cdot F_c^1, \text{ N}, \qquad (2.3.10)$$

where k — contact type factor, number of contact areas; for point contact k = 1, for linear contact k = 2, for plane contact k = 3;

F_c^1 — force of contact pressure per elementary contact area.

Force of contact pressure F_c "moving contact - fixed contact" reduced to contacts is calculated by empirical formula:

$$F_c = k \cdot I_{eq}^2 \cdot \frac{k_L \cdot \pi \cdot H_B}{16 \cdot \lambda^2 \cdot \left[arccos\left(\frac{\Theta_{cond}}{\Theta_{h.cont.area}}\right)\right]^2}, \qquad (2.3.11)$$

where I_{eq} — equivalent current of the main contour, which is equal $206.45\ A$;

k_L — Lorentz number, which is equal $2.3 \cdot 10^{-8}\ (Wt * Ohm/°C)^2$;

λ — heat conductivity of material of current carrying conductor, which is equal $350\ Wt/(m \cdot °C)$;

H_B — contact material Brinell hardness, which is equal $600 \cdot 10^6\ H/m^2$;

Θ_{cond} — temperature of conductor at the point distant from the contact area;

$\Theta_{h.cont.area}$ — temperature of contact area heating;

If contacts are faced with silver plates or cermet then values λ and H_B should be selected from tables of plates material.

When performing the calculation the largest value between I_{rat} and I_{eq} is selected. Equivalent current I_{eq} is a current that would cause the same heating of current-carrying parts as the actual rated current during long-term flow, in conjunction with additional heating contacts with an electric arc.

Temperature of conductor Θ_{cond} at the point distant from the contact area is calculated by formula:

$$\Theta_{cond} = \frac{I_{eq}^2 \cdot \rho_0}{k_{ht} \cdot P_{s.c} \cdot S_{s.c}} + \Theta_{env} + 273, \quad (2.3.12)$$

where ρ_0 — resistivity of KMK-A20, which is equal $2.5 \cdot 10^{-8}\ Ohm * m$;

k_{ht} — heating transfer coefficient, which is equal 9 $\frac{\text{W}}{\text{m}^2 \cdot {}^\circ\text{C}}$;

$P_{s.c}$ — perimeter of switching contact, which is equal:

$$2 \cdot (a_{mc}^{act} + b_{mc}^{act}) = 2 \cdot (3 + 20) = 46 \cdot 10^{-3}\ m;$$

$S_{s.c}$ — cross-sectional area of contact, which is equal:

$$a_{mc}^{act} \cdot b_{mc}^{act} = 3 \cdot 20 = 60 \cdot 10^{-6}\ m^2;$$

Θ_{env} — environmental tempeature, which is equal 40°C.

$$\Theta_{cond} = \frac{206.45^2 \cdot 2.5 \cdot 10^{-8}}{9 \cdot 46 \cdot 10^{-3} \cdot 60 \cdot 10^{-6}} + 40 + 273 = 355.896\ K.$$

Temperature of heating $\Theta_{h.cont.area}$ of contact area is calculated by formula:

$$\Theta_{h.cont.area} = \Theta_{cond} + \tau_{cont.area}^{s.c}, \quad (2.3.13)$$

where Θ_{cond} — temperature of conductor at the point distant from the contact area, which is equal $355.896\ K$;

$\tau_{cont.area}^{s.c}$ — contact area temperature excess of main switching contacts, which is equal $10 \div 15°$.

$$\Theta_{h.cont.area} = 355.896 + 10 = 365.896\ K.$$

Heating temperature of contact area $\Theta_{h.cont.area}$ shouldn't exceed recrystallization temperature of electrical contact material Θ_{recr}. Values of voltages U_{recr}, U_{melt} and temperature of recrystallization Θ_{recr} and melting Θ_{melt}.

In the result of performed calculations, the following parameters of the main switching contacts are defined:

F_c — force of contact pressure, which is equal 34.338 H;

Θ_{cond} — temperature of the conductor at the point distant from the contact area, which is equal 82.896 °C;

$\Theta_{h.cont.area}$ — heating temperature of the contact area, which is equal 92.896 °C;

Θ_{recr} — recrystallization temperature of electrical contact material, which is equal 150 °C.

2.3.4 Calculation of transition resistance of switching contacts

Transition resistance of the main switching contacts R_{tr} is calculated by several methods using theoretical and practical dependence. The highest value of R_{tr} is used for further calculations.

Calculation of transition resistance of switching contacts by theoretical dependence:

Transition resistance of switching contacts $R_{tr.theor}$ is calculated by formula (1-st method):

$$R_{tr.theor} = \frac{\rho_0 \cdot (1 + \alpha \cdot \theta_{perm}^{s.c})}{2 \cdot r \cdot k}, \tag{2.3.14}$$

where ρ_0 — resistivity of KMK-A20, which is equal $2.5 \cdot 10^{-8}$ Ohm·m ;

α — temperature coefficient of contact material resistance, which is equal $4.4 \cdot 10^{-3}$ 1/°C;

$\theta_{perm}^{s.c}$ — permissible temperature of heating, which is equal 105°C;

r — radius of circular contact area of contact touch, depending on the type of deformation, m.

k — contact type factor, number of contact areas, which is equal 2.

Elastic deformation of micro protrusions on the contact surface occurs with insignificant values of pressing force (up to 0.01 H). With increasing of pressing force up to 0.1 ÷ 0.15 H occurs plastic deformation, resulting in hardening of the material. With further increasing of pressing force up to hundreds of Newton's elastic deformation of metal layer occurs again and with even greater pressure, plastic deformation of layer occurs again.

In case of plastic deformation, the radius r of the circular contact area of contacts touch is calculated by the empirical formula:

$$r = \sqrt{\frac{F_c^1}{\pi \cdot H_B}}, \qquad (2.3.15)$$

where H_B — contact material Brinell hardness, which is equal $600\ H/mm^2$;

$F_c^1 = \frac{F_c}{k}$ — force of contact pressure per one contact area, which is equal $17.169\ H$.

$$r = \sqrt{\frac{17.169}{3.14 \cdot 600}} \cdot 10^{-3} = 9.544 \cdot 10^{-5}\ m.$$

$$R_{tr.theor} = \frac{2.5 \cdot 10^{-8} \cdot (1 + 4.4 \cdot 10^{-3} \cdot 105)}{2 \cdot 9.544 \cdot 10^{-5} \cdot 2} = 9.574 \cdot 10^{-5}\ Ohm.$$

Calculation of R_{tr} by empirical formula:

Calculation of transition resistance of switching contacts $R_{tr.theor}$ is performed by formula (2-nd method):

$$R_{tr.emp} = \frac{k_{surf}}{(0.102 \cdot F_c)^m} \cdot (1 + \frac{2}{3} \cdot \alpha \cdot \theta_{per}^{s.c}), \quad (2.3.16)$$

where k_{surf} — coefficient depending on the material and contact surface condition, which is equal $0.2 \cdot 10^{-3}$;

F_c — $f$orce of contact pressure of the main contacts, which is equal $34.338\ H$;

m — coefficient of contact surface form, which is equal 0.7;

α — temperature coefficient of contact material resistance, which is equal $4.4 \cdot 10^{-3}\ 1/°\text{C}$;

$\theta_{perm}^{s.c}$ — permissible heating temperature, which is equal $105°\text{C}$.

$$R_{tr.emp} = \frac{0.2 \cdot 10^{-3}}{(0.102 \cdot 34.338)^{0.7}} \cdot (1 + \frac{2}{3} \cdot 4.4 \cdot 10^{-3} \cdot 105) =$$

$$= 1.088 \cdot 10^{-4}\ Ohm.$$

Calculation of R_{tr} by graph dependences:

As a result of numerous experiments in laboratory conditions and on operating full-scale objects, the dependences of R_{tr} on the value of the force of contact pressure $R_{tr} = f(F_c)$ were determined for various materials used in electrical apparatus design.

Due to the fact that current I_{eq} in the direct current contactor flows through resistance, then there will be a voltage drop. The larger the R_{tr} value is, the greater the value of power heat losses will be released at the switching contacts, which leads to their increased heating and acceleration of the oxidation processes of the contacting surfaces.

The graphs show the experimental dependences $R_{tr} = f(F_c)$, which make it possible to estimate the order of R_{tr} depending on the material of the main contacts.

According to the third method, the transition resistance of the switching contacts R_{tr} has the following value:

$$R_{tr.gr} = 0.18 \cdot 10^{-4}\ Ohm.$$

2.3.5 Calculation of the voltage drop and heating temperature of switching contacts

When switching contacts are closed voltage drop in the current carrying contour consists of the transition resistance of switching contacts and transition resistances of dismountable and detachable connections.

The value of the voltage drop in the transition resistance of the switching contacts can be obtained by measurement. In addition to the value of the transition resistance concentrated in the contact area, the measured value includes the value of the resistance of the metal of the contact located between the points of application of the measuring electrodes and the contact area. But the resistance of the metal is insignificant in comparison with the value of the transition resistance R_{tr}.

Therefore, the voltage drop $U_{s,c}$ on closed switching contacts can be approximately expressed by the formula:

$$U_{sc} = I_{eq} \cdot R_{tr}, \tag{2.3.16}$$

where I_{eq} — equivalent current in the main current contour of contactor, which is equal $206.45\ A$;

$R_{tr} = 1.088 \cdot 10^{-4}\ Ohm.$

$$U_{sc} = 206.45 \cdot 1.088 \cdot 10^{-4} = 0.022 \text{ mV}.$$

In existing designs of devices, the voltage drop U_c on the clean contacts should be within the following limits:

— for contacts operating in air: U_{sc} = 2 ÷ 30 mV;

— for water cooled contacts: U_{sc} = up to 30 ÷ 40 mV.

Anyway, the voltage drop across the contacts should be less than the recrystallization voltage U_{recr}. In addition to the recrystallization voltage, the recrystallization temperature of the main contacts metal θ_{recr} is used.

The heating temperature of the contact area $\theta_{h.cont.area}$ shouldn't not exceed the metal recrystallization temperature θ_{recr} to ensure the reliable operation of the switching contacts. Also, the heating temperature of the contact area $\theta_{h.cont.area}$ should be significantly lower than the temperature of melting θ_{melt}, at which welding of contacts occurs, and shouldn't not reach the boiling point θ_{boil}.

The excess of temperature of the contact area $\tau_{c.m}^{s.c}$ is calculated according to the calculated value of the voltage drop U_c on the switching contacts. Calculated value is compared with the previously accepted value of $\tau_{c.m}^{s.c}$ calculated by the formula (2.3.17).

Contact area temperature of switching contacts excess over contact material is calculated by formula:

$$\tau_{c.m}^{s.c} = \frac{U_c^2}{8 \cdot \rho_0 \cdot \lambda}, \qquad (2.3.17)$$

where U_c — voltage drop on closed switching contacts, which is equal $0.022\ mV$;

ρ_0 — resistivity, which is equal $2.5 \cdot 10^{-8}\ Ohm * m$;

$\lambda = 350\ Wt/(m \cdot ℃)$.

$$\tau_{c.m}^{s.c} = \frac{0.022^2}{8 \cdot 2.5 \cdot 10^{-8} \cdot 350} = 7.206℃.$$

The refined value of heating temperature of contact area $\theta_{h,cont,area}$ is calculated by the formula:

$$\theta_{h.cont.area} = \theta_{cond} + \tau_{c.m}^{s.c}, \qquad (2.3.18)$$

where θ_{cond} — temperature of conductor at the point distant from the contact area, which is equal $82.896℃$;

$\tau_{c.m}^{s.c}$ — contact area temperature of switching contacts excess over contact material, which is equal 7.206℃.

$$\theta_{h.cont.area} = 82.896 + 7.206 = 90.102℃.$$

It is necessary to calculate the value of the excess of the temperature of the contact area $\tau_{c.m}^{s.c}$ of the switching contacts according to the reference data. The condition must be met:

$$\theta_{h.cont.area} \leq \theta_{perm}^{s.c} \tag{2.3.19}$$

As a result of the calculations, the following values of the parameters of the switching contacts were obtained and accepted:

U_{sc} — voltage drop on closed switching contacts, which is equal $0.022\ mV$;

$\tau_{c.m}^{s.c}$ — contact area temperature of switching contacts excess over contact material, which is equal 7.206°C;

$\theta_{h,cont,area}$ — heating temperature of contact area of switching contacts.

2.3.6 Calculation of permissible value of the current I_{perm} through the switching contacts

The permissible value of the current I_{perm} through the closed switching contacts provides the possibility of the contact node to implement the specified operating mode taking into account the contact materials, the design form of the contact surface, the accepted value $\tau_{c.m}^{s.c}$.

Value of permissible current I_{perm} is calculated by formula:

$$I_{perm} = (0.5 \div 0.8) \cdot \frac{U_{recr}}{R_{tr}}, \tag{2.3.20}$$

$where\ U_{recr}$— recrystallization voltage of contact metal, which is equal $0.09\ V$;

R_{tr} — value of transition resistance, which is equal $1.088 \cdot 10^{-4} Ohm$.

$$I_{perm} = 0.7 \cdot \frac{0.09}{1.088 \cdot 10^{-4}} = 579\ A.$$

2.3.7 Calculation of the value of contact welding current

When currents, which are significantly higher than the rated ones (during overloads, starts, short circuits), flow through the switching contacts, there occurs an increased heating of contacts and they are welded. Thermal and electrodynamic stabilities are important parameters, which are expressed in the values of the maximum permissible current. Welding of contacts may not be the cause of failure of the device if the disconnecting mechanism is able to open the welded contacts.

2.3.8 Calculation of initial current of switching contacts welding

Calculation of initial current of switching contacts welding I_{weld}^{in} is permormed both according to the theoretical dependences and the experimental data.

The theoretical method is based on the ratio that establishes the relationship between the voltage drop in the contact U_c and the steady-state heating temperature of the contact area. The calculation is performed by the following relationship:

$$I_{weld}^{in} = A \cdot \sqrt{k_{c.s}} \cdot \sqrt{F_c}, \tag{2.3.21}$$

where I_{weld}^{in} — initial welding current of contact material;

A — characteristic coefficient;

$k_{c.s} = 2$;

F_c — force of contact pressure, which is equal 3.4338 kgF .

Characteristic coefficient A is calculated by formula:

$$A = \sqrt{\frac{32 \cdot \lambda \cdot \theta_{h.cont.area.ref} \cdot (1 + \frac{1}{3} \cdot \alpha \cdot \theta_{h.cont.area.ref})}{\pi \cdot H_B \cdot \rho_0 \cdot (1 + \frac{2}{3} \cdot \alpha \cdot \theta_{h.cont.area.ref})}}, \tag{2.3.22}$$

where λ — heat conductivity of conductor material, which is equal $350\ Wt/(m * ℃)$;

$\theta_{h.cont.area.ref}$ — heating area of contact area, which is equal 90.102°C;

α — temperature coefficient of contact material resistance, which is equal $4.4 \cdot 10^{-3}\ 1/$°C;

ρ_0 — resistivity of KMK-A20, which is equal $2.5 \cdot 10^{-8}\ Ohm * m$;

H_B — contact material Brinell hardness, which is equal 600 · $10^6\ H/m^2$;

$$A = \sqrt{\frac{32 \cdot 350 \cdot 90.102 \cdot (1 + \frac{1}{3} \cdot 4.4 \cdot 10^{-3} \cdot 90.102)}{3.14 \cdot 600 \cdot 10^6 \cdot 2.5 \cdot 10^{-8} \cdot (1 + \frac{2}{3} \cdot 4.4 \cdot 10^{-3} \cdot 90.102)}}$$

$$= 437.908\ A/kgF.$$

$$I_{weld}^{in} = 437.908 \cdot \sqrt{2} \cdot \sqrt{34.338} = 3.629 \cdot 10^3 A.$$

Calculation of the I_{weld}^{in} by the experimental data is performed by formula:

$$I_{weld.exp}^{in} = k_{weld} \cdot \sqrt{F_c}, \quad (2.3.23)$$

where k_{weld} — coefficient of contact value, which is equal $1300\ A/H^{0.5}$;

F_c — force of contact pressure, which is equal $34.338\ H$.

$$I_{weld.exp}^{in} = 1300 \cdot \sqrt{34.338} = 7.618 \cdot 10^3 A.$$

Obtained values of initial welding current are compared with each other and lower value is taken:

$$I_{weld}^{in} = 3.629 \cdot 10^3\ A.$$

Calculation of current of switching contacts welding is performed by formula:

$$I_{weld} = 10 \cdot I_{eq}, \quad (2.3.24)$$

$$I_{weld} = 10 \cdot 206.45 = 2.065 \cdot 10^3 A.$$

2.3.9 Calculation of electrodynamic repulsive forces

The electrodynamic forces of the F_{EDF} between the switching contacts arise when high currents flow through them, these forces tend (due to the narrowing of the current lines) to reduce the pressing force of the F_c contacts and even discard them. This causes an increase in the contact resistance R_{tr} of the contacts, vibration of the moving contact, the formation of an arc and, with an excessively high current, welding of the contacts.

Calculation of electrodynamic repulsive force F_{EDF} is performed by formula:

$$F_{EDF} = I_{weld}^2 \cdot 10^{-7} \cdot ln\frac{S_{s.c}}{S_0}, \qquad (2.3.25)$$

where $S_{s.c}$ — cross-section area of contact without constriction of current lines, which is equal $60\ mm^2$;

S_0— sectional area of contact zone at the point of current lines constriction,which is equal $0.073\ mm^2$;

σ_{cr} — limit crushing strength, which is equal $470\ H/mm^2$.

$$F_{EDF} = (2.065 \cdot 10^3)^2 \cdot 10^{-7} \cdot ln\frac{60}{0.073} = 2.86\ H.$$

In the result of calculation following value of F_{EDF} was obtained:

$F_{EDF} = 2.86\ H$, which is less, then $F_c = 34.338\ H$.

Thus, electrodynamic repulsive force F_{EDF} will have no effect on the current transfer process and snatch gap will not happen.

2.3.10 Calculation of the switching contacts wear

The wear of the switching contacts depends on many factors and occurs both when the current circuit is closed and when it is opened. A measure of contact wear is the reduction in dip (linear wear) and the volume or mass of metal removed from the contact surface. Mostly wear occurs due to electrical erosion when closing and opening contacts.

Switching durability *N* is a number of switchings or the permissible number of switching cycles.

This value is calculated by the formula:

$$N = \frac{V_{wear}}{V_{cl} + V_{op}} = \frac{V_{wear} \cdot \gamma}{G_{cl} + G_{op}}, \quad (2.3.26)$$

where N — switching durability, which is equal $1 * 10^6$ cycles;

V_{wear} — part of the volume of a pair of contacts that will be subject to wear, which is equal;

γ — the specific density of the material contacts KMK-A20, which is equal $9.5 \cdot 10^3\ kg/m^3$;

V_{cl} — specific volumetric wear with one closing of the switching contacts;

V_{op} — specific volumetric wear with one opening of the switching contacts;

G_{cl} — specific mass wear with one closing of switching contacts;

G_{op} — specific mass wear with one opening of switching contacts.

2.3.11 Calculation of specific mass wear of switching contacts

According to the empirical dependence the total average mass wear of a pair of contacts (one electrical arc) with one switching on and off the current of more than 20 A will be equal to:

$$G_{cl} + G_{op} = k_{un} \cdot (k_{cl} \cdot I_{eq}^2 + k_{op} \cdot n_{tr} \cdot I_{eq}^2) \cdot 10^{-9}, \quad (2.3.27)$$

where k_{un} — coefficient of unevenness that takes into account the unequal wear of the anode and cathode material, which is equal 1.1 ÷ 3;

k_{cl} — factor of contact material wear when closing, which is equal $0.01 \cdot 10^{-3}\ kg/A^2$;

k_{op} — factor of contact material wear when opening, which is equal $0.08 \cdot 10^{-3} kg/A^2$;

n_{tr} — tripping current ratio, which is equal 3;

$$G_{cl} + G_{op} = 0.01 \cdot 10^{-3} \cdot (0.01 \cdot 10^{-3} \cdot 206.45^2 + 0.08 \cdot 10^{-3} \cdot 3 \cdot 206.45^2) \cdot 10^{-9} = 2.131 \cdot 10^{-8}\ kg.$$

2.3.12 Calculation of the contact volume wearing part and linear contact wear

Calculation of switching contacts volume part that will be subjected to wear is performed by formula:

$$V_{wear} = \frac{N}{\gamma} \cdot (G_{cl} + G_{op}), \qquad (2.3.28)$$

$$V_{wear} = \frac{1 \cdot 10^6}{9.5 \cdot 10^3} \cdot 2.131 \cdot 10^{-8} = 2.243 \cdot 10^{-6}\ m^3.$$

Calculation of switching contact linear wear is performed by formula:

$$L_{wear} = \frac{V_{wear}}{S_{mc}^{act}}, \qquad (2.3.29)$$

where S_{mc}^{act} — actual contact area of movable contact, which is equal $460 \cdot 10^{-6}\ m^2$;

$$L_{wear} = \frac{2.243 \cdot 10^{-6}}{460 \cdot 10^{-6}} = 4.877 \cdot 10^{-3}\ m.$$

Wear of each switching contact (or facing plate) up to 0.5 ÷ 0.75 of the original thickness is allowed.

2.3.13 Calculation of the snatch gap

Snatch gap is the value of displacement of the movable contact at the level of its point of contact with the fixed contact in case the fixed contact is removed.

Snatch gap provides reliable circuit closure when the thickness of the contacts decreases due to erosion of their material because of the action of an electric arc. The value of the snatch gap determines the margin of contact material for wear during the operation of the contactor.

The technical value of the snatch gap can be calculated from the linear wear L_{wear} of the switching contact:

$$\sigma_{sg} = 2 \cdot L_{wear} \tag{2.3.30}$$

$$\sigma_{sg} = 2 \cdot 4.877 \cdot 10^{-3} = 9.753 * 10^{-3}\ m.$$

Technical value of the snatch gap was selected $\sigma_{sg} = 10\ mm$

2.4 Calculation of arc extinguishing system

Extinguishing of an electric arc in devices of low voltage (up to 1000 volts) is one of the urgent problems, which contains a very complex set of issues in electrical engineering and physics. The task of arc-extinguishing system design is to ensure that the system meets the following requirements:

- should have sufficient switching capacity to switch on and off currents flowing under given conditions;
- should have minimal arcing time;
- should have minimal dimensions of arcing system;
- should have minimal sound and light effects.

Arc extinguishing in the DC chute with longitudinal slot in a transverse magnetic field is used when it is not possible to extinguish the arc by mechanical stretching and due to electrodynamic forces arising from the interaction of the magnetic field of the current which flows through the parts of the current carrying contour and the arc.

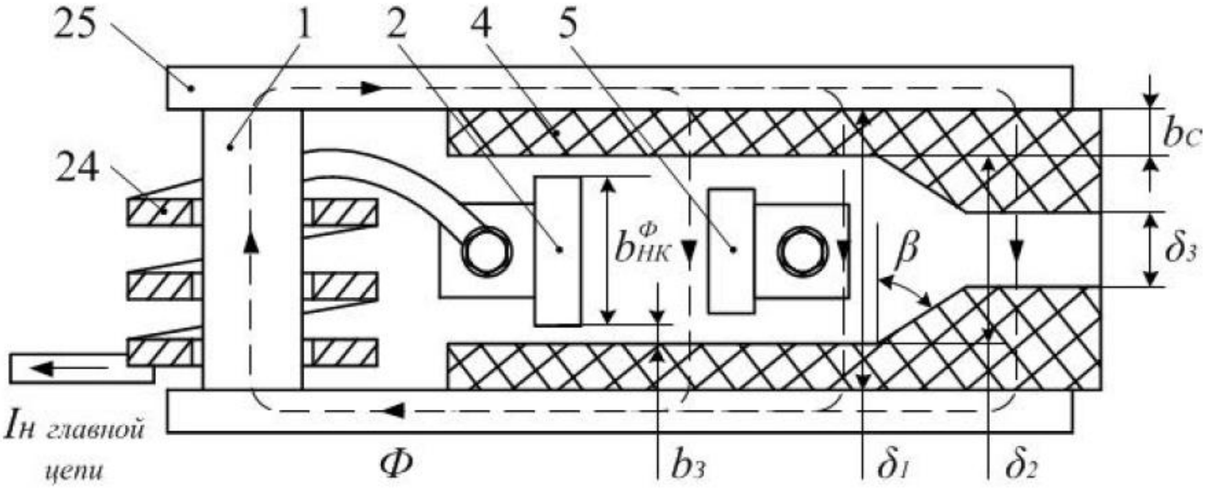

Figure 2.3 – Construction scheme of arcing chute with current coil

Chute has two side walls 4 with thickness b_w made from arc heat resistant electrical insulating material, switching contacts 2. Distance between walls in the place of location of contacts is δ_2. Width of technological gap b_3 between fixed contact 2 and chute wall is equal 2 mm. Pole plates 25 of electromagnetic system are adjoined to the external surface of walls. Electromagnetic system has core 1 and arc extinguishing coil 24. Distance between pole plates is δ_1. Electromagnetic system creates magnetic flux F, which flows through pole plates in in the zone of formation and burning of the arc, followed by disappearance after the extinction of the arc.

When contacts 2 and 5 are opened, an arc is formed between them. Due to the emerging forces F_{arc} the arc D is lengthened, enters a narrow slot δ_3, while its support points move along the arcing horns. In order to reduce the dimensions of the chute and the contactor, as well as to reduce weight and save materials, the arc can exit the chute.

Long arc length results in large dimensions of the camera and apparatus. Increase in the length of the arc with the same overall dimensions of the chute can be obtained by using a zigzag slot.

To drive the arc into a narrow slot, it is necessary to have a smooth transition with the angle of narrowing of the arc-extinguishing chute β from the wide contact part of the chute δ_2 to the slot δ_3 and create a sufficient strength H of the transverse magnetic field.

Intensity of magnetic field H must be sufficient to drive the arc into the gap δ_3 show the values of the minimum intensity H of the magnetic field, sufficient to drive the arc into a narrow slot.

It should be noted that when the arc-extinguishing coil is connected in series, its magnetizing force is proportional to the value of the tripping current.

The magnetizing force and the cross-section of the magnetic circuit 1 are calculated so that at small breaking currents there is no saturation, and almost the entire MF falls on the air gap δ_1 between the poles of the magnetic circuit, that is, to the contact gap from which it is necessary to push the formed arc. At high currents, the magnetic circuit must be saturated in order to reduce the intensity *H* of the magnetic field in the air gap between the poles and thereby reduce the speed of the arc, the intensity of its extinguishing, overvoltage and wear of the contacts. The absence and presence of saturation of the magnetic circuit can be determined by the magnetization curve of the magnetic circuit obtained during calculation of the arc extinguishing magnetic system.

The intensity *H* of the magnetic field should be optimal in terms of contact wear during the most frequent current trippings. When the contacts are opened, a short isthmus of molten metal appears between them. At low intensity *H* of the magnetic field, increased wear of contacts 2 and 5 occurs due to metal evaporation due to the long duration of arc burning. With a high intensity *H* of the magnetic field, the wear of the contacts increases due to the ejection (splashing) of the molten metal of the switching contacts by electrodynamic forces.

The presence of an external magnetic field causes sharp reduction of the contact opening in the region of low currents and insignificantly affects the arc extinguishing process at currents of 100 A and above. The most optimal magnetic induction is $B = 0.0069\,T$.

2.4.1 Calculation of critical length of extinguished arc

During the process of extinguishing, the electric arc is stretched to the critical length l_{cr}, after which it breaks up into parts and goes out. The l_{cr} value can be calculated by the following empirical formula:

$$l_{cr} = k_{cr} \cdot U_{rat} \cdot \sqrt[3]{I_{tr}}, \qquad (2.4.1)$$

where k_{cr} — coefficient of the critical length of arc, equals $(7 \div 13)\cdot 10^{-5}$ m/V×A;

U_{rat} — rated voltage of the main contour;

I_{tr} — limit tripping current;

$$I_{tr} = n_{tr} \cdot I_{eq},$$

$$I_{tr} = 3 \cdot 206.45 = 619.351\,A;$$

$$l_{cr} = 10 \cdot 10^{-5} \cdot 220 \cdot \sqrt[3]{619.351} = 0.188\,m$$

The coefficient k_{cr} depends on the value of the inductance included in the load resistance R_l of the main countour of the contactor.

2.4.2 Calculation of plate-pole magnetic system area

When using a slot chute, the break of the limiting current I_{tr} is accompanied by the arc going out of the chute by 0.1 ÷ 0.2 m. Thus, the area of the side surface S_{ac} of the chute with typical for contactors aspect ratio 1:2 is calculated by formula:

$$S_{ac} = \frac{(0.02 \times l_{cr}^2)}{k_{us}}, \qquad (2.4.2)$$

where k_{us} — coefficient of arc chute space usage;

$$S_{ac} = \frac{0.02 \cdot 0.188^2}{0.7} = 1.01 \cdot 10^{-3}\ m^2.$$

Ferromagnetic pole-plate area S_{pp} which provides supply of a magnetic field to the arc burning zone is calculated

$$S_{pp} = 0.4 \cdot S_{ac}, \qquad (2.4.3)$$

$$S_{pp} = 0.4 \cdot 1.01 \cdot 10^{-3} = 4.04 \cdot 10^{-3}\ m^2.$$

2.4.3 Calculation of distance between pole plates

Value of air (non-magnetic) clearance δ_1 in the magnetic system of arc chute is equal to distance between poles and depends on actual width of the fixed contact b_{fc}^{act}. Except this, there is provided technical gap b_g between chute walls and contact b_{fc}^{act}, also width of wall b_w is taken into account.

Distance between pole plates is calculated by formula:

$$\delta_1 = (b_{fc}^{act} + 2b_g + 2b_w) \cdot 10^{-3}, \qquad (2.4.4)$$

where b_{fc}^{act} — actual width of fixed contacts, which is equal 25 mm;

b_g — width of the gap between fixed contact and arc extinguishing chute, which is equal 2 mm;

b_w — thickness of the arc extinguishing chute, which is equal 5 mm;.

$$\delta_1 = (25 + 2 \cdot 2 + 2 \cdot 5) \cdot 10^{-3} = 0.039\ m.$$

2.4.4 Calculation of magnetic flux in pole plates zone

The parameters of the arc-extinguishing coil 24 are determined by the average value of the magnetic induction B in the zone of the pole plates, the value of which affects the electromagnetic force F_{EM}, which have influence on the electric arc. Decreasing of the magnetic induction B reduces the efficiency of arc extinguishing (the arc burning time increases). Increasing of the magnetic induction B leads to an increase of switching overvoltages and increased wear of the switching contacts.

Experience in design and operation has shown that the value of the magnetic induction $B = 0.0069\ T$ provides an acceptable time for the arc extinguishing within 0.05 ÷ 0.1 s and relatively low overvoltage at the contacts of the electrical apparatus.

The value of the magnetic flux of the F_{pp} in the zone of the pole plates is calculated by the formula:

$$F_{pp} = B_{ave} \cdot S_{pp}, \tag{2.4.5}$$

where B_{ave} — average value of magnetic induction, which is equal 0.0069 T;

S_{pp} — pole-plate area of arc chute, which is equal $4.04 \cdot 10^{-3}\ m^2$;

$$F_{pp} = 0.0069 \cdot 4.04 \cdot 10^{-3} = 2.788 \cdot 10^{-5}\ Wb.$$

The value of the magnetic flux of the F_c in the core 1 of the current coil (Figure 2.3) can be calculated by the formula:

$$F_c = k_{ms} \cdot F_{pp}, \tag{2.4.6}$$

where k_{ms} — coefficient of magnetic stray, which is equal 1.1;

F_{pp}— value of magnetic flux in plate zone, which is equal $2.788 \cdot 10^{-5}\ Wb$;

$$F_c = 1.1 \cdot 2.788 \cdot 10^{-5} = 3.067 \cdot 10^{-5}\ Wb.$$

Magnetic resistance of magnetic circuit steel is negligible in comparison with the magnetic resistance of gap between poles. Consequently, in calculation of induction B_s it is possible to take into account only magnetic resistance of gap between poles. So, induction B_s is calculated by formula:

$$B_{ave} = \mu_0 \cdot H = \frac{\mu_0 \cdot (I \times w)_{acc}}{\delta_1 \cdot k_{ms}}, \tag{2.4.7}$$

where $(I \times w)_{acc}$ — magnetizing force of arc extinguishing current coil;

μ_0 — magnetic constant, which is equal $1.26 * 10^{-6}\ H/m$;

w — turns number of current coil.

Calculation of magnetizing force of current coil is performed by formula:

$$(I \times w)_{acc} = \frac{B_{ave} \cdot \delta_1 \cdot k_{ms}}{\mu_0}, \tag{2.4.8}$$

$$(I \times w)_{acc} = \frac{0.0069 \cdot 0.039 \cdot 1.1}{1.26 \cdot 10^{-6}} = 234.929\ A.$$

2.4.5 Calculation of turns number of arc extinguishing current coil

Turns number w_{acc} of arc extinguishing current coil is calculated by formula:

$$w_{acc} = \frac{(I \times w)_{acc}}{0.5 \cdot I_{eq}}, \tag{2.4.9}$$

$$w_{acc} = \frac{234.929}{0.5 \cdot 206.45} = 2.276.$$

In the formula (2.4.4.9), the coefficient 0.5 allows us to take into account the fact that the induction of the B_c should be provided with the average value of the tripping current in the circuit, changing during the arc extinguishing from I_{eq} to 0. Calculated value of w_{acc} is rounded to the nearest larger number.

2.4.6 Selection of bus technical parameters for current coil

Arc extinguishing coil is made from rectangular copper bus, wound on narrow edge.

The technical parameters of the bus are following:

a — thickness of current carrying bus, which is equal 4 mm;

b — width of current carrying bus, which is equal 16 mm;

k_g — bus geometry factor, which is equal 4;

S — bus cross-section area, which is equal 64 mm^2.

2.4.7 Calculation of cross-sectional area of current coil core

Cross-sectional area S_c of current coil core should be sufficient to prevent saturation of steel. It allows to maintain a linear relationship between the magnetic flux F_c and the current I_{eq} that creates it in a wide range of current loads. Core saturation should occur at tripping currents $I_{tr} = (2.2 \div 3.5)I_{eq}$.

The cross-sectional area S_c of the ferromagnetic core of the arc-extinguishing current coil is calculated by the formula:

$$S_c = \frac{F_c}{B_{ave}}, \tag{2.4.10}$$

$$S_c = \frac{3.067 \cdot 10^{-5}}{0.0069} = 4.445 \cdot 10^{-3}\ m^2.$$

Calculation of core diameter is performed by the formula:

$$d_c^{calc1} = \sqrt{\frac{4 \cdot S_c}{\pi}}, \tag{2.4.11}$$

$$d_c^{calc1} = \sqrt{\frac{4 \cdot 4.445 \cdot 10^{-3}}{3.14}} = 0.075\ m.$$

To calculate the actual value of the core diameter, the obtained value is rounded up to a larger whole number.

d_c^{act1} — actual diameter arc extinguishing coil core, which is equal 20 mm.

2.5 Calculation of additional contacts

Auxiliary contacts are an integral part of the contactor and are intended for electrical connection of the contactor with external controls, signaling, etc. In different types of contactors, they can be point, linear or planar.

In the calculated DC contactor point type of contact is accepted. Silver is used as the auxiliary contact material. Depending on the value of the current I_{ac} through the auxiliary contacts, the diameter d_c and the thickness c^* of the contact linings:

I_{ac} — current, which flows through auxiliary contacts, which is equal 10 A;

d_{ac} — diameter of the contact lining, which is equal 5 mm;

c^* — thickness of the contact lining, which is equal 1 mm.

The value of the specific pressing of the auxiliary contacts f_p is selected in the range of 0.05 ÷ 0.1 N/A, depending on the value of the current I_{ac}. Next step is calculation of the force of the final pressing F_{cs}^{f} and the force of the initial pressing F_{cs}^{in} of the compression spring, which acts on the block contacts:

f_p — specific pressing, which is equal 0.1 N/A;

I_{ac} — current, which flows through auxiliary contacts, which is equal 10 A;

F_{cs}^{f} — force of the final pressing of the spring,

$$F_{cs}^{f} = f_p \cdot I_{ac}, \qquad (2.5.1)$$

$$F_{cs}^{f} = 0.1 \cdot 10 = 1\ N;$$

F_{cs}^{in} — force of the initial pressing of the spring,

$$F_{cs}^{in} = 0.5 \cdot F_{cs}^{f}, \qquad (2.5.2)$$

$$F_{cs}^{in} = 0.5 \cdot 1 = 0.5\ N.$$

To connect auxiliary contacts to the external control and automation elements, the technical parameters of the connecting wires are selected:

DC% — duty cycle, which is equal 60%;

I_{ac} — current, which flows through auxiliary contacts, which is equal 10 A;

S_{wire} — cross-sectional area of the wire, which is equal 0.5 mm^2.

2.6 Kinematic calculation of the electromagnetic drive

The task of kinematics is to determine the movement of the links of the mechanism, independent from the forces acting on them. The purpose of the kinematic diagram is to give a visual and accurate view of the transmission and transformation of movement by the links of the mechanism. The kinematic diagram is built for the most characteristic positions of the movement cycle of the mechanism, including for the two extreme positions - the on and off position of the apparatus. One of the characteristic positions of switching devices is the moment when the switching contacts are touched.

All links and kinematic pairs of the mechanism are depicted on the kinematic diagram in conventional designations, their relative position and connection with other parts of the apparatus are indicated. The diagram, if possible, indicates the main data characterizing the kinematics of the mechanism:

— stroke value or angle of rotation of the driven and driving links;

— theoretical shoulder lengths, gear ratios;

— location and direction of vectors of forces or moments of forces;

— other data, for example, for electromagnetic mechanisms - operating air gap, for the mechanisms of switching contacts - opening, snatch gap, slipping and rolling of the moving contact.

In the electromagnetic contactor, both driving and opposing forces act. Forces and pairs of forces (moments) are divided into the following types:

— driving forces or pairs of forces of driving electromagnetic, spring, electric motor and other mechanisms. These forces are applied to leading link.

— forces of useful resistances. For switching devices - pressing forces contacts made by springs.

— forces of harmful resistance. These are the forces of friction in kinematic pairs, hydrodynamic drag forces, the forces of gas pressure in arc extinguishing chute.

— the forces of gravity. The action of these forces can be both beneficial and harmful.

— electrodynamic forces. These forces become significant with high currents, such as short-circuit currents, and they must be taken into account. Electrodynamic forces can be useful and harmful.

— forces and moments of inertia forces. These forces arise during unsteady movement of the mechanism - when the links move with acceleration and deceleration.

The forces of inertia do positive and negative work, depending on from their direction. During the period of the movement cycle of the mechanism forces of inertia is zero. When constructing a static characteristic, it not taken into account.

— reaction forces in kinematic pairs.

2.6.1 Characteristics of the opposing forces

Calculation of the initial compression force of the contact springs of all poles: Figure 2.4 shows typical design diagrams of electromagnetic-spring mechanisms of DC contactors, as well as the corresponding kinematic diagrams in the on state of the contactor, when $\delta = \delta_{min}$. The armature 11 of the electromagnet can move relative to the axis of rotation O under the action of either the electromagnetic force F_{em}, or the force F_{rs} of the return spring and the force F_{cs} of the contact spring. In addition, the contact holder 7 with the movable contact 5 has the ability to rotate on the prism 10. This technical solution allows to create an F_{cs} force on the main contacts 2 and 5 when snatch gap occurs.

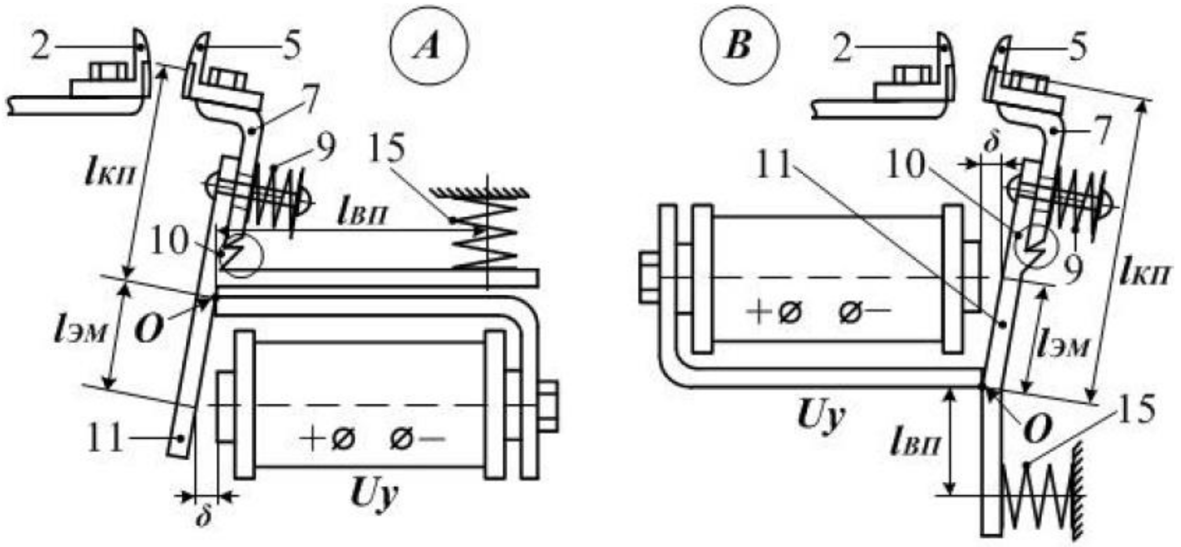

Figure 2.4 —. Typical design diagrams of electromagnetic-spring mechanisms of contactors A, B.

The armature of the electromagnet is attracted to its core under the action of the force F_{em} on the arm l_{em} of the application of the electromagnetic force. In this case, the force of the contact spring pressing F_{cs} on the shoulder l_{cs} was formed. In addition, the force of the F_{em} is counteracted by the force of the return spring F_{rs} on the shoulder lВП. The action of gravity and other forces is neglected in the calculation.

To perform calculations of the contact spring 9 and the return spring 15, it is necessary to consider the arms of the application of forces:

— the shoulder of application l_{em} of the traction force of the electromagnet F_{em} (point O is the axis of symmetry of the electromagnet core);

— the shoulder of application l_{cs} of the force of the contact spring F_{cs} (point O - the middle of the contacting surface of the movable main contact 5);

— the shoulder of the application l_{rs} of the force of the return spring F_{rs} (point O - the middle of the support platform of the return spring 15).

With a relatively small working gap of the electromagnet (10 ÷ 12 mm), to obtain an opening σ_{op} of the main switching contacts, sufficient for reliable extinguishing of the electric arc, the ratio of the shoulders must be within 1,0 ÷ 1,9.

The acting forces of all springs must be brought to the working gap δ along the symmetry axis of the electromagnet core, i.e. to the place of application of the electromagnetic force F_{em}. The spring forces are brought to the working gap in order to be able to match the driving and counter-driving forces at the moment of switching on of the contactor.

The movement of the apparatus mechanism can be considered as movement along a certain trajectory of a material point, to which all acting forces are brought, both driving forces and forces of resistance to movement. This point is called the reduction point, and the forces are called reduced. Pairs of forces can also be reduced to one link of reduction.

The reduced forces and moments of forces in their action should be equivalent to the action of driving forces and moments. The value of the reduced force F^* is determined from the condition that its work on a possible displacement of the point of application is equal to the work of the actual force (or moment).

In the following calculations, the values referred to the working clearance δ are denoted with a dot, for example the reduced value of the force F^*.

Two-link lever-hinge mechanisms are widespread in electrical devices, any force F acting on the shoulder *l* can be reduced to the point of application of the electromagnetic force F_{em} located on the shoulder l_{em}, based on the dependence:

$$F^* = (\frac{l}{l_{em}}) \cdot F, N, \qquad (2.6.1)$$

where F^* — force reduced to the shoulder *l*.

2.6.2 Calculation of full value of contact gap and snatch gap

At snatch gap of the main contact 5 (see Fig. 2.4) from one extreme position (contacts 2 and 5 are open) to the second extreme position (contacts 2 and 5 are closed), the working gap δ of the electromagnet drive varies from δ_{max} up to $\delta_{min} = 0$.

The value of the switching contacts opening σ_g is calculated by the empirical formula:

$$\sigma_g = 0.42 \cdot 10^{-3} \cdot U_{nom} \cdot 3.1 \cdot \sqrt{I_{tr}}, \qquad (2.6.2)$$

$$\sigma_g = 0.42 * 10^{-3} \cdot 220 \cdot 3.1 \cdot \sqrt{619.351} = 7.129\, mm.$$

We select the technical value of the contact $\sigma_g = 7.2\, mm.$

The total value of the opening and the snatch gap of the switching contacts are calculated:

$$\sigma = \sigma_g + \sigma_{br}, \qquad (2.6.3)$$

where σ_g — value of contact gap, which is equal 7.2 mm.

σ_{sg} — value of snatch gap, which is equal 10 mm.

$$\sigma = 7.2 + 10 = \ 17.2\, mm.$$

According to the results of the calculation σ, it is necessary to determine the maximum value of the working gap of the electromagnet δ_{max}, which should not be more than 10 ÷ 12 mm. Otherwise, it is necessary to change the ratio of the shoulders in the range of 1.0 ÷ 1.9 or apply another typical design scheme (A or B) of the solenoid-spring mechanism of the contactor in accordance with Figure 2.4.

The working gap δ_{max} must be as short as possible to ensure the design value σ. This will reduce the size, power and operating temperature of the electromagnet, eliminate vibration of the main contacts when and thereby increase the service life of the contactor.

$$\delta_{max} = (\frac{l_{em}}{l_{cs}}) \cdot \sigma, \qquad (2.6.4)$$

$$\delta_{max} = 0.588 \cdot 17.2 = 10.114\, mm$$

Technical value of the working gap $\delta_{max} = 10.2\ mm$.

The critical clearance of the electromagnet δ_{cr} is calculated, corresponding to the moment of touching the main contacts when the armature moves from the position δ_{max} through the point δ_{cr} to the final value δ_{min}. To eliminate the sticking of the armature to the pole piece due to residual magnetization when the solenoid coil is disconnected, the gap $\delta_{min} = 0$.

$$\delta_{cr} = (\frac{l_{em}}{l_{cs}}) \cdot \sigma_g, \tag{2.6.5}$$

$$\delta_{cr} = 0.588 \cdot 7.2 = 4.234 \approx 4.3\ mm.$$

The value of the initial compression force F_{cs}^{*in} of contact springs of all poles p, reduced to the working clearance δ, is calculated by the formula:

$$F_{cs}^{*in} = (\frac{l_{cs}}{l_{em}}) \cdot F_c \cdot p, \tag{2.6.6}$$

$$F_{cs}^{*in} = 1.7 \cdot 34.338 \cdot 1 = 58.374\ N.$$

Calculation of the final compression force of the contact springs is performed by formula:

$$F_{cs}^{*f} = 1.5 \cdot F_{cs}^{*in}, \tag{2.6.7}$$

$$F_{cs}^{*f} = 1.5 \cdot 58.374 = 87.562\ N.$$

Calculation of the final compression force of the return spring is performed by formula:

$$F_{rs}^{*f} = k_{rs} \cdot F_{cs}^{*in}, \tag{2.6.8}$$

$$F_{rs}^{*f} = 0.5 \cdot 58.374 = 29.128\ N.$$

Calculation of the initial compression force of the return spring is performed by formula:

$$F_{rs}^{*in} = k_{rs} \cdot F_{rs}^{*f}, \tag{2.6.9}$$

$$F_{rs}^{*in} = 0.5 \cdot 29.128 = 14.594\ N.$$

Based on the performed calculations, the characteristic of the opposing forces $F^* = f(\delta)$ is plotted, reduced to the working gap δ of the electromagnet. Dependence of the opposing forces $F^* = f(\delta)$ on the value of the working gap δ is shown in Figure 2.5. Each straight line is constructed according to two calculated values (points) of the reduced forces: F_{rs}^{*in} and F_{rs}^{*f} forces of the return spring, F_{cs}^{*in} and F_{cs}^{*f} forces of the contact spring.

The value of the force of the return spring F_{cs}^{*f} at a critical clearance δ_{cr} can be determined from the graph in Figure 2.5 or calculated by the formula:

$$F_{rs}^{*cr} = F_{rs}^{*in} + (\frac{\delta_{cr}}{\delta_{max}} \cdot F_{rs}^{*in}), \tag{2.6.10}$$

$$F_{rs}^{*cr} = 14.594 + (\frac{4.234}{10.114} \cdot 14.594) = 20.703\ N.$$

Calculation of the opposing forces F_{cr}^{*} at a critical gap δ_{cr}, which corresponds to the moment of the main contacts touching when the armature of the electromagnet moves:

$$F_{cr}^{*} = F_{rs}^{*cr} + F_{cs}^{*in}, \tag{2.6.11}$$

$$F_{cr}^{*} = 20.703 + 58.374 = 79.077\ N.$$

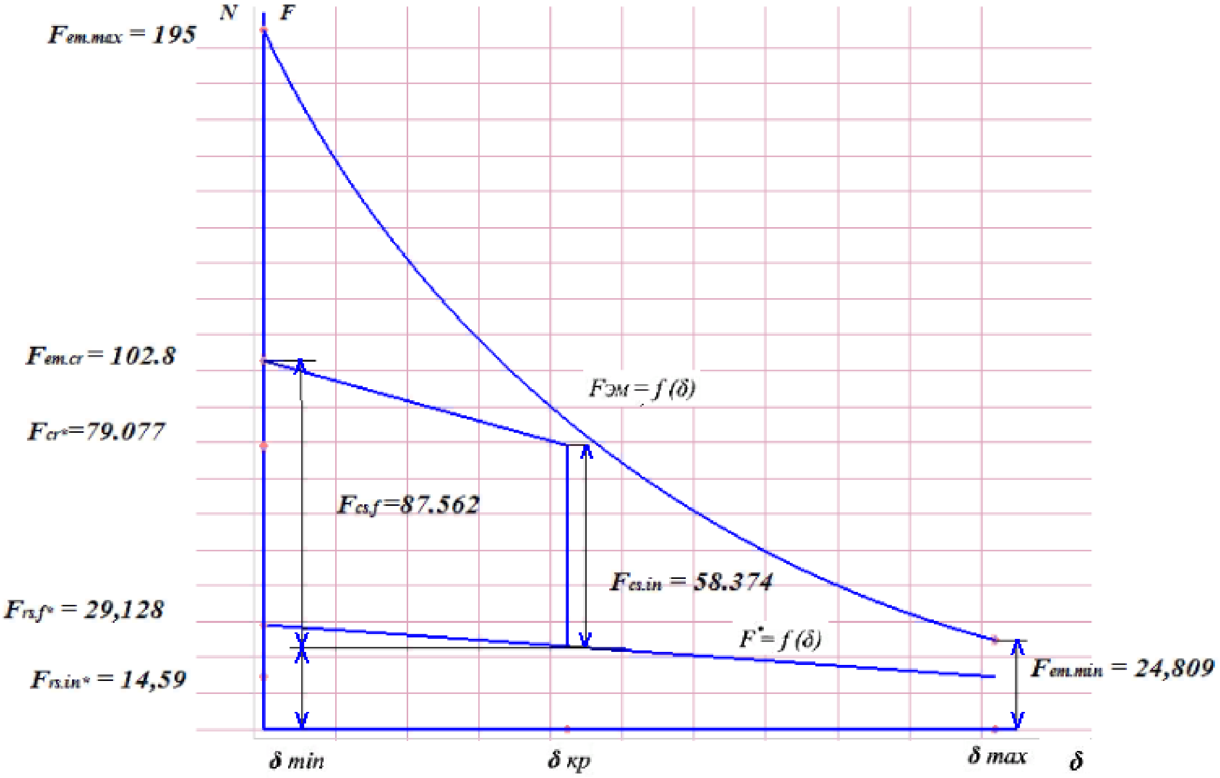

Figure 2.5 — Traction $F_{em} = f(\delta)$ and opposing characteristics $F* = f(\delta)$ reduced to δ.

According to the known value of the force F_{cr}^{*} at a critical gap δ_{cr} is the force F_{em}^{cr}, which the electromagnet should develop at δ_{cr}.

$$F_{em}^{cr} = k_{fs} \cdot F_{cr}^{*}, \tag{2.6.12}$$

where k_{fs} — force safety factor, which is equal 1.3.

$$F_{em}^{cr} = 1.3 \cdot 79.077 = 102.8\ N.$$

Calculation of the point corresponding to the required minimum F_{em}^{min} developed by the electromagnet at the maximum working gap δ_{max} is performed by the formula:

$$F_{em}^{min} = k_{fs} \cdot F_{rs}^{*in}, \tag{2.6.13}$$

$$F_{em}^{min} = 1.3 \cdot 14.594 = 24.809\ N.$$

The traction characteristic of the electromagnet $F^* = f(\delta)$ is drawn out through the points F_{em}^{max} and δ_{min}. The graph determines the approximate value of the electromagnet force F_{em}^{max} at a working gap δ_{min}.

Value of F_{em}^{max} calculated by the graph:

$$F_{em}^{max} = 195\ N.$$

It should be noted that the gap $\delta_{min} \neq 0$ is provided by the so-called “peel-off” plate with a thickness of 0.2 to 0.5 mm made of diamagnetic material, as a rule, of brass.

2.6.3 Calculation of the coil springs

Almost every electrical device has one or more springs. Springs of electrical devices perform a responsible role, so determine the main characteristics of the devices, therefore, their calculation is of great importance.

The action of the spring is based on the use of the potential energy stored by the spring, due to its preliminary deformation by the forces of electromagnetic, pneumatic, electric motor, manual or other mechanism.

Springs and spring mechanisms have important properties: forces are proportional to deformations and do not depend on their position in space.

The most widely used are springs in electrical apparatus: flat cantilever springs of rectangular cross-section and cylindrical helical compression and extension springs.

Coil springs twisted from a wire or bar are used when it is necessary to obtain significant deflections.

Since the previously performed calculation was carried out with the forces brought to the axis of symmetry of the electromagnet core (the forces are reduced to the working gap of the electromagnet), then to calculate the real technical parameters of the springs, it is necessary to perform the reverse transformation, i.e. bring the action of the forces directly to the location of the springs in the contactor.

It should be noted that the calculation of the parameters of the springs is of a qualitative nature, since the averaged values of the arms of the application of forces and their ratio are used. Nevertheless, this approach turns out to be justified and makes it possible to trace the basic laws of the calculation. The information on the leverage ratio required for the calculation can be obtained from Figure 2.4.

2.6.4 Calculation of the technical parameters of the return spring

When the electromagnet is triggered, the armature moves from position δ_{max} to position $\delta_{min} \neq 0$. In this case, the force of the return spring, reduced to the working clearance of the electromagnet, changes from the value F_{rs}^{*in} (the armature is released, but there is already a preliminary compression force of the spring) to the value F_{rs}^{*f} (the armature is attracted, the compression force of the spring is maximum).

The actual (not reduced to the working clearance of the electromagnet) pressing force of the return spring F_{rs} is calculated by the formula:

$$F_{rs} = (\frac{l_{em}}{l_{rs}}) \cdot (F_{rs}^{*f} - F_{rs}^{*in}), \qquad (2.6.14)$$

$$F_{rs} = (\frac{10}{25}) \cdot (29.187 - 14.594) = 5.837\ N.$$

The actual deflection of the return spring f_{1rs} is calculated from the previously calculated value of the working air gap δ_{max}:

$$f_{1rs} = (\frac{l_{rs}}{l_{em}}) \cdot \delta_{max}, \qquad (2.6.15)$$

$$f_{1rs} = 2.5 \cdot 10.114 = 25.284\ N.$$

To perform following calculations it is necessary to select the return spring index:

$$c_{1rs} = 20.$$

Calculation of the diameter of the wire of the return spring d_{1rs}^{calc}:

$$d_{1rs}^{calc} = \sqrt{\frac{8 \cdot F_{rs} \cdot c_{1rs}}{\pi \cdot \sigma_{cr}}}, \tag{2.6.16}$$

$$d_{1rs}^{calc} = \sqrt{\frac{8 \cdot 5.837 \cdot 20}{3.14 \cdot 470}} = 0.795\, mm.$$

Based on the calculated value d_{1rs}^{calc} from table values, the actual value of the diameter of the carbon wire d_{1rs} is calculated:

$$d_{1rs} = 0.8\, mm.$$

Average diameter of the return spring D_{1rs} is equal:

$$D_{1rs} = c_{1rs} \cdot d_{1rs}, \tag{2.6.17}$$

$$D_{1rs} = 20 \cdot 0.8 = 16\, mm.$$

Number of the active turns of the return spring n_{1rs} is calculated by formula:

$$n_{1rs} = \frac{f_{1rs} \cdot G \cdot d_{1rs}}{8 \cdot F_{rs} \cdot (c_{1rs})^3}, \tag{2.6.18}$$

where f_{1rs} — actual deflection of the return spring, which is equal 25.284 N;

F_{rs} — actual pressing force of the return spring, which is equal 5.837 N;

c_{1rs} — return spring index, which is equal 20;

G — torsional elastic shear modulus, which is equal 79500 N/mm^2.

$$n_{1rs} = \frac{25.284 \cdot 79500 \cdot 0.8}{8 \cdot 5.837 \cdot 20^3} = 4.304,$$

$$n_{1rs} = 5.$$

The winding pitch of the return spring t_{1rs} and its free length l_{rs}^{free} are calculated as follows:

$$t_{1rs} = d_{1rs} + \frac{f_{1rs}}{n_{1rs}}, \qquad (2.6.19)$$

$$t_{1rs} = 0.8 + \frac{25.284}{5} = 5.857\ mm;$$

$$l_{rs}^{free} = n_{1rs} \cdot t_{1rs} + 1.5 \cdot d_{1rs},$$

$$l_{rs}^{free} = 5 \cdot 5.857 + 1.5 \cdot 0.8 = 30.484\ mm.$$

The return spring has the following technical parameters:

F_{rs} — actual pressing force of the return spring, which is equal 5.837 N;
f_{1rs} — actual deflection of the return spring, which is equal 25.284 N;
c_{1rs} — return spring index, which is equal 20;
d_{1rs} — actual value of the diameter of the carbon wire, which is equal 0.8 mm;
D_{1rs} — average diameter of the return spring, which is equal 16 mm;
n_{1rs} — number of the active turns of the return spring, which is equal 5;
t_{1rs} — winding pitch of the return spring, which is equal 5.857 mm;
l_{rs}^{free} — free length of the return spring, which is equal 30.484 mm.

2.6.5 Calculation of the technical parameters of the contact spring

Calculation of the technical parameters of the contact spring is performed similar to the previously performed calculation of the return spring.

The actual (not reduced to the working clearance of the electromagnet) pressing force of one contact spring F_{cs} is calculated by the formula:

$$F_{cs} = (\frac{l_{cs}}{l_{em}}) \cdot \frac{1}{p} \cdot (F_{cs}^{*f} - F_{cs}^{*in}), \quad (2.6.20)$$

$$F_{cs} = 1.6 \cdot \frac{1}{1} \cdot (87.562 - 58.374) = 49.618\ N.$$

The actual deflection of the contact spring f_{1cs} is calculated from the previously calculated value of the snatch gap σ_{sg}:

$$f_{1cs} = (\frac{l_{em}}{l_{cs}}) \cdot \ \sigma_{sg}, \quad (2.6.21)$$

$$f_{1cs} = 0.588 \cdot 10 = 5.88\ mm.$$

To perform following calculations it is necessary to select the contact spring index c_{1cs}:

c_{1cs} — index of the contact spring, which is equal 5.

Calculation of the contact spring wire diameter d_{1cs}^{calc}:

$$d_{1cs}^{calc} = \sqrt{\frac{8 \cdot F_{cs} \cdot c_{1cs}}{\pi \cdot \sigma_{cr}}}, \quad (2.6.22)$$

$$d_{1cs}^{calc} = \sqrt{\frac{8 \cdot 49.618 \cdot 5}{3.14 \cdot 470}} = 1.159\ mm.$$

Based on the calculated value d_{1cs}^{calc} from table values, the actual value of the diameter of the carbon wire d_{1cs} is calculated:

$$d_{1cs} = 1.2\ mm.$$

Average diameter of the return spring D_{1cs} is equal:

$$D_{1cs} = c_{1cs} \cdot d_{1cs}, \tag{2.6.23}$$

$$D_{1cs} = 5 \cdot 1.2 = 6\ mm.$$

Number of the active turns of the return spring n_{1cs} is calculated by formula:

$$n_{1cs} = \frac{f_{1cs} \cdot G \cdot d_{1cs}}{8 \cdot F_{cs} \cdot (c_{1cs})^3}, \tag{2.6.24}$$

where f_{1cs} — actual deflection of the contact spring, which is equal 5.88 N;

F_{cs} — actual pressing force of the contact spring, which is equal 49.618 N;

c_{1rs} — contact spring index, which is equal 5;

G — torsional elastic shear modulus, which is equal 79500 N/mm^2.

$$n_{1cs} = \frac{5.88 \cdot 79500 \cdot 1.2}{8 \cdot 49.618 \cdot 5^3} = 11.305,$$

$$n_{1cs} = 12.$$

The winding pitch of the contact spring t_{1cs} and its free length l_{cs}^{free} are calculated as follows:

$$t_{1cs} = d_{1cs} + \frac{f_{1cs}}{n_{1cs}}, \tag{2.6.25}$$

$$t_{1cs} = 1.2 + \frac{5.88}{12} = 1.69\ mm;$$

$$l_{cs}^{free} = n_{1cs} \cdot t_{1cs} + 1.5 \cdot d_{1cs},$$

$$l_{rs}^{free} = 12 \cdot 1.69 + 1.5 * 1.2 = 22.08\ mm. \tag{2.6.26}$$

The contact spring has the following technical parameters:

F_{cs} — actual pressing force of the contact spring, which is equal 49.618 N;

f_{1cs} — actual deflection of the contact spring, which is equal 5.88 N;

c_{1rs} — contact spring index, which is equal 5;

d_{1rs} — actual value of the diameter of the carbon wire, which is equal 1.2 mm;

D_{1rs} — average diameter of the contact spring, which is equal 6 mm;

n_{1rs} — number of the active turns of the contact spring, which is equal 12;

t_{1rs} — winding pitch of the contact spring, which is equal 1.69 mm;

l_{rs}^{free} — free length of the contact spring, which is equal 22.08 mm.

2.7 Calculation of the drive electromagnet

Currently used electromagnetic mechanisms have a variety of design forms of magnetic circuits and coils, as well as methods of supplying the coils. The most commonly used typical design diagrams of electromagnetic-spring mechanisms of contactors and the corresponding kinematic diagrams in the on state are shown in Figure 2.4.

When calculating a direct current electromagnet according to the given operating conditions of the mechanism for which the electromagnet is intended, and according to the dependence of the magnitude of the required force on the stroke of the driving link of the mechanism, the constructive form of the electromagnet is selected. The dimensions of the magnetic circuit and the coil are determined so that the cross-section of the magnetic circuit is sufficient to conduct the magnetic flux necessary to create the required electromagnet force. The dimensions of the "window" of the magnetic circuit must be sufficient to accommodate the coil. The magnetizing force of the coil must be sufficient to create the required magnetic flux. In this case, the coil must have such a heat transfer that, for a given operating mode, its temperature does not exceed the permissible value for the adopted class of heat resistance of insulating materials. Thus, the task of calculation is to determinate the dimensions and the create the structure of the electromagnet according to the specified parameters.

On the basis of a number of performed calculations and experiments on electromagnets of various design forms, a method was proposed for choosing the optimal design form according to the geometric indicator ("design factor") G_{ind}. For direct current electromagnets, the geometric indicator G_{ind} is calculated by the formula:

$$G_{ind} = \frac{\sqrt{F_{em}^{min}}}{\delta_{max} \cdot 10^{-3}}, \qquad (2.7.1)$$

$$G_{ind} = \frac{\sqrt{24.809}}{10.114 \cdot 10^{-3}} = 492.493\ H^{0.5}/m.$$

Analyzing the dependence of F_{em} and δ_{max} on the design parameters of the electromagnet, it is possible to make conclusion that the geometric index G_{ind} characterizes the ratio of the outer diameter of a cylindrical electromagnet or an electromagnet coil D_c to its length (height) l_c.

Each design form of an electromagnet, designed optimally in terms of economy in terms of weight, corresponds to a certain range of the value of G_{ind}, at which the specific consumption of materials is the lowest.

The values for DC electromagnets refer to continuous operation with an operability close to 11.5 kgf × cm and a temperature rise of 70°C.

For the manufacture of magnetic cores of both DC and AC electromagnets, as a rule, soft magnetic low-carbon ferromagnetic materials are used. The main characteristic of a magnetic material is the dependence of the magnetic induction *B* value on the strength of the magnetic field *H* - the magnetization curve. The magnetization curves of soft magnetic materials are given in the reference data.

In DC electromagnets, parts of the magnetic circuits are made from rods, strips and sheets, or they are cast in thickness that corresponds to the design section of the part. In medium-sized electromagnets, in the absence of strict requirements for reducing the coercive (holding) force and high magnetic permeability, it is advisable to make the magnetic circuit parts from high-quality structural low-carbon steel.

To optimize further calculations of the DC drive electromagnet, the following assumptions are made:

— the working air gap is small in comparison with the dimensions of the magnetic circuit and the core;

— the magnetic field in the air gap is uniform, i.e. within the area of the pole (end face) of the electromagnet core, the induction B is constant;

— there are no scattering fluxes;

— for design reasons, the pole piece in the electromagnet is not provided;

— non-working clearances are negligible.

During calculation the dimensions of the core of the magnetic circuit, the value of the initial induction in the working air gap B_δ^{min} with the released armature (δ_{max}) is selected depending on the value of the geometric index G_{ind} according to the reference data:

G_{ind} — geometrical index, which is equal $492.493\ H^{0.5}/m$;

B_δ^{min}— initial magnetic induction in the working gap δ_{max}, which is equal 0.14 T.

Induction *B* with the released armature (δ_{max}) must be chosen such that, with the armature pulled, the maximum induction in the core would be at the knee (bend) of the magnetization curve. Induction B_δ^{min} in the working air gap with the released armature for most power electromagnets is taken in the range of 0.1 ÷ 1.0 T.

2.7.1 Calculation of the cross-sectional area of the core pole

The required cross-sectional area of the pole $S_{cs.p}$ is calculated according to the selected magnetic induction B_δ^{min} in the working gap when the armature of the electromagnet is released, when δ_{max}. To calculate the area $S_{cs.p}$, the Maxwell equation of the electromagnetic force F_{em}^{min} for a DC electromagnet is used. Transforming this equation, we obtain the next formula:

$$S_{cs.p} = \frac{2 \cdot \mu_0 \cdot F_{em}^{min}}{(B_\delta^{min})^2}, \tag{2.7.2}$$

$$S_{cs.p} = \frac{2 \cdot 1.26 \cdot 10^{-6} \cdot 24.809}{(0.14)^2} = 3.19 \cdot 10^{-3} m^2.$$

2.7.2 Calculation of the diameter of the electromagnet core

Diameter of the electromagnet core d_c is calculated by the formula:

$$d_c = \sqrt{\frac{4 \cdot S_{cs.p}}{\pi}}, \tag{2.7.3}$$

$$d_c = \sqrt{\frac{4 \cdot 3.19 \cdot 10^{-3}}{3.14}} = 0.064\, m.$$

2.7.3 Selection of the electromagnet coil material

The coil must provide the required magnetizing force of the electromagnet operation, the temperature of its heating must not be higher than the maximum permissible for the adopted class of insulation heat resistance. In the production of coils of devices, a large number of brands of winding wires are used, mainly round, less often square and rectangular. Enameled wires have an important advantage - a small thickness of insulation, which increases the fill factor of the winding space k_f^w and leads to a decrease in the geometric dimensions of the coil.

When using fiber-insulated wires it is necessary to consider that silk insulation is approximately one and a half times thinner than cotton insulation. Natural materials are being successfully replaced by synthetic ones, such as artificial fibers.

Varnished cloths, insulating tapes, insulating papers, etc. are used as materials that insulate the winding current-carrying wires outside the coils and individual elements (rows, layers) of the windings inside them.

Varnishes, compounds and enamels are used for impregnation, coating of the outer surface and gluing the inner insulation of the coils (the turns of the wire are glued to each other).

Structural materials of the frames and other auxiliary materials include plastics, low-carbon steel, brass, copper. Electro cardboard, fiber, getinax, textolite, fiberglass, solders, rosin, threads, twine, etc. also are used in the manufacture.

The coil winding of an electromagnet can be wound using the following technologies:

— directly onto the insulated core of the electromagnet;

— on an insulated metal bush, which is installed on the core (fits tightly on the core);

— on a frame made of insulating material or frameless.

With different technologies, both the shape and design change, and the conditions for heat removal and the value of the coil heating temperature change. The winding is wound, as a rule, turn to turn. Between the layers, additional insulation can be laid, especially in windings for a voltage of more than 220V, to increase the electrical strength.

After manufacturing, the coil with the wrapped winding is impregnated, by dipping into a varnish bath in air or in a vacuum chamber, with electrical insulating varnish and subjected to thermal drying at a temperature and process duration specified by technical conditions. After this technological process, the winding becomes monolithic, since all the voids between the turns are filled. This leads to an improvement in the quality of insulation, improved thermal conductivity and other physical and chemical properties of an electrical product.

2.7.4 Calculation of winding dimensions and value of the magnetizing power of coil

The dimensions of the coil of an electromagnet completely depend on the value of the magnetizing force $(I \times w)_{c.em}$ required for operation, which the winding must create.

In a rationally designed electromagnet, the magnetizing force $(I \times w)_{c.em}$ calculated by the formula:

$$(I \times w)_{c.em} = 1.6 \cdot \frac{B_{\delta}^{min} \cdot \delta_{max}}{\mu_0}, \qquad (2.7.4)$$

$$(I \times w)_{c.em} = 1.6 \cdot \frac{0.14 \cdot 10.114 \cdot 10^{-3}}{1.26 \cdot 10^{-6}} = 1.798 * 10^3 A.$$

2.7.5 Calculation of the area and sectional side of the winding

The cross-sectional area S_w of the winding required to accommodate the required number of turns of insulated copper wire is calculated by the formula:

$$S_w = \frac{(I \times w)_{c.em}}{j_w^{calc} \cdot k_f^w}, \qquad (2.7.5)$$

$$S_w = \frac{1.798 \cdot 10^3}{2 \cdot 0.65} = 1.383 * 10^3\ mm^2.$$

The preliminary value of the k_f^w is taken according to the reference data, depending on the diameter of the winding wire d_{ww}^{Cu}. In subsequent calculations, the values of d_{ww}^{Cu} and k_f^w are refined.

Based on the analysis of existing structures, the following values of the ratio $l_{w.pr}/h_{w.pr}$ for direct current electromagnets with an external swinging armature can be taken:

$$l_{w.pr}/h_{w.pr} = 6. \qquad (2.7.6)$$

An increase in the ratio l_w/h_w leads to a decrease in copper consumption due to an increase in the cooling surface of the coil and an improvement in heat transfer. However, in this case, the core leakage flux increases and the useful flux in the working gap decreases, which leads to an increase in the required MF winding. In addition, this leads to an increase in the response time of the DC electromagnet.

Determination of the length (height) of the winding l_w and the width (thickness) of the winding h_w is carried out in accordance with the formulas:

$$h_w = \sqrt{S_w \cdot \frac{h_{w.pr}}{l_{w.pr}}}, \tag{2.7.7}$$

$$h_w = \sqrt{1383 \cdot \frac{1}{6}} = 15.183\ mm;$$

$$l_w = \frac{S_w}{h_w},$$

$$l_w = \frac{1383}{15.183} = 91.095\ mm.$$

To calculate the parameters of the winding wire, it is necessary to determine the the average length of the turn l_{ave}^{ext}, located on the average diameter of the electromagnet winding D_{ave}, which is calculated by the formula:

$$l_{ave}^{t} = \pi \cdot D_{ave}, \tag{2.7.8}$$

$$l_{ave}^{t} = 3.14 \cdot 83.183 = 261.326\ mm.$$

Cross-section of the winding wire S_{ww}^{calc} is calculated by the formula:

$$S_{ww}^{calc} = (I \times w)_{c.em} \cdot \frac{\rho_0 \cdot (1 + \alpha \cdot (\theta_{perm}^{ww} - \theta_{env})) \cdot l_{ave}^{t}}{U_{op}}, \tag{2.7.9}$$

$$S_{ww}^{calc} = 1.798 \cdot 10^3 \cdot\cdot \frac{1.62 \cdot 10^{-8} \cdot (1 + 4.3 \cdot 10^{-3} \cdot (105 - 40)) \cdot 261.326 \cdot 10^{-3}}{48} =$$

$$= 2.029 \cdot 10^{-7}\ m^2.$$

The diameter of the winding wire d_{ww}^{calc} is calculated by the formula:

$$d_{ww}^{calc} = \sqrt{\frac{4 \cdot S_{ww}^{calc} \cdot 10^{-6}}{\pi}}, \tag{2.7.10}$$

$$d_{ww}^{calc} = \sqrt{\frac{4 \cdot 2.029 \cdot 10^{-1}}{3.14}} = 0.508\, mm.$$

An equal or the nearest larger in diameter copper winding wire with the following technical characteristics is selected from the reference data:

Wire brand ПЭЛ — enameled wire; insulation heat resistance class - A (105 ºC);
d_{ww}^{Cu} — diameter of the copper winding wire, which is equal 0.530 mm;
d_{ww}^{ins} — external diameter of wire with insulation, which is equal 0.570 mm;
S_{ww}^{Cu} — actual copper area of the winding wire, which is equal 0.221 mm^2.
Calculation of the number of winding turns is performed by formula $\omega_{c.em}$:

$$w_{c.em} = k_f^w \cdot \frac{S_w}{S_{ww}^{Cu}}, \tag{2.7.11}$$

$$w_{c.em} = 0.68 \cdot \frac{1.383 \cdot 10^3}{0.221} = 4263.$$

The active resistance of the winding R_{perm}^w, heated to the permissible temperature of θ_{perm}^{ww} is calculated by the formula:

$$R_{perm}^w = w_{c.em} \cdot \frac{l_{ave}^t \cdot \rho_0 \cdot (1 + \alpha \cdot (\theta_{perm}^{ww} - \theta_0))}{S_{ww}^{Cu}}, \tag{2.7.12}$$

$$R_{perm}^{w} = 4263 \cdot \frac{261.326 \cdot 10^{-3} \cdot 1.62 \cdot 10^{-8} \cdot (1+4.3 \cdot 10^{-3} \cdot (105-40))}{0.221 \cdot 10^{-6}} = 104.665 \text{ Ohm}.$$

Calculations of the actual current values in winding ($I_w^1, I_w^{1.1}, I_1^{0.85}$), current density ($j_w^1, j_w^{1.1}, j_1^{0.85}$) and magnetizing force ($(I \times w)_{c.em}^1, (I \times w)_{c.em}^{1.1}, (I \times$

$w)^{0.85}_{c.em}$) at rated increased by 10% and decreased by 15% value of the control circuit voltage U_c are performed by formulas:

$$I_w = \frac{U_c}{R^w_{perm}}; \tag{2.7.13}$$

$$j_w = \frac{I_w}{S^{Cu}_{ww}}; \tag{2.7.14}$$

$$(I \times w)_{c.em} = I_w * \omega_{c.em}. \tag{2.7.15}$$

The calculation results are presented in the form of table 2.1

Table 2.1

I^1_w	0.459	A	current in the electromagnet winding at rated value $U_c = 48\ V$
$I^{1.1}_w$	0.504	A	current in the electromagnet winding at value $U^{1.1}_c = 52.8\ V$
$I^{0.85}_w$	0.39	A	current in the electromagnet winding at value $U^{0.85}_c = 40.8\ V$
j^{calc}_w	2	A/mm^2	calculated value of current density
j^1_w	2.079	A/mm^2	current density in winding at I^1_w
$j^{1.1}_w$	2.287	A/mm^2	current density in winding at $I^{1.1}_w$
$j^{0.85}_w$	1.767	A/mm^2	current density in winding at $I^{0.85}_w$
$(I \times w)_{c.em}$	1798	A	calculated value of coil MF
$(I \times w)^1_{c.em}$	1955	A	coil MF at I^1_w
$(I \times w)^{1.1}_{c.em}$	2150	A	coil MF at $I^{1.1}_w$
$(I \times w)^{0.85}_{c.em}$	1662	A	coil MF at $I^{0.85}_w$

The maximum value of the power P^{max}_{em} consumed by the electromagnet winding, i.e. power of active losses, is calculated by the formula:

$$P_{em}^{max} = {I_w^{1.1}}^2 \cdot R_{perm}^w, \qquad (2.7.16)$$

$$P_{em}^{max} = 0.504^2 \cdot 104.665 = 26.636\, Wt.$$

When performing a simplified thermal calculation of the coil, it is assumed that heat transfer occurs only from the outer and inner surfaces of the electromagnet winding. Outer surface area of the electromagnet winding S_w^{out} is calculated by formula:

$$S_w^{out} = \pi \cdot D_w^{ext} \cdot l_w, \qquad (2.7.17)$$

$$S_w^{out} = 3.14 \cdot 98.365 \cdot 10^{-3} \cdot 91.095 \cdot 10^{-3} = 0.028\, m^2.$$

Calculation of the inner surface of the winding S_w^{in} is performed by:

$$S_w^{in} = \pi \cdot D_w^{int} \cdot l_w, \qquad (2.7.18)$$

$$S_w^{in} = 3.14 \cdot 68 \cdot 10^{-3} \cdot 91.095 \cdot 10^{-3} = 0.019\, m^2.$$

The calculation of the heating temperature of the winding θ_w^{calc} is perfomed by formula:

$$\theta_w^{calc} = \frac{P_{em}^{max}}{k_{ht} \cdot (S_w^{out} + k_{ht}^{in} \cdot S_w^{in})} + \theta_{env}, \qquad (2.7.19)$$

$$\theta_w^{calc} = \frac{26.636}{10 \cdot (0.028 + 0.9 \cdot 0.019)} + 40 = 99.46\, ℃.$$

Calculated value θ_w^{calc} is less then value of the permissible heating temperature of winding wire θ_{perm}^{ww}. Thus, calculation is correct.

2.8 Conclusion

Calculation of the 220 V, 160 A electromagnetic DC current contactor was performed. Calculated parameters of the contactor listed in the Table 2.2 .

Table 2.2

№	Parameter	Value
1	U_{rat} — rated voltage of the main circuit	220 V
2	I_{rat} — rated current of the main circuit	160 A
3	U_c — rated voltage of the control circuit	48 V
4	I_{ac} — current through auxiliary contacts	10 A
5	n_{tr} — tripping current ratio	3
6	$DC\%$ — duty cycle	40 %
7	z — permissible number of switching cycles per hour	1200
9	p — number of the main contacts (poles)	1
9	N — switching wear resistance	1 000 000 cycles
10	Material of the contact holder	Copper (Cu)
11	Material of the current carrying contour	Copper (Cu)
12	Material of the main contacts	Copper (Cu)
13	Facing of the main contacts	КМК – А20
14	Copper wire grade	ПЭЛ

3 OCCUPATIONAL SAFETY

Since the topic "220 V, 160 A switching device to control the moving vehicle electric motor" involves calculations (work, research) on the premises (laboratory) equipped with visual display terminals, measures to ensure safety, electrical safety, occupational health and hygiene, fire safety for the premises (laboratory) equipped with personal computers will be considered.

Based on the analysis of the existing equipment and technological processes on the premises (laboratory) equipped with personal computers with visual display terminals, according to GOST (State Standard) 12.0.003-2015 (1999) “Occupational safety standards system. Dangerous and harmful production effects. Classification” [22], the following dangerous and harmful production factors were identified:

1. Factors of physical nature:

-result from the peculiarities of working with PC:

a) increased level of electrostatic field;

b) increased level of electromagnetic radiation;

c) the risk of injury due to unsatisfactory ergonomic characteristics of the workplace;

d) danger of electric shock and fire danger.

- result from the violations of sanitary and hygienic conditions:

a) insufficient level of illumination of the working area;

b) increased level of acoustic noise and vibration;

c) unsatisfactory parameters of the microclimate in the premises.

2. Factors of psychophysiological nature:

- static physical overload: work in a monotonous position in the conditions of restriction of the general muscular activity at mobility of hands;

- neuropsychiatric overload:

a) mental strain;

b) eye strain;

c) monotony of work;

d) emotional overload.

The above factors individually and together have a negative impact on the human body and can cause the following health disorders:

- visual disturbances (lachrymation, eye pain, aches in the eyebrow area, blurred contours, blurred images, Sikka syndrome, general visual impairment), with the main reasons being: irrational lighting, lighting specifics of PC workplaces, unsatisfactory ergonomic characteristics of the monitor workplace organization and non-compliance with the work regime;
- musculoskeletal disorders (spinal injuries, pain in the neck, back, shoulders or its swelling, chronic sprains, overexertion of the entire muscular system), with the main reasons being: insufficient ergonomics of the workplace and non-compliance with the work regime .
- neuropsychiatric disorders (increased general fatigue, headache, poor sleep, irritability, anxiety, restlessness, depression, decreased reaction rate), with the main reasons being: monotony of work, insufficient ergonomics of the workplace exposure to electromagnetic waves emitted by the PC and monitor.

3.1 Occupational safety measures

To eliminate possible injuries to personnel and reduce the impact of harmful production factors on the health of personnel when performing their duties the following measures are provided:

Organizational measures

In accordance with the requirements of НПАОП (NPAOP) 0.00-4.12-05 "Типового положення про порядок проведення навчання і перевірки знань з питань охорони праці" ["Standard regulations on the procedure for training and testing of knowledge on health and safety"] [23], at enterprises, taking into account the specifics of production and the requirements of regulations on labor protection, the relevant regulations of enterprises on training on labor protection are developed and approved, also training plans are formed. In order to prevent possible injuries, all employees and students during labor and professional training before work and during work are subjected to training and instruction on occupational safety (introductory, primary, repeated, unscheduled, targeted).

According to the law of Ukraine "Про охорону праці" [“About occupational safety”] [24] when concluding an employment contract for remote work, working from home, the employer is obliged to systematically instruct (train) the employee on occupational safety and fire safety as to the use of the employee equipment and tools recommended or provided by the employer.

Such instruction (training) can be conducted remotely, using information and communication technologies, in particular by video call.

When performing work under an employment contract for remote work, for working from home, the employee determines his workplace by himself and is responsible for ensuring safe and harmless working conditions, and the employer is responsible for the safety and proper technical condition of equipment and means of production transferred to the employee to perform remote or home-based work. When performing work under an employment contract for home work, the workplace defined by the employee must be characterized by the presence of a fixed area, technical means or a set necessary for production, services, work or functions provided by the constituent documents.

3.2 Sanitary-hygiene measures

According to ДСанПІН (DSanPIN) 3.3.2.007-98 "Державні санітарні правил і норми роботи з візуальними дисплейними терміналами електронно-обчислювальних машин" ["State sanitary rules and regulations for work with visual display terminals of electronic computers"] [25] when arranging the elements of the workplace of the PC user were taken into account:

- working posture of the user;
- space for user placement;
- the ability to review the elements of the workplace;

- the ability to keep records, post documentation and materials used by the user.

The design of the PC user's workplace ensures the maintenance of the optimal working posture. PC workstations are located relative to the windows so that natural light falls from the side, mainly on the left. The distance between desktops with video monitors (in the direction of the rear surface of one video monitor and the screen of another video monitor) is 2.2 m, and the distance between the side surfaces of video monitors is not less than 1.5 m, which meets the established standards.

The screen of the video monitor is at a distance of 650 mm from the user's eyes. The design of the desktop should provide optimal placement on the work surface of the equipment used, taking into account its design features, the nature of the work performed. At the same time the use of working tables of various designs meeting modern requirements of ergonomics is allowed.

The surface of the desktop should have a reflection coefficient of 0.5-0.7. The height of the working surface of the table for adult users should be adjustable within 680-800 mm; in the absence of such a possibility, the height of the working surface of the table should be 725 mm. The modular dimensions of the work surface of the table for the PC, on the basis of which the structural dimensions should be calculated, should be considered: width – 800, 1000, 1200 and 1400 mm, depth – 800 and 1000 mm with non-adjustable height equal to 725 mm.

The work table must have a legroom of at least 600 mm in height, at least 500 mm in width, at least 450 mm in depth at the knees, and at least 650 mm in the level of the outstretched leg.

The design of the work chair (armchair) should provide support for a rational working posture while working on a personal computer, allow you to change posture to reduce static tension in the muscles of the neck and back to prevent the development of fatigue. The working chair (chair) should be lifting and rotating, adjustable in height and angles of the seat and back, as well as the distance of the back from the front edge of the seat, with adjustment of each parameter realized freely, easily carried out to have a reliable fixation. The surface of the seat, back and other elements of the chair (armchair) should be semi-soft, with non-slip, poorly electrified and breathable coating, which provides easy cleaning.

The workplace of the PC user should be equipped with a footrest, has a width of at least 300 mm, depth of at least 400 mm, height adjustment up to 150 mm and the angle of the support surface of the stand up to 20 degrees. The surface of the stand is corrugated and has a side edge 10 mm high.

The keyboard is located on the table surface at a distance of 100-300 mm from the edge facing the user, or on a special, height-adjustable work surface, separated from the main desktop.

EU directive 90/270 EEC in section on the minimum safety and health requirements for work with display screen equipment strictly regulates safe working conditions and health protection requirements for people working with computers, making the following requirements for working with the monitor:

- the symbols on the screen must be clear and well distinguished;
- the image must be free of flicker;
- brightness and / or contrast should be easy to adjust;
- screens must be free from glare and reflection;
- radiation must be reduced to extremely low levels.

Levels of ionizing and non-ionizing electromagnetic fields and radiation of monitors, which are considered safe for human health are regulated by НПАОП (NPAOP) 0.00-1.28-10 "Правила охорони праці під час експлуатації електронно-обчислювальних машин" ["Occupational safety rules during operation of electronic computers"] and ДСанПіН (DSanPiN) 3.3.2.007-98 "Державні санітарні правила і норми роботи з візуальними дисплейними терміналами електронно-обчислювальних машин" ["State sanitary rules and regulations for work with visual display terminals of electronic computers"] [26].

For monitors that do not meet these standards, to provide protection against ionizing and non-ionizing electromagnetic fields and radiation of monitors, it is required to:

- install a protective filter for the screen that reduces the alternating electric and electrostatic fields;

- install a protective coating on the rear and side walls of the monitor, mount special shielding panels on the back and sides of the monitor and install partitions between different users.

PC is an electrical installation with a supply voltage of up to 1000 V, thus it and everything related to its operation are subject to electrical safety requirements. Therefore, to ensure the safety of the PC users and service personnel, laboratories equipped with visual display terminals meet electrical safety requirements according to the НПАОП (NPAOP) 40.1-1.01-97 "Правила безпечної експлуатації електроустановок" ["Rules of safe operation of electrical installations"] [27].

According to the requirements of ДСН (DSN) 3.3.6.042-99 "Державні санітарні норми мікроклімату виробничих приміщень" ["Sanitary norms of microclimate of industrial premises"] [28] and ГОСТ (GOST) 12.1.005-88 (1991) "Occupational safety standards system. General sanitary requirements for working zone air" [29], work in the office (laboratory) belongs to the category of "light" Iб – light physical work performed sitting, standing or associated with walking and accompanied by some physical stress, so there are set the following optimal and acceptable weather conditions:

- in the cold period of the year at permanent workplaces temperature: optimum – 21-23°C, admissible – 20-24°C; relative humidity: optimal – 40-60%, allowable – 75%; air velocity: optimal – not more than 0.1 m/s, permissible – not more than 0.2 m/s;

- in the warm period of the year at permanent workplaces temperature: optimum – 22-24°C, admissible – 21-28°C; relative humidity: optimal – 40-60%, allowable – 60% at a temperature of 27°C; speed of air movement: optimal – no more than 0,2 m/s, admissible – no more than 0,1-0,3 m/s;

These parameters are provided by systems of heating, conditioning and aeration according to requirements ДБН (DBN) В.2.5-67:2013 "Опалення, вентиляція та кондиціонування" ["Heating, ventilation and air conditioning"] [30].

According to the requirements of ДБН (DBN) В.2.5-28-2009 "Інженерне обладнання будинків і споруд. Природне і штучне освітлення" ["Engineering equipment of buildings and structures. Natural and artificial lighting"] [31] natural and artificial lighting is provided on the premises (laboratory) with a PC. Unsatisfactory lighting reduces the productivity of PC users, and is responsible for possible appearance of myopia, fatigue.

The lighting system meets the following requirements:

-lighting in the workplace corresponds to the nature of visual work, which is determined by three parameters:

- object of distinction – the smallest size of the object considered on the monitor of the personal computer and workstation;

- background, which is characterized by the reflection coefficient;

- contrast of object and background;

- it is necessary to ensure a sufficiently uniform distribution of brightness on the working surface of the monitor, as well as within the surrounding space;

- there are no sharp shadows on the work surface;

- there is no glare in the field of view (increased brightness of surfaces that glow and cause glare);

- the amount of illumination is constant during operation;

- the optimal direction of light flux and the required composition of light is chosen correctly.

Natural lighting on premises with CT is carried out through light slots (windows), oriented mainly to the north or northeast so that it provides a coefficient of natural light not less than 1.5%. To protect from direct sunlight, which creates direct and reflected glare on the surface of screens and keyboards, sun protection devices are provided, blinds are installed on the windows.

Artificial lighting in rooms with workplaces equipped with PCs is carried out by a system of general uniform lighting.

The illumination value on the surface of the desktop, as well as in the screen area is 300 lux. ЛБ (LB) type fluorescent lamps are mainly used as artificial light sources.

Sound pressure levels in octave bands, sound levels and equivalent sound levels in workstations equipped with PCs meet the requirements of ДСанПіН (DSanPiN)

3.3.2.007-98 "Державні санітарні правила і норми роботи з візуальними дисплейними терміналами електронно-обчислювальних машин" ["State sanitary rules and regulations for working with visual display terminals of electronic computers"] [25] and ДСН (DSN) 3.3.6-037-99 "Санітарні норми виробничого шуму, ультразвуку та інфразвуку" ["Sanitary standards of industrial noise, ultrasound and infrasound"] [32] do not exceed 50 dBA.

Reduction the noise level on the premises is performed by the following means and measures:

- using PC power supplies with fans on rubber suspensions;
- using PCs in which the temperature sensors are mounted on the power supply and at critical points on the motherboard (processor, chipset chips), which allows you to programmatically adjust both the moments of turning on the fans and their speed;
- using PCs in which the fan on the processor is installed by the manufacturer (VOC processor);
- using of motherboards format ATX and ATX-cases format, which allows you to adjust the autonomous speed and time of unlocking the fan on the power supply from the mains;
- using 24-38x high-speed CD-ROMs for devices that make less noise than 48-50x high-speed CD-ROMs, or use a drive with simultaneous reading of multiple CD tracks or software that allows you to reduce the speed;
- replacement of dot matrix needle printers with inkjet and laser printers, which provide a much lower sound pressure level during operation;
- using shared printers located at a considerable distance from most workstations of PC users;
- reduction of noise on the way of its distribution through placement of a sound-proof fence in the form of walls, partitions, cabins;
- acoustic treatment of premises – reduction of energy of reflected sound waves by increasing the area of sound absorption (placement on the surfaces of the premises of sound-absorbing cladding, location on the premises with artificial sound absorbers).

Requirements to the PC users' work and rest hours are determined depending on the nature of work performed by the user in accordance with the requirements of ДСанПіН (DSanPiN) 3.3.2.007-98 "Державні санітарні правила і норми роботи з візуальними дисплейними терміналами електронно-обчислювальних машин" ["State sanitary rules and regulations for work with visual display terminals of electronic computers"] [25].

The following PC users work and rest hours with a regular 8-hour day shift are established, depending on the nature of work:

- for software developers there should be assigned a regulated break for rest lasting 15 minutes every hour;

-for PC operators there should be assigned a regulated break for rest lasting 15 minutes every 2 hours;

-for typesetting machine operators there should be assigned a regulated break for rest lasting 15 minutes every hour;

In cases, when production circumstances do not allow the use of regulated breaks, the duration of continuous work with the PC should not exceed 4 hours. In the case of a 12-hour work shift, the regulated breaks must be set within the first 8 hours of work similar to the breaks for the 8-hour work shift, and during the last 4 hours of work, regardless of the nature of work, every hour for 15 minutes.

To reduce the negative impact of monotonous work on the employee, some operations should be alternated, for example, entering text using the keyboard and editing text, and so on. To reduce nervous and emotional stress, fatigue of the eye, to improve cerebral circulation, to overcome the adverse effects of hypodynamics, to prevent fatigue, it is advisable to use some breaks to perform a set of exercises.

Active recreation should consist of a set of gymnastic exercises aimed at:

- reducing nervous tension;

- muscle relaxation;

- restoration of the functions of physiological systems that are disrupted during the labor process;

- reducing eye fatigue;

- improving cerebral circulation.

3.3 Measures for fire safety

Based on the analysis of substances and materials used on the premises with video display terminals, according to the ДСТУ (DSTU) Б В.1.1-36:2016 "Визначення категорій приміщень, будинків та зовнішніх установок за вибухопожежною та пожежною небезпекою" ["Determination of the categories of premises, buildings and outdoor installations by explosion and fire hazard"] [33], the premises (laboratory) with the personal computer belong to productions of category "D" on fire danger – space on the premises in which there are solid combustible substances and materials. As the premises (laboratory) equipped with the personal computer with display screen equipment belong to productions of category "D" on fire danger, according to requirements of ДБН (DBN) В.1.1-7:2016 "Пожежна безпека об’єктів будівництва. Загальні вимоги" ["Fire safety of construction sites. General requirements"] [34] it has, therefore, the II degree of fire resistance.

From technical and organizational measures of fire prevention on the premises (laboratory) equipped with the personal computer with display screen equipment the following fire-prevention measures are taken. On the power equipment, power and lighting circuits, in accordance with the requirements of paragraph 3.1 "ПУЕ" ["Arrangement of Electrical Installations"] [38], protective devices are installed that turn off the power supply from the area of the electrical circuit in which a short circuit has occurred. Premises with computers are equipped with an automatic fire alarm system in accordance with the requirements НАПБ (NAPB) Б.06.004-97 "Перелік однотипних за призначенням об'єктів, які підлягають обладнанню автоматичними установками пожежогасіння та пожежної сигналізації" [List of objects of the same type for the purpose, which are subject to equipment with automatic fire extinguishing and fire alarm systems] [35], and ДБН (DBN) В.2.5-13-98 "Інженерне обладнання будинків і споруд. Пожежна автоматика будинків і споруд" ["Engineering equipment of buildings and structures. Fire automation of houses and buildings"] [36] with smoke detectors and portable carbon dioxide fire extinguishers installed in accordance with НАПБ (NAPB) Б.03.001-2004 "Типові норми належності вогнегасників" ["Typical norms of belonging of fire extinguishers"] [35], taking into account the maximum permissible concentration of fire extinguishing liquid in accordance with the requirements of the "Правила пожежної безпеки в Україні" ["Fire safety rules in Ukraine"] [38], thermal fire detectors are installed in other premises. Approaches to fire extinguishers are free.

Since the premises equipped with a PC with video display terminal has an area of 39 m, in accordance with the requirements of clause 3.8 section "Типові норми належності вогнегасників" [Typical norms of belonging of fire extinguishers], ДСТУ (DSTU) 4297:2004 "Пожежна техніка. Технічне обслуговування вогнегасників. Загальні технічні вимоги" ["Firefighting equipment. Maintenance of fire extinguishers. General technical requirements"] [39] for extinguishing live electrical installations, carbon dioxide fire extinguishers of the ВВК-3,5 type are provided to the number of 2 pieces (at the rate of one fire extinguisher with the value of fire extinguishing substance charge of 3 kg and more: for 20 m of the premises area). The distance between fire extinguishers and places of possible fires does not exceed 10 m.

3.4 Conclusion

Measures to ensure safety, industrial sanitation, occupational health and fire safety, provided for the premises (laboratory) equipped with personal computers with visual display terminals guarantee safe and comfortable working conditions for personnel.

4 ECONOMIC SECTION

The main idea of this project is production of a DC contactor with parameters 220 V, 160 A. This electric apparatus is used in control circuits of general industrial stationary installations and in control circuits of electric motors of moving vehicles. The device is characterized by high switching and mechanical wear resistance.

Description of the potential market is presented in the Table 4.1.

Table 4.1 - Preliminary description of the potential market

№	Market indicators	Characteristics
1	The main competitors	КТП contactors, Albright contactors, КПВ contactors
2	Market dynamics	Stagnate
3	Restrictions for entry	advertising, customer loyalty, network effect, agreement with partners

Description of the potential customers is presented in the Table 4.2.

Table 4.2 – Preliminary description of potential customers

№	Need that forms the market	Target audience (target market segments)	Consumer requirements
1	The necessity of switching DC circuits	Industrial enterprises	Reliability and uninterrupted operation, maintainability, favorable price
2	The need to switch the control circuits of electric motors	Transport companies (railway and city electric transport)	Reliability and uninterrupted operation, maintainability, favorable price

SWOT- analysis is presented in the Table 4.3. .

Table 4.3 - SWOT- analysis

Strengths:	Weaknesses:
- favorable price in comparison with foreign competitors; - significant volumes of deliveries; - high quality, reliability and maintainability.	- lack of a well-known name and reputation of the brand; - weak market representation; - lack of a wide customer base.
Opportunities:	**Threats:**
- conclusion of new contracts; - entering the international market.	- high competition in the market; - price competition; - market stagnation.

The SWOT-analysis showed that the idea has several strengths and opportunities that can ensure the success of its implementation, but there are also weaknesses and threats that may hinder the implementation of the idea. Which indicates the presence of certain risks.

Calculation of the production workers salary is presented in the Table 4.4.

Table 4.4 - Number and salary fund of production workers

Categories of employees	Number, persons		Tariff rate for the category of work performed, UAH /	Effective fund of working hours,	Tariff salary, UAH	Premium %	Sum of premium, UAH	Annual salary fund, UAH.	Single social payment, UAH
	per shift	per day							
1	2	3	4	5	6	7	8	9	10
Production workers, including: 1. Main workers	10	10	72.87	1976	143991	15	21598,6	1655896,5	364297,23
2. Auxiliary workers	5	5	54.65	1976	107998	10	10799,8	593989	130677,58
3. Duty and repair staff	7	7	48.58	1976	95994	10	9599,4	739153,8	162613,836
Total number of production workers	22	22	X	X	X	X	41997,8	2989039,3	657588,646

The number of hours in the effective working time fund is determined by the formula:

$$К_{роб.г.рік} = К_{роб.г} \cdot К_{раб.дн}, \qquad (4.1)$$

where $К_{раб.г}$ — number of working hours per day, at 40 hours working week;

$К_{раб.дн}$ — number of official working days in 2021 in Ukraine;

$$К_{роб.г.рік} = 8 \cdot 247 = 1976 \text{ hours.}$$

The tariff rate is determined by the formula:

$$\text{Тс} = \text{ЗП} \div (\text{РЧ} \div 12), \tag{4.2}$$

where ЗП — salary according to the position;

РЧ — number of working hours in 2021;

12 — number of months.

$$\text{Тс1} = 12000 \div (1976 \div 12) = 72.87 \text{ UAH/hour};$$

$$\text{Тс2} = 9000 \div (1976 \div 12) = 54.65 \text{ UAH/hour};$$

$$\text{Тс3} = 8000 \div (1976 \div 12) = 48.58 \text{ UAH/hour};$$

Tariff earning for the year is determined by the formula:

$$\text{Тз} = \text{Тс} \cdot \text{РЧ} \qquad (4.3);$$

$$\text{Тз1} = \text{Тс1} \cdot \text{РЧ} = 72.87 \cdot 1976 = 14399\ UAH;$$

$$\text{Тз2} = \text{Тс2} \cdot \text{РЧ} = 54.65 \cdot 1976 = 107998\ UAH;$$

$$\text{Тз3} = \text{Тс3} \cdot \text{РЧ} = 48.58 \cdot 1976 = 95994\ UAH;$$

The amount of the premium for the year is determined by the formula:

$$\text{Рп} = \text{Тз} \cdot \text{Пв}, \tag{4.4}$$

where Пв — premium %;

Тз — tariff earnings for the year.

$$\text{Рп1} = \text{Тз1} \cdot \text{Пв1} = 143991 \cdot 0.15 = 21598.6\ UAH;$$

$$\text{Рп2} = \text{Тз2} \cdot \text{Пв2} = 107998 \cdot 0.1 = 10799.8\ UAH;$$

$$\text{Рп3} = \text{Тз3} \cdot \text{Пв3} = 95994 \cdot 0.1 = 9599.4\ UAH.$$

The annual salary fund for each category of employees is determined by the formula:

$$Фзп = (Тз + Рп) \cdot к \tag{4.5},$$

where к — number of employees of a certain category.

$$Фзп1 = (Тз1 + Рп1) \cdot к1 = (143991 + 21598.6) \cdot 10 = 1655896.5\ UAH;$$

$$Фзп2 = (Тз2 + Рп2) \cdot к2 = (107998 + 10799.5) \cdot 5 = 593989\ UAH;$$

$$Фзп3 = (Тз3 + Рп3) \cdot к3 = (95994 + 9599.1) \cdot 7 = 739153.8\ UAH.$$

The general salary fund is determined by the formula:

$$Фзп.заг = Фзп1 + Фзп2 + Фзп3; \tag{4.6}$$

$$Фзп.заг = 1655896.5 + 593989 + 739153.8 = 2989039{,}3\ UAH.$$

The SSC rate is 22%, so the calculation is made according to the following formula:

$$ЄСВ = Фзп \cdot 22\% \tag{4.7}$$

$$ЄСВ1 = Фзп1 \cdot 22\% = 1655896.5 \cdot 0.22 = 364297.23\ UAH;$$

$$ЄСВ2 = Фзп2 \cdot 22\% = 593989 \cdot 0.22 = 130677.58\ UAH;$$

$$ЄСВ3 = Фзп3 \cdot 22\% = 739153.8 \cdot 0.22 = 162613.836\ UAH.$$

$$ЄСВзаг = ЄСВ1 + ЄСВ2 + ЄСВ3 = 364297.23 + 130677{,}58 + 162613.836 = 657588{,}646\ UAH.$$

Calculation of the cost of salaries of administrative staff is presented in the Table 4.5.

Table 4.5 - Number and salary fund of administrative staff

Position	Number of people	Salary, UAH	Premium percentage to salary,%	Sum of premium UAH	Monthly salary, UAH	Annual fund wages, UAH	SSC, UAH
1	2	3	4	5	6	7	8
Director	1	30000	15	4500	34500	414000	91080
Chief Accountant	1	16000	10	1600	17600	211200	46464
Total	2	46000	X	6100	52100	625200	137544

The amount of the premium is determined by the formula:

$$П = ПО \cdot ПВ, \tag{4.8}$$

where ПО — salary;

ПВ — percent premium to the salary.

$$П1 = 30000 \cdot 0.15 = 4500\ UAH;$$
$$П2 = 16000 \cdot 0.1 = 1600\ UAH.$$

The monthly salary is determined by the formula:

$$ЗПм = ПО + П, \tag{4.9}$$
$$ЗПм1 = ПО1 + П1 = 30000 + 4500 = 34500\ UAH;$$
$$ЗПм2 = ПО2 + П2 = 16000 + 1600 = 17600\ UAH.$$

Calculation of material costs for raw materials and materials for the production of the contactor is presented Table 4.6.

Table 4.6 - Calculation of material costs

Material costs	Standard per one. product	Production program	Volume of raw materials	Price	Sum, UAH
1	2	3	4	5	6
Technical silver	0.021 kg	7500 pcs	157.5 kg	13000/kg	2047500
Copper	0.8 kg	7500 pcs	6000 kg	100/kg	600000
Steel	1 kg	7500 pcs	7500	6/кг	45000
Other materials	-	7500 pcs	-	-	650000
Total					3342500

Material costs for raw materials are calculated by the following formula:

$$\text{МВ} = \text{ОС} \cdot \text{Ц}, \tag{4.10}$$

where ОС — volume of raw materials, kg;

Ц — the price of raw materials, UAH/kg.

$$\text{ОС} = \text{Н} \cdot \text{ВП}, \tag{4.11}$$

where Н — standard per product, kg;

ВП — production program, pcs.

$$\text{ОС1} = 0.021 \cdot 7500 = 157.5\ kg;$$
$$\text{ОС2} = 0.8 \cdot 7500 = 6000\ kg;$$
$$\text{ОС3} = 1 \cdot 7500 = 7500\ kg;$$

$$\text{МВ1} = 157.5 \cdot 13000 = 2047500\ UAH;$$
$$\text{МВ2} = 6000 \cdot 100 = 600000\ UAH;$$

$$МВ3 = 7500 \cdot 6 = 45000\ UAH.$$

$$МВзаг = МВ1 + МВ2 + МВ3 + МВ4 =$$

$$= 2047500 + 600000 + 45000 + 650000 = 3342500\ UAH.$$

Calculation of the cost of consumed services for the production of the contactor is presented in Table 4.7.

Table 4.7 - Calculation of the consumed services cost

Type of services	Standard per product	Production program	Amount of services	Tariffs	Sum, UAH
1	2	3	4	5	6
Power supply	2	7500	15000	1.01	15150
Water supply	0.5	7500	3750	16	60000
Total					75150

Consumed services cost is calculated by formula:

$$ВСП = ОП \cdot Т, \tag{4.12}$$

where ОП — amount of services;

Т — service tariff.

$$ОП = Н \cdot ВП, \tag{4.13}$$

where Н — standard per product;

ВП — production program, pcs.

$$ОП1 = Н1 \cdot ВП = 2 \cdot 7500 = 15000\ UAH;$$

$$ОП2 = Н2 \cdot ВП = 0.5 \cdot 7500 = 3750\ UAH;$$

$$ВСП1 = ОП1 \cdot Т1 = 15000 \cdot 1.01 = 15150\ UAH;$$

$$ВСП2 = ОП2 \cdot Т2 = 3750 \cdot 16 = 60000\ UAH;$$

Calculation of depreciation of core funds taking into account their initial cost is presented in Table 4.8.

Table 4.8 – Calculation of depreciation of core funds

Group of core funds	Depreciation rate	The initial cost of depreciation	Received core funds		Sum, UAH
			Data	In. cost	
Machines and equipment	6.666%	1800000	01.01	1800000	120000
Vehicles	10%	1000000	01.01	1000000	100000
Production and household equipment	20%	800000	01.01	800000	160000
Total		3600000		3600000	380000

The depreciation rate is calculated by the formula:

$$НА = Пварт \backslash ТКВ, \qquad (4.14)$$

where Пварт — initial cost, UAH;

ТКВ — useful life of fixed assets, years.

$$НА1 = Пварт1 \backslash ТКВ1 = 1800000 \backslash 15 = 120000\ UAH;$$

$$НА2 = Пварт2 \backslash ТКВ2 = 1000000 \backslash 10 = 100000\ UAH;$$

$$НА3 = Пварт3 \backslash ТКВ3 = 800000 \backslash 5 = 160000\ UAH.$$

The depreciation rate in % is calculated by the formula:

$$НА\% = (НА\backslash Пварт) \cdot 100\% \qquad (4.15)$$

$$НА1\% = НА1\backslash Пварт1 \cdot 100\% = (120000/1800000) \cdot 100 = 6.666\%$$
$$НА2\% = НА2\backslash Пварт2 \cdot 100\% = (100000/1000000) \cdot 100 = 10\%$$
$$НА3\% = НА3\backslash Пварт3 \cdot 100\% = (160000/800000) \cdot 100 = 20\%$$

An estimate of costs per unit and per total product is given in table 4.9:

Table 4.9 – Estimate of costs

Калькуляційні статті	Costs	
	у розрахунку на одиницю продукції, UAH.	у розрахунку на весь обсяг продукції, UAH.
Raw materials	445.6	3342500
Power supply	2.02	15150
Water supply	8	60000
Total	**455.62**	**3417150**
Salary of production workers	398,538	2989039,3
SSC	87.678	657588,646
Depreciation	50.666	380000
Costs for maintenance and operation of the core funds, current repairs	9.6	72000
Total production expences	546,483	4098600
Production cost	**1002,103**	**7515750**
Administrative expenses	101.7	762750
Total cost	**1103,8**	**8278500**

Costs per unit of output are calculated by the formula:

$$\text{Витр.}1 = \text{Витр.в.обсяг}/\text{обсяг.прод.} \quad (4.17)$$

Current repair costs were calculated as 2% of the cost of core funds.

The calculation of expected income and financial result for an innovative project is presented in Table 4.10

Table 4.10 - Calculation of the financial result

№ of period	Production volumes	Sales volumes	The balance of unsold products	Cost	Income	Expences	Financial result
1	1650	800	850	2500	2000000	1821270	178730
2	1800	1200	600	2500	3000000	1986840	1013160
3	1950	1500	450	2500	3750000	2152410	1597590
4	2100	1800	300	2500	4500000	2317980	2182020
Разом	7500	5300	2200	X	13250000	8278500	4971500

Income is calculated by the formula:

$$Д = ОР \cdot Ц, \quad (4.18)$$

where ОР — Sales value, pcs;

Ц — price, UAH.

$$Д1 = ОР1 \cdot Ц1 = 800 \cdot 2500 = 2000000\, UAH;$$

$$Д2 = ОР2 \cdot Ц2 = 1200 \cdot 2500 = 3000000\, UAH;$$

$$Д3 = ОР3 \cdot Ц3 = 1500 \cdot 2500 = 3750000\, UAH;$$

$$Д4 = ОР4 \cdot Ц4 = 1800 \cdot 2500 = 4500000\, UAH.$$

Expenses are calculated by the formula:

$$В = ОВ \cdot СБ, \quad (4.19)$$

where ОВ — production volume, pcs;

СБ — unit cost of production, UAH.

$$В1 = ОВ1 \cdot СБ = 1650 \cdot 1103.8 = 1821270\ UAH;$$
$$В2 = ОВ2 \cdot СБ = 1800 \cdot 1103.8 = 1986840\ UAH;$$
$$В3 = ОВ3 \cdot СБ = 1950 \cdot 1103.8 = 2152410\ UAH;$$
$$В4 = ОВ4 \cdot СБ = 2100 \cdot 1103.8 = 2317980\ UAH.$$

Financial result is calculated by the formula:

$$ФР = Д - В; \quad (4.20)$$
$$ФР1 = Д1 - В1 = 2000000 - 1821270 = 178730 \text{ UAH};$$
$$ФР2 = Д2 - В2 = 3000000 - 1986840 = 1013160 \text{ UAH};$$
$$ФР3 = Д3 - В3 = 3750000 - 2152410 = 1597590 \text{ UAH};$$
$$ФР4 = Д4 - В4 = 4500000 - 2317980 = 2182020 \text{ UAH};$$

After calculation of the financial result, it is possible to calculate the payback:

$$ТО = СВ/Д, \quad (4.21)$$

where СВ — the amount of investment, UAH;

$Д_р$ — total income per year, UAH.

$$ТО = 8278500/13250000 = 0{,}624 \text{ years}.$$
$$ТО = 0{,}624 \cdot 12 = 7{,}488 \approx 7{,}5\ month.$$

Conclusion

During the implementation of the economic section of the diploma project, comprehensive economic calculation of DC contactor production with parameters 220 V, 160 A was carried out. During this calculation was given a preliminary description of the market and the target consumer, SWOT-analysis, estimated production costs. According to the results of economic calculation, the financial result of the innovative project is a net income of 4971500 UAH and a payback period of 7,5 months.

CONCLUSIONS

When solving one of the tasks, design of electromagnetic contactors, MK series was selected as the basis for the project due to its high mechanical wear resistance and switching wear resistance, maintainability and ease of exploitation. As a result of the analysis of possible directions of design improvement, it was decided to increase the switching durability by using of KMK-A20 contact pads.

During the implementation of diploma project, calculation of technical parameters of electromagnetic DC contactor was carried out. Results of calculation is presented in Table 5.

Table 5

Parameter	Value
U_{rat} — rated voltage of the main circuit	220 V
I_{rat} — rated current of the main circuit	160 A
U_c — rated voltage of the control circuit	48 V
I_{ac} — current through auxiliary contacts	10 A
I_{eq} — equivalent current	206.45 A
a — actual thickness of current carrying bus	4 mm
b — actual width of current carrying bus	16 mm
k_g — actual bus geometry coefficient	4
j_{act} — actual current density in the current carrying bus	3.2 A /mm^2
Θ_b — temperature of the current carrying buses (rated mode)	82.21°C
$I_{sc}^{1s}(\Theta_{perm})$ — current value when time of s.c. is equal 1 s	$8.892 \cdot 10^3$ A
$I_{sc}^{5s}(\Theta_{perm})$ — current value when time of s.c. is equal 5 s	$3.977 \cdot 10^3$ A
$I_{sc}^{10s}(\Theta_{perm})$ — current value when time of s.c. is equal 10 s	$2.812 \cdot 10^3$ A

a_{fc} — thickness of flexible connection	$4.6 \cdot 10^{-3}$ mm

Continuation of Table 5

b_{fc} — width of flexible connection	$25 \cdot 10^{-3}$ mm
n_{fc} — number of wires connected in parallel	3
d_{bolt} — diameter of bolt for contact fastening	6 mm
n — number of bolts in contact connection	4
R_c — transition resistance of contact surfaces	$5.009 \cdot 10^{-7} \Omega$
τ_c — temperature exceeding of contact connection	$8.428°C$
b_{mc}^{*} — width of movable contact	20 mm
b_{fc}^{*} — width of fixed contact	25 mm
h^{*} — height of the facing plate	14 mm
c^{*} — thickness of the facing plate	3 mm
$j_{l.act}$ — actual linear current density	$10.323\, A/mm$
$j_{s.act}$ — actual current density	$3.441\ A/mm$
a_{mc}^{act} — actual thickness of the main movable contact	3 mm
b_{mc}^{act} — actual width of the main movable contact	20 mm
c_{mc}^{act} — actual length of the main movable contact	23 mm
h_{mc}^{act} — actual height of the main movable contact	23 mm
a_{fc}^{act} — actual thickness of the main fixed contact	3 mm
b_{mc}^{act} — actual width of the main fixed contact	25 mm
c_{mc}^{act} — actual length of the main fixed contact	28 mm
h_{mc}^{act} — actual height of the main fixed contact	28 mm
$F_{cont}^{cont.hold}$ — force of contact pressure	$4588\, H$
R_{tr} — value of the transition resistance	$1.088 \cdot 10^{-4}\ \Omega$

U_{sc} — voltage drop on closed switching contacts	0.022 mV
$\tau_{c.m}^{s.c}$ — contact area temp of switching contacts excess over contact material	7.206℃

End of Table 5

$\theta_{h.cont.area}$ — value of heating temperature of contact area	90.102℃
I_{perm} — permissible current through the closed switching contacts	$579\ A$
I_{weld}^{in} — initial welding current of contact material	$3.629 \cdot 10^3 A$
F_{EDF} — electrodynamic repulsive force	$2.86\ H$
V_{wear} — part of the volume of a pair of contacts that will be subject to wear	$2.24 \cdot 10^{-6}\ m^3$
L_{wear} — switching contact linear wear	$4.87 \cdot 10^{-3}\ m.$
l_{cr}— critical length of the electric arc	$0.188\ m$
S_{ac} — the area of the arc chute side surface	$1.01 \cdot 10^{-3}\ m^2$
S_{pp}— pole-plate area	$4.0 \cdot 10^{-3}\ m^2.$
δ_1 — resistance between pole plates	$0.039\ m$
F_{pp} — value of the magnetic flux	$2.788 \cdot 10^{-5}\ Wb$
F_c — magnetic flux in the core	$3.067 \cdot 10^{-5}\ Wb$

After design calculation of the electromagnetic contactor, comprehensive economic calculation of DC contactor production with parameters 220 V, 160 A was carried out. According to the results of economic calculation, the financial result of the innovative project is a net income of 4971500 UAH per year and a payback period of 7,5 months.

Thus, aim of the diploma project was reached. Designed contactor has technical and economic justification. Due to improved design, contactor will guarantee reliability and uninterrupted operation.

LIST OF REFERENCES

1. Александров, Г. Н. Проэктирование электрических аппаратов: учебник для вузов [Текст] / Г.Н. Александров, В. В. Борисов, Г.С. Каплан и др.; под ред. Г. Н. Александрова. – Л.: Энергоатомиздат, Ленингр. отд-ние, 1985. – 448 с.

2. Александров, Г. Н. Теория электрических аппаратов: учебник для вузов [Текст] / Г. Н. Александров. – М.: Высшая школа, 1985. – 312 с.

3. Близняков, О. В. Дослідження та випробування електричних апаратів: Навчальний посібник [Текст] / О. В. Близняков.
– Запоріжжя: ЗНТУ, 2005. – 94 с.

4. Дмитриевский, В. С. Расчет и конструирование электрической изоляции [Текст] / В. С. Дмитриевский. – М. Энергоатомиздат, 1981. – 392с.

5. Клименко, Б. В. Електричні апарати. Електромеханічна апаратура комутації, керування та захисту. Загальний курс: навчальний посібник [Текст] / Б. В. Клименко. – Харків: Точка, 2012. –340 с.

6. Клименко, Б. В. Електричні та магнітні пристрої, електричні аксесуари, електричні установки. Терміни, тлумачення, коментарі: навчальний посібник [Текст] / Б. В. Клименко. – Харків: Точка, 2009. – 272 с.

7. Клименко, Б. В. Комутаційна апаратура, аппаратура керування, запобіжники. Терміни, тлумачення, коментарі: навчальний посібник [Текст] / Б. В. Клименко. – Харків: Талант, 2008. – 208 с.

8. Романычева, Э.Т. Разработка и оформление конструкторской документации РЭА: Справочное пособие. [Текст] / Э. Т. Романычева и др. – М.: Радио и связь, 1983. – 256 с.

9. Сахаров, П.В. Проєктирование электрических аппаратов [Текст]/ П. В. Сахаров. – М.: Энергия,1977. 560 с.

10. Снігірьов, В.М. Електромеханічні апарати автоматики [Текст]/ В.М.Снігірьов, Л.Б. Жорняк. – Запоріжжя: ЗНТУ, 2016 – 120 с. Електронний ресурс: http://eir.zntu.edu.ua/handle/123456789/3991

11. Справочник конструктора РЭА [Текст] / Под ред. Р. Г. Варламова. – М.: Радио и связь, 1985. – 354 с.

12. Таев, И. С. Электрические аппараты управления [Текст] / И.С. Таев. – М.: Высшая школа,1984. – 247 с.

13. Чунихин, А.А. Электрические аппараты [Текст]/ А.А.Чунихин. – М.; Энергоатомиздат, 1988. – 720 с.

14. ДСТУ ГОСТ 2.307:2013 Единая система конструкторской документации. Нанесение размеров и предельных отклонений (ГОСТ 2.307-2011.IDT).

15. Снігірьов В. М. Електромеханічні апарати автоматики / В. М. Снігірьов, Л. Б. Жорняк. – Запоріжжя : ЗНТУ, 2016 –120 с.

16. Методичні вказівки до виконання дипломного проєкту бакалавра студентами спеціальності 141 «Електроенергетика, електротехніка та електромеханіка» (освітні програми «Електричні та електронні апарати» та «Електромеханічне обладнання енергоємних виробництв») всіх форм навчання / уклад.: П. Д. Андрієнко, Л. Б. Жорняк, В. В. Василевський. – Запоріжжя: НУ «Запорізька політехніка», 2020. – 66 с.

17. Методичні вказівки до виконання курсового проєкту з дисципліни «Основи проєктування електромеханічних пристроїв та систем» студентами спеціальності 141 «Електроенергетика, електротехніка та електромеханіка» (освітні програми «Електричні та електронні апарати» та «Електромеханічне обладнання енергоємних виробництв») всіх форм навчання/ уклад.: Л. Б. Жорняк, О. О. Каплієнко, І.С. Шило. – Запоріжжя: НУ «Запорізька політехніка», 2020. – 40 с.

18. Методичні вказівки до виконання курсового проєкту за фахом студентами спеціальності 141 «Електроенергетика, електротехніка та електромеханіка» (освітні програми «Електричні та електронні апарати» та «Електромеханічне обладнання енергоємних виробництв») всіх форм навчання / уклад.: П. Д. Андрієнко, Л. Б. Жорняк, В. В. Василевський. – Запоріжжя: НУ «Запорізька політехніка», 2020. – 43 с.

19. Методичні вказівки до виконання лабораторних та контрольних робіт з дисципліни «Електричні апарати керування» студентами, що навчаються англійською мовою, на денній формі навчання для підготовки бакалаврів за спеціальністю 141 «Електроенергетика, електротехніка та електромеханіка» за освітньою програмою «Електричні та електронні апарати» / уклад.: Л. Б. Жорняк,С. В. Войтенко – Запоріжжя : ЗНТУ, 2018. – 82 с.

20. Методичні вказівки до виконання лабораторних та контрольних робіт студентами всіх форм навчання при вивченні дисципліни «Електричні апарати керування» для підготовки бакалаврів за спеціальністю 141 «Електроенергетика, електротехніка та електромеханіка» з подальшим навчанням за освітньою програмою «Електричні та електронні апарати» / уклад.: Л. Б. Жорняк, В. В. Василевський – Запоріжжя : ЗНТУ, 2019. – 86 с.

21. Методичні вказівки до виконання розділу «Охорона праці» в дипломних проектах (роботах) студентів - бакалаврів усіх спеціальностей, денної та заочної форм навчання / Укл.: М. О. Журавель, С. М. Журавель – Запоріжжя: ЗНТУ, 2018 – 24 с.

22. ДСТУ ГОСТ 12.0.003-2015 «Система стандартов безопасности труда. Опасные и вредные производственные факторы» (12.0.003-2015.IDT).

23. НПАОП 0.00–4.12.05. «Типове положення про порядок проведення навчання і перевірки знань з питань охорони праці».

24. Закон України «Про охорону праці» від 04.02.2021 № 1213-IX // Відомості Верховної Ради України. – 1992. – № 49. – 668 с.

25. ДСанПіН 3.3.2.007-98 «Государственные санитарные правила и нормы работы с визуальными дисплейными терминалами электронно-вычислительных машин».

26. НПАОП 0.00-1.28-10. «Про затвердження правил охорони праці під час експлуатації електронно-обчислюючих машин».

27. НПАОП 40.1-1.01-97. «Правила безпечної експлуатації електроустановок».

28. ДСН 3.3.6.042-99. «Санитарные нормы микроклимата

производственных помещений».

29. ДСТУ ГОСТ 12.1.005-88 «Общие санитарно-гигиенические требования к воздуху рабочей зоны» (12.1.005-88.IDT).

30. ДБН В.2.5-67:2013 «Опалення, вентиляція та кондиціонування».

31. ДБН В.2.5-28-2009 «Інженерне обладнання будинків і споруд. Природне і штучне освітлення».

32. ДСН 3.3.6-037-99 «Санітарні норми виробничого шуму, ультразвуку та інфразвуку».

33. ДСТУ Б В.1.1-36:2016 «Визначення категорій приміщень, будинків та зовнішніх установок за вибухопожежною та пожежною небезпекою».

34. ДБН В.1.1-7:2016 «Пожежна безпека об’єктів будівництва. Загальні вимоги».

35. НАПБ Б.06.004-97 «Перелік однотипних за призначенням об'єктів, які підлягають обладнанню автоматичними установками пожежогасіння та пожежної сигналізації».

36. ДБН В.2.5-13-98 «Інженерне обладнання будинків і споруд. Пожежна автоматика будинків і споруд».

37. НАПБ Б.03.001-2004 «Типові норми належності вогнегасників».

38. НАПБ А.01.001-2014 «Правила пожежної безпеки в Україні».

39. ДСТУ 4297:2004 «Пожежна техніка. Технічне обслуговування вогнегасників. Загальні технічні вимоги».

40. ПУЕ Правила улаштування електроустановок.

41. Электромагнитные контакторы серии МК : веб-сайт. URL: http://astics.by/kontaktory/kontaktory-mk/?p=3.

42. Контакторы электромагнитные серии МК : веб-сайт. URL: http://www.laborant.ru/eltech/07/1/3/03-97.htm.

43. Контакторы переменного и постоянного тока МК: веб-сайт. URL: https://www.cheaz.ru/products/lve/contactors/ac-dc/mk.html.

44. Электромагнитные контакторы типа МК: веб-сайт. URL: https://rusvolt.su/kontaktors/mk.

45. Контакторы постоянного тока серии МК: веб-сайт. URL: http://www.1-etk.ru/catalog/195/80.

46. Контакторы электромагнитные КПВ-603 : веб-сайт. URL: http://www.1-etk.ru/catalog/195/78/.

47. Контакторы постоянного тока КПВ 600 : веб-сайт. URL: https://www.cheaz.ru/products/lve/contactors/dc/kpb-600.html.

48. Электромагнитные контакторы серии КПВ 600 : веб-сайт. URL:https://etk-oniks.ru/articles/nizkovoltnaya-apparatura/kontaktory-i-puskateli/kontaktory-postoyannogo-toka-tipa-kpv-600/.

49. Контакторы серий КПВ-600: веб-сайт. URL: https://electro.mashinform.ru/kontaktory-v-tom-chisle-s-bezdugovoj-kommutaciej-reversory/kontaktory-serij-kpv600-kpv620-i-ktpv600-obj547.html.

50. Электромагнитные контакторы постоянного тока серии КН и КНУ : веб-сайт. URL: http://www.laborant.ru/eltech/07/1/3/36-98.htm.

51. Электромагнитные контакторы постоянного тока серии КН и КНУ : веб-сайт. URL: https://electro.mashinform.ru/kontaktory-v-tom-chisle-s-bezdugovoj-kommutaciej-reversory/jelektromagnitnye-kontaktory-postojannogo-toka-serii-kn-i-knu-obj542.html.

52. Контакторы электромагнитные серии КН и КНУ : веб-сайт. URL: http://morsnabspb.ru/market/kontaktory_knt_kn_kuv/kontaktor_kn/kontaktor_kn153/#:~:text=%D0%9A%D0%BE%D0%BD%D1%82%D0%B0%D0%.

53. Контакторы электромагнитные постоянного тока серии КН : веб-сайт. URL: https://www.elmash.ru/ru/prod6.