Форма № 24

МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ
НАЦІОНАЛЬНИЙ УНІВЕРСИТЕТ «ЗАПОРІЗЬКА ПОЛІТЕХНІКА»

Фізико-технічний інститут, електротехнічний факультет
(повне найменування інституту, назва факультету)

Електричні та електронні апарати
(повна назва кафедри)

Пояснювальна записка

до дипломного проєкту (роботи)
магістр
(ступінь вищої освіти (освітній ступінь))

на тему Дослідження зовнішньої ізоляції оптоволоконного трансформатора струму 110 кВ, 3000 А

Виконав: студент Ім курсу, групи Е-410ма
спеціальності (напряму підготовки)
141 – Електроенергетика, електротехніка та електромеханіка
(код і назва напряму підготовки, спеціальності)
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Рецензент Сахно О. А.
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м.Запоріжжя
2021 рік

Форма № 25

МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ

Національний університет «Запорізька політехніка»

(повне найменування вищого навчального закладу)

Інститут, факультет Фізико-технічний інститут, електротехнічний факультет

Кафедра Електричні та електронні апарати

Ступінь вищої освіти (освітній ступінь) магістр

Спеціальність 141 – Електроенергетика, електротехніка та електромеханіка

(код і назва)

Напрям підготовки Електричні машини і апарати

(код і назва)

ЗАТВЕРДЖУЮ

Завідувач кафедри Андрієнко П. Д.

“____” ________________20___року

З А В Д А Н Н Я

НА ДИПЛОМНИЙ ПРОЄКТ (РОБОТУ) СТУДЕНТУ

Ганжі Анастасії Володимирівні

(прізвище, ім’я, по батькові)

1. Тема проекту (роботи) Оптоволоконний трансформатор струму 110 кВ, 3000 А

керівник проекту (роботи) Жорняк Людмила Борисівна, к. т. н., доцент

(прізвище, ім’я, по батькові, науковий ступінь, вчене звання)

затверджені наказом вищого навчального закладу від “21” 10 2021 року № 392

2. Строк подання студентом проєкту (роботи) 06.12.2021

3. Вихідні дані до проєкту (роботи) I_r=3000 А, U_r=110 кВ

4. Зміст розрахунково-пояснювальної записки (перелік питань, які потрібно розробити)

Вступ; 1. Огляд існуючих конструкцій трансформаторів струму; 2. Аналіз існуючих ізоляторів та оптоволоконних трансформаторів струму; 3. Огляд ізоляційних конструкцій трансформаторів; 4. Розрахунок основних складових оптоволоконного трансформатора струму; 5. Безпека праці та безпека в надзвичайних ситуаціях; 6. Собівартість та ціна товару.

5. Перелік графічного матеріалу (з точним зазначенням обов’язкових креслень)

1. ГКІЮ 671214.023 ВЗ А1, 1 лист;
2. ГКІЮ 686155.023 ВЗ А1, 1 лист.
3. ГКІЮ 411612.023 СК А1, 1 лист;
4. ГКІЮ 685526.023 СК А2, 1 лист;
5. ГКІЮ 671214.023 РГД А2, 1 лист.

6. Консультанти розділів проекту (роботи)

Розділ	Прізвище, ініціали та посада консультанта	Підпис, дата	
		завдання видав	прийняв виконане завдання
1 – 4	Жорняк Л. Б., к.т.н., доцент	01.10.2021	
5	Скуйбіда О. Л., к.т.н., доцент	25.10.2021	
6	Пожуєва Т. О., к.е.н., доцент	18.10.2021	
	Соболь Ю. О., к.ф.н., доцент	01.10.2021	

7. Дата видачі завдання 01-10-2021

КАЛЕНДАРНИЙ ПЛАН

№ з/п	Назва етапів дипломного проекту (роботи)	Строк виконання етапів проекту (роботи)	Примітка
1	Огляд існуючих конструкцій апаратів, що подібні заданому	01.10.2021-08.10.2021	
2	Аналіз існуючих ізоляторів та оптоволоконних трансформаторів струму	09.10.2021-17.10.2021	
3	Огляд та вибір зовнішньої ізоляції трансформатора	18.10.2021-25.10.2021	
4	Попередній та уточнений розрахунок шино-проводу	26.10.2021-31.10.2021	
5	Розрахунок термічної стійкості при короткому замиканні	01.11.2021-11.11.2021	
6	Електодинамічний розрахунок при короткому замиканні	12.11.2021-16.11.2021	
7	Розрахунок зовнішньої ізоляці	17.11.2021-21.11.2021	
8	Охорона праці	22.10.2021-28.11.2021	
9	Собівартість та ціна продукції	29.11.2021-05.12.2021	
10	Виконання креслень трансформатора	06.12.2021-13.12.2021	

Студент ____________ Ганжа А. В.
(підпис) (прізвище та ініціали)

Керівник проекту (роботи) ____________ Жорняк Л. Б.
(підпис) (прізвище та ініціали)

ABSTRACT

EN: 116 p., 30 fig., 19 tables, 83 references.

CURRENT TRANSFORMER, OPTICAL FIBER, EXTERNAL INSULATION, FIBER OPTIC CURRENT TRANSFORMER, FARADAY'S EFFECT, CURRENT.

Topicality. In high voltage devices, the most important element of the structure is electrical insulation, which affects both the structure and their operational reliability. Current transformer is one of the important elements of power supply systems. The reliability of these devices depends on the continuous supply of electricity to consumers. Prolonged operation in rated mode, as well as operation in emergency mode leads to a gradual deterioration of the properties of the transformer, especially the quality of insulation. In this regard, some of the transformers at power plants and substations require replacement or repair.

The relevance of the master's thesis project is explained by the fact that increasing the operational reliability and efficiency of current transformers is possible by improving external insulation, use of the latest technological solutions, as well as monitoring tests. All this leads to an extension of the service life of the equipment.

Object of research is external insulation of fiber-optic transformer current 110 kV and rated current 3000 A

The subject of research is fiber-optic current transformer of 110 kV and nominal current of 3000 A

The purpose of the work is to study the possibilities of increasing the reliability of current transformers by improving its external insulation.

Research method. For calculating of the main parameters of 110 kV, 3000 A fiber optic current transformer (FOCT), the analytical and numerical methods is used. For scoping and precised calculation of busduct, thermal analysis under the short-circuit mode and electrodynamic analysis, under the short-circuit mode the numeriacal method is used, proposed by Kryuchkov, Sakharov, Aleksandrov and Nikitenko [4, 12, 13, 14]. The calculation of external insulation is performed by the analytical method, proposed by V.V. Afanasiev and G.N. Alexandrov [5, 6].

All the sections of the master's thesis project are made according to the methodical instructions for the preparation and defense of master's thesis for students of

all forms of education of the second (master's) level of higher education in the specialty 141 - Electric power, electrical engineering and electromechanics [23].

The first section presents the analysis of existing high-voltage current transformers, including the advantages and disadvantages of current transformers.

In the second section the overview of existing structures and development of FOCT is considered.

In the third section, the overview of external insulation is carried out

In the fourth section, the calculation of dynamic stability and the intexternal insulation of the current transformer is performed.

In the fifth section, the calculation of the electrical strength of the insulation of current transformer is performed.

Publications. Fylymonenko, A. V. Fiber Optic 110 – 150 kV Current Transformers [Текст]: / A. V. Fylymonenko, S. Y. Yatsura, L. B. Zhorniak // Електромеханічні та енергетичні системи. Методи моделювання та оптимізації. Збірник матеріалів XVIII Міжнародної науково-практичної конференції молодих учених і спеціалістів 04 –06 листопада 2020 року. – Кременчук, КрНУ, 2020. – С. 69-73.

2. Fylymonenko A. Fiber optic current and voltage sensors / A. Fylymonenko, V. Vasilevskiy. // Збірник наукових праць національного університету «Запорізька політехніка». – 2020. – №95. – С. 23–25.

Abstract. At the master's thesis project, a 110 kV current transformer with a current of 3000A is investigated with improved technical and economic indicators obtained through the use of a new type of measurements with the help of optic fiber. The NXT Phase fiber optic current transformer developed by Profotech is chosen as an analogue. Current transformers with various external insulation are investigated. Short-cut calculation of the busduct, precised thermal design, conductor’s temperature under the short circuit mode, electrodynamic calculation, as well as calculation of external insulation are performed. The probability of using fiber optic current transformers in near future is analyzed. A comparative analysis of high-voltage measuring current transformers with oil insulation and of fiber optic current transformer is performed. The technical and economic assessment of the current transformer is carried out, the measures on labor protection and safety in emergency situations are considered.

CONTENT

INTRODUCTION

Electricity is the basis of the economy of any country. The role of electricity is explained by the versatility of its usage, the ability to transmit over, practically, any distance and concentration on a very large scale. The ease of process automation when using electricity makes it an indispensable utility energy.

The last 20 years of development of our country progress are characterized by the rapid energy headway. This contributes to the growth of all branches of the national economy and other spheres of activity of the country's population. A characteristic feature of the development of energy at the present stage is an increase in the capacity of thermal, nuclear and hydroelectric power stations under construction.

In connection with the rise of transmitted capacities, an expansion of the length of the power lines length, there is a continuous increase in the nominal voltage and current of electrical equipment installed in power systems. They serve to distribute powerful flows of electric energy in the cities of our country and ensure the reliable operation of power plants in emergency conditions, as well. In connection with the integration of power systems, the short-circuit currents increase significantly.

Accordingly, all listed above factors lead to the need to create new equipment, one of the types of which are current transformers (CTs). Over the past time, in development of energy, in the field of design and calculation of CT significant changes have happened. Fiber optic current transformers are entering the arena of rapidly developing technologies. Optical transformers represent a breakthrough new technology offering several significant benefits.

Accordingly, extensive studies of their performance are carried out and also the big attention is paid to the external insulation of CT. Because as it is written in work of Zhornyak, Afanasiev, Leonov, and Karpuk : “Insulation is an essential element in the design of electrical appliances and has a significant impact on both its design and operational reliability, especially in ultrahigh voltage devices” [18]. It is known that the trouble proof operation of networks, the service life of highvoltage equipment, the safety of maintenance directly depends on the quality of the insulators, and especially on their material, reliability, type and number of ribs.

Thus, in order to improve quality and reliability of CTs, many regulations have been issued, which define new requirements for current transformers.

When mentioning innovations, most people think of inventing completely new products, however innovation is achieved by finding new ways of combining and improving existing technologies [52].

Hence this graduate work will be devoted to the issues how we can improve or combine existing technologies to get new ways of measurements and achive the progress.

1 OVERVIEW OF EXISTING CONSTRUCTIONS OF CURRENT TRANSFORMERS

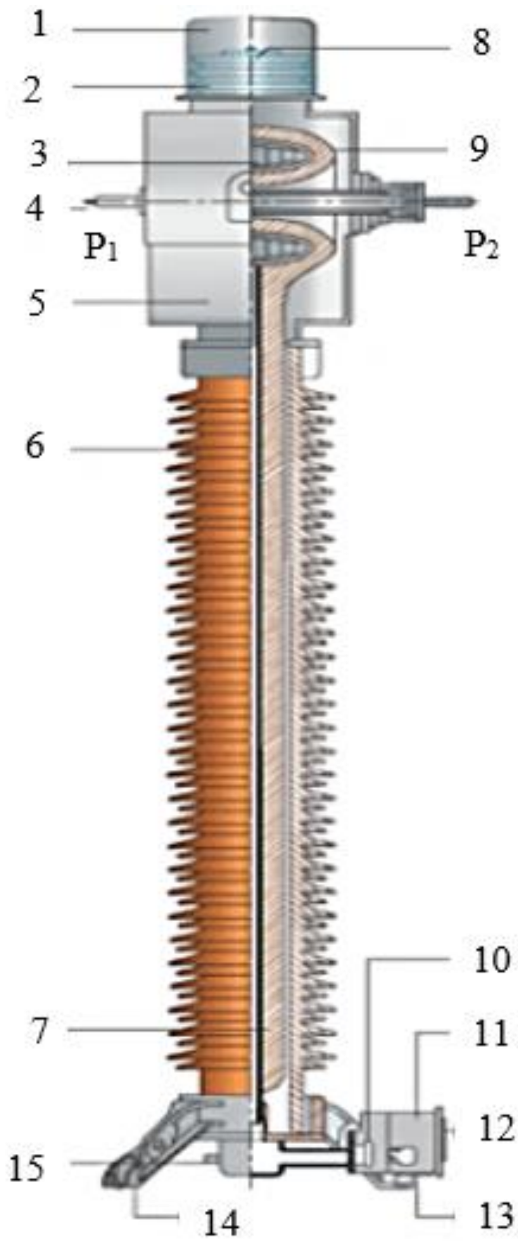
A current transformer (CT) is a type of transformer used for reducing or multiplying of alternating current (AC). It produces a current in secondary winding that is proportional to the current in its primary winding. CTs are the current-sensing units of the power system and are used at generating plants, power electrical substations, and in industrial and commercial electric power distributions.

High-voltage measuring CT is the main measuring device in the electric power industry and differed from that used in low-voltage technology in the level of insulation between the primary and secondary windings. In the CT, the primary winding is isolated from the secondary to full voltage. The secondary winding in operation has a potential close to the ground potential, since one end of this winding is usually grounded. With the help of CTs, it is possible to measure and take into account high voltage current devices low voltage available for direct observation by personnel, and reduce to measurement of any primary current, for example 5 or 1 A [37].

Measuring CTs differ from power CTs by the following features:

- the measuring CT works in conditions close to short circuit, since the resistance in the secondary circuit is very small. This mode is a normal mode of operation, while for a power CTs, the short circuit mode is emergency;
- induction in the measuring CT is not constant and is determined by the measu-
- ring current and the operating mode of the transformer, while induction is constant in the power transformer;
- the current in the secondary circuit of the measuring CTs to certain extent does not depend on the load resistance and basically changes in accordance with the change of the primary current. In a power CTs, the primary current changes depending on the load of the secondary winding.

The general view of the CT presented in Figure 1.1.



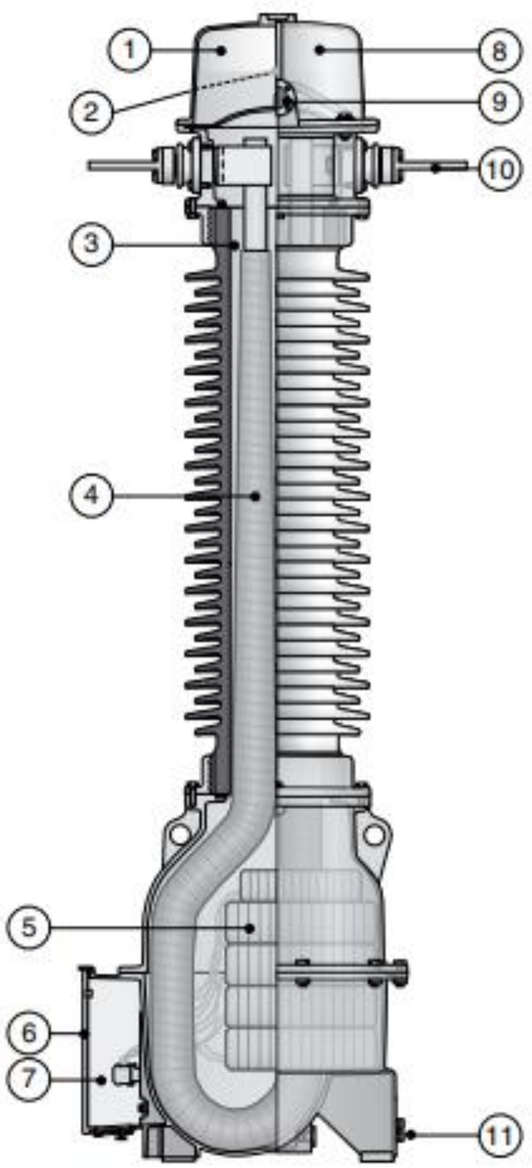
1 – aluminum case; 2 – stainless steel bellows;
3 – core of a secondary winding; 4 – output of the primary winding;
5 – aluminum case; 6 – insulator;
7 – capacitor terminal; 8 – oil filler plug

Figure 1.1 – General view of CT [39]

Below is shown an example of the current design of the existing current transformer, its features and advantages.

Low-oil measuring current transformer by IMB, tank type with U-shaped primary winding, as shown in Figure 1.2 [28].

The design of this transformer complies with the requirements of IEC and IEEE.



1 – gas pillow-block; 2 – oil fill cap (not shown);

3 – quartz sand; 4 – paper insulated conductor;

5 – cores / secondary windings; 6 – secondary terminal box;

7 – capacitive output; 8 – expansion system;

9 – oil level gauge; 10 – primary output;

11 – grounding terminal.

Figure 1.2 – Low-oil measuring current transformer IMB [28]

The producers of ABB Power Technologies AB company [28], speaking about measuring transformers, write in article about main parameters, benefits and disadvantages of low-oil measuring current transformer IMB.

The primary winding consists of one or more parallel aluminum or copper U-shaped conductors made as an input with capacitive plates. The technology of insulation winding is automatized, which improves quality, simplifies the process and its controllability. The conductors are insulated with special paper having high dielectric and mechanical strength, low dielectric losses, and high resistance to aging.

The measurement cores are made of nickel alloy, which possesses low loss (i.e., high accuracy class) and low level of saturation. Cores for protection are made of high-quality steel tape with an oriented structure. The secondary winding consists of a copper wire with two-layer enamel insulation, so current leakage between the windings and between the additional soldering of the windings is negligible.

Impregnation of windings is as follows: the winding is dried in vacuum. After assembling of the transformer, all free interior space (approximately 60 %) is filled with pure dry quartz sand. A transformer prepared in this way is evacuated and filled with degassed mineral oil, which is mixed with sand, penetrates the insulation and impregnates it. After that, the transformer is sealed.

The base of the transformer is an aluminum tank, in which cores with secondary windings are located. The insulator mounted on the tank's top is a high-strength porcelain cover with brown glaze. Also, the tire may be made of silicon organic rubber. The transformer seal system consists of O-rings.

IMB transformers are equipped with an expansion system mounted above the upper end of the porcelain cover. The hermetic expansion system as a working element in which nitrogen is used, allows to compensate changes in the volume of oil in the entire range of operating temperatures. The use of a nitrogen cushion makes it possible to increase the operational reliability of the transformer and to minimize its maintenance.

Capacitive lining in the insulation of the primary conductor can be used as a capacitive voltage divider. For this, soldering is removed from the penultimate layer of capacitive lining through the bushing in the tank wall. The advantage of capacitive output is that it allows to check the state of insulation by measuring the dielectric loss angle (tanδ) under high voltage. The output also can be used to indicate the presence of voltage, synchronization, etc., however, its output power is limited by the low capacity of the layers. The connected load must be less than 10 kΩ, and if the terminal is not used, it must be grounded.

This type of the transformers are designed to operate in all climatic zones of the world - from poles to deserts

The impermeability of the IMB transformer, as well as the low and equally distributed electric field strength in the insulation of the primary winding, guarantee the reliability of the transformer for over 30 years.

The low-oil measuring current transformer IMB, has some advantages such as:

- the unique technology of filling the internal volume of the transformer with quartz sand allows to reduce the oil volume, as well as to provide increasing mechanical stability of the cores and primary winding during transportation and the impact of short-circuit currents;
- the use of aluminum alloys guarantees high transformer resistance to corrosion without any additional protective measures;
- transformers can be equipped with a large number of cores of the secondary windings or cores with a large cross section, by increasing the volume of the tank;
- the design of IMB transformers has high mechanical strength, ensuring their reliable operation during earthquakes without the use of dampers.

1.1 Main parameters and operational characteristics of current transformers

In accordance with ГОСТ 7746-89 "Current transformers. General technical requirements» the main parameters and operational characteristics of measuring current transformers are [37]:

- rated voltage – the affected value of the line voltage at which the CT is designed to operate (indicated in the CT passport data). For current TT the following values are accepted: 0.66 kV; 6 kV; 10 kV; 15 kV; 20 kV; 24 kV; 27 kV; 35 kV; 110 kV; 150 kV; 220 kV; ... 1150 kV;

- rated primary current I_{1n} (indicated in the passport data) passing through the primary winding, at which continuous operation of the CT is provided. Current scale: 1 A; 5 A; 10 A; 15 A; 20 A; 30 A; ... 1000 A; 1500 A; ... 40,000 A;
- rated secondary current I_{2n} (indicated in the CT passport data) passing in the secondary winding. The rated secondary current is assumed equal to 1 A (with a rated primary current up to 4000 A) or 5 A. By agreement with the customer, the manufacture of CT I_{2p} = 2 A or 2.5 A is allowed;
- secondary load of the CT Z_{2n} - corresponds to the total resistance of its external secondary circuit, expressed in Ohms, with an indication of the power factor cosφ 0.8, at which the established accuracy class of the CT or the maximum ratio of the primary current relative to its rated value, is called the rated secondary load of the CT $Z_{2n.r.}$ For domestic transformers, the following values of the rated secondaryload $Z_{2n.r}$, expressed in voltamperes are, with power factor cosφ 0.8; 2.5; 5; 10; 15; 20; 25; 30; 40; 50; 60; 75; 100;
- the CT transformation coefficient is equal to the ratio of the primary current to the secondary one;
- the resistance of CTs to mechanical and thermal influences is characterized by the current of electrodynamic resistance and the current of thermal resistance. Electrodynamic resistance current I_D is equal to the largest amplitude of the short-circuit current for the entire duration of its flow, which the CT can withstand without damage that impedes its further proper operation;
- the current of electrodynamic resistance can also be characterized by the multiplicity k_D, which is the ratio of the electrodynamic resistance current to the amplitude of the nominal primary current. The requirement of electrodynamic resistance extends to busbar, built-in and split CTs;
- the current of thermal resistance characterizes the ability of a CT to withstand the thermal effects of a short-circuit current. To comment the thermal stability of a CT, it is necessary to know not only the value of the current passing through the

transformer, but also the time of its passage, or in other words, to know the total amount of heat generated, which is proportional to the product of the square of the current I_t and the time of its passage t_T. This time, in it's turn, depends on the parameters of the network in which the CT is installed, and varies from one to several seconds;

- mechanical loads, determined by wind pressure at a speed of 40 m/s on the surface of the CT and the tension of the supply wires, which should be at least:
  a) 500 N for current transformers up to and including 35 kV;
  b) 1000 N for current transformers from 110 kV up to 220 kV;
  c) 1500 N for current transformers 330 kV and higher.

1.2 Advantages and disadvantages of current transformers

V. N. Grechukhin [11] in his article reports, that CTs have some pros and cons. For example, there are advantages such as:

- high accuracy class from 0.2 % up to 0.5 %. In laboratory CTs where there is no high voltage insulation, an accuracy class of 0.1 % and higher is achievable;
- the simplicity and reliability of CTs in networks of 6 kV – 10 Kv – 35 kV;
- the temperature stability of the characteristics of the CT.

However, in addition to advantages listed above there are some disadvantages:

- the saturation of the magnetic circuit of the electromagnetic CT with the aperiodic component of the short circuit (SC) current and the lack of transmission of information about the primary current in the first periods of the emergency transient, when this information is most needed for relay protection and automation systems for successful localization and liquidation of the accident (current transformation errors by electromagnetic CTs reach 90 % in this mode);
- problems with high-voltage insulation, as indicated by unfavorable accident statistics of current transformers (from 110 kV up to 750 kV) at power electrical stations and substations in recent years;

– the explosion and fire hazard of current transformers of existing structures is fundamentally unavoidable, not only in oil-filled current transformers. In SF6 gas CTs, an explosion is also inevitable during a breakdown of the main insulation.

1.3 Contemporary requirements for current transformers

At the present stage of development of the electric power industry of Ukraine, classical measurement methods based on the electromagnetic principles have reached the limit of their capabilities and cannot satisfy new requirements. They have arisen due to technological revolution of the last several decades. As it is noted in the article of Zubia, Casado, Aldabaldetrek and others, “Unimaginable technological advances in the area of information and communications technology, the electrical sector had turned into an anachronism using the technology of last century” [3]. Therefore, the modern development of electrical complexes and systems requires the introduction of the latest designs of instruments and equipment [19]. As a result, the so-called optical-electronic (OE) measurement methods make it possible to realize the requirements of consumers. They are based on the use of optical communication between the primary and secondary transducers of the measuring system. Such methods use a completely different, more promising approach, based on the use of the magneto-optical Faraday's effect. Most often, this effect realized in fiber optic current transformers (FOCT) used in combination with modern digital signal processing and data transmission technologies.

As Chunikhin A. A. and Zhavoronkov M. A. reports in their work, “currently, the development of the FOCT is produced by leading companies around the world (NXTPhase, Siemence, Профотек, ABB, Airak). Such transformers are considered to be the next generation of transformers, because they eliminate defects of the analog transformers and meet all the necessary requirements” [15]:

– speed, wide frequency range up to 6 kHz;
– large overload capacity, wide dynamic range;
– lack of influence of short circuits;
– high electrical insulation resistance with compact dimensions;

– light weight, ease of installation;

– fire safety, environmental friendliness.

Today, it is known that the sensitive element (optical fiber) can be made in 3 versions in accordance with the requirements.

Busbar performance. The sensing element is mounted on the bus. For voltages above 20 kV, fiber optic cables are lowered inside the insulator. The design may contain an additional holding insulator or may be mounted directly on the pole of the high voltage switch, as presented in Figure 1.3.

a – the busbar with sensing element, < 20 kV;

b – the busbar with tilted sensing element, > 20 kV;

c – the current busbar, 35 kV;

d – the voltage busbar with sensing element ≥ 500 kV.

Figure 1.3 – Tire performance of optical fiber [30]

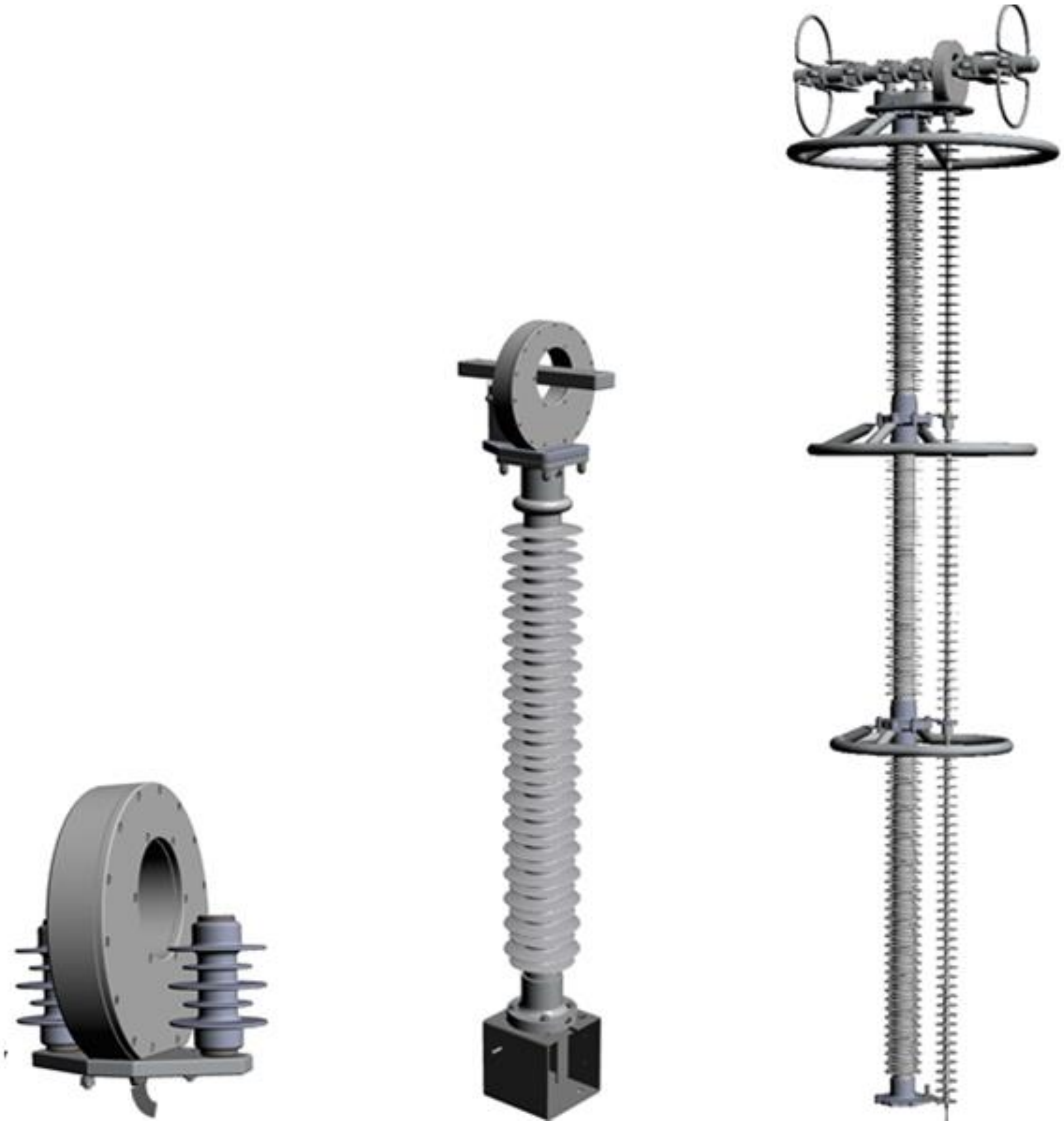
Flexible design for use on DC and AC. A flexible sensing element (optical fi-ber) is wound on AC or DC bus, high voltage cables, transformer input cables, etc. They are installed at voltage of ≤5 kV, as presented in Figure 1.4.

a – flexible sensing element is wounded on AC bus;

b – flexible sensing element is wounded on DC bus.

Figure 1.4 – Flexible design of optical fiber [30]

Performance of sensing element in different types of transformers. The sensing element is mounted on an insulator filled with gel. The insulator is mounted on a stand to protect the cable coming from the bottom flange and to securely install the high-voltage column, this type of transfoemers work in range from 5 kV up to 750 kV, they are presented in Figure 1.5.



a – fiber optic current transformer;

b – fiber optic current and voltage transformer;

c – fiber optic voltage transformer.

Figure 1.5 – Types of fiber optic transformers [30]

However in addition to sensors and optical fiber, special attention in the FOCT is given to the insulation. The issue of insulation is still of current interest, since only due to the choice of highquality material, the correct shape of the ribs, the FOCT acquires also flexibility, inensitivity to external influences and easily of mounted [1].

2 ANALYSES OF EXISTING INSULATORS AND FIBER-OPTIC CURRENT TRANSFORMERS

Current transformers are critical pieces of infrastructure in the electric grid that are both extremely expensive and difficult to replace. These transformers often have long lead times for replacement, and failures can create long service disruptions. This project has developed a new suite of sensors designed to give early warning of the impending failure of these important transformers before it is too late and a major failure occurs [45].

The authors, V. V. Afanasiev and Adon'yev report in their article “world experience shows that during recent years, the energy sector has grown significantly, the construction of intersystem power lines of extra-high voltage direct and alternating current has started, the mass generation of power plants with pulse currents of up to 10^6 A and more has begun, the need has arisen for the development of reference devices for measuring the parameters of the electric transmission process energy in the field and laboratory conditions. All this has led to the development of new methods for measuring electrical quantities based on the achievements of optoelectronics, semiconductor technology, and computer technology” [7]. Gradually, fiber-optic measuring current transformers, new generation transformers, have been created by using novel fiber optic sensors instead of conventional existing technologies. With the help of new technologies, we are able to measure transformer characteristics indicative of impending failures in ways that were not previously possible [45].

They consider, that the Implementation of FOCT to the electric power industry mainly depends on success in the development and intercalation of relay protection, automation system and measuring instruments on the elements of analog and digital computing with low power consumption from their output circuits. Thus, quite a lot of attention is paid to this direction.

Fibre optic technology is one of the solutions to achieve the digital substation. It is ‘immune’ to EMI/RFI and has reached a level of maturity that has helped push down costs. Moreover, optical sensor technology does not require a power source at the point of measurement and the light source can be hundreds of meters away – even outside the substation itself [44].

As well as the authors say, that electrotechnical plants and research institutes of a number of foreign countries (USA, Japan, France, Germany, England) also pay considerable attention to the development of OE methods and FOCT, as evidenced by a large number of printing works and patents” [7].

Thus nowadays, fiber optic current transformers are gaining more popularity today. Canadian, Russian, American, German, etc. FOCT are rapidly replacing analog transformers worldwide. And it is known that a fiber-optic current transformer is characterized by the following benefits [43]:

- reduced size and weight are attractive benefits compared to conventional oil-filled equipment, allowing placement in compact substations or in retrofit applications where space may be limited;
- a very high stability in a wide temperature range and in an increased frequency band is also a considerable advantages;
- lightweight dry-type insulator and window head design allow pedestal mounting or suspension from a rigid bus;
- broad dynamic range makes this CT particularly suited for both high-precision metering and protection applications at the same time;
- accurate measurement of DC and AC to the 100th harmonic and the measurement of phase angle is a must for new Smart Grid applications.

The specialists of Profotech company, report in their article, “the Canadian company NXT Phase is one of the first creators of this type of device. Since 2002, the devices of this company have been tested on existing high-voltage power lines in different countries. In Russia, the best practical results on the creation of domestic devices of this type have been obtained at the company Profotek CJSC” [30]. Regretfully, in Ukraine there is no manufacturer of this kind of transformer but there are the researchers in this area.

2.1 Design and principle of operation of fiber optic current transformers

Let’s consider the main types of FOCT manufactured by Profotech, as shown in Figure 2.1 and NXTPhase, in Figure 2.3 and Optical Electronic Current Transformer GDGL manufactured by RHM International, as shown in Figure 2.4.

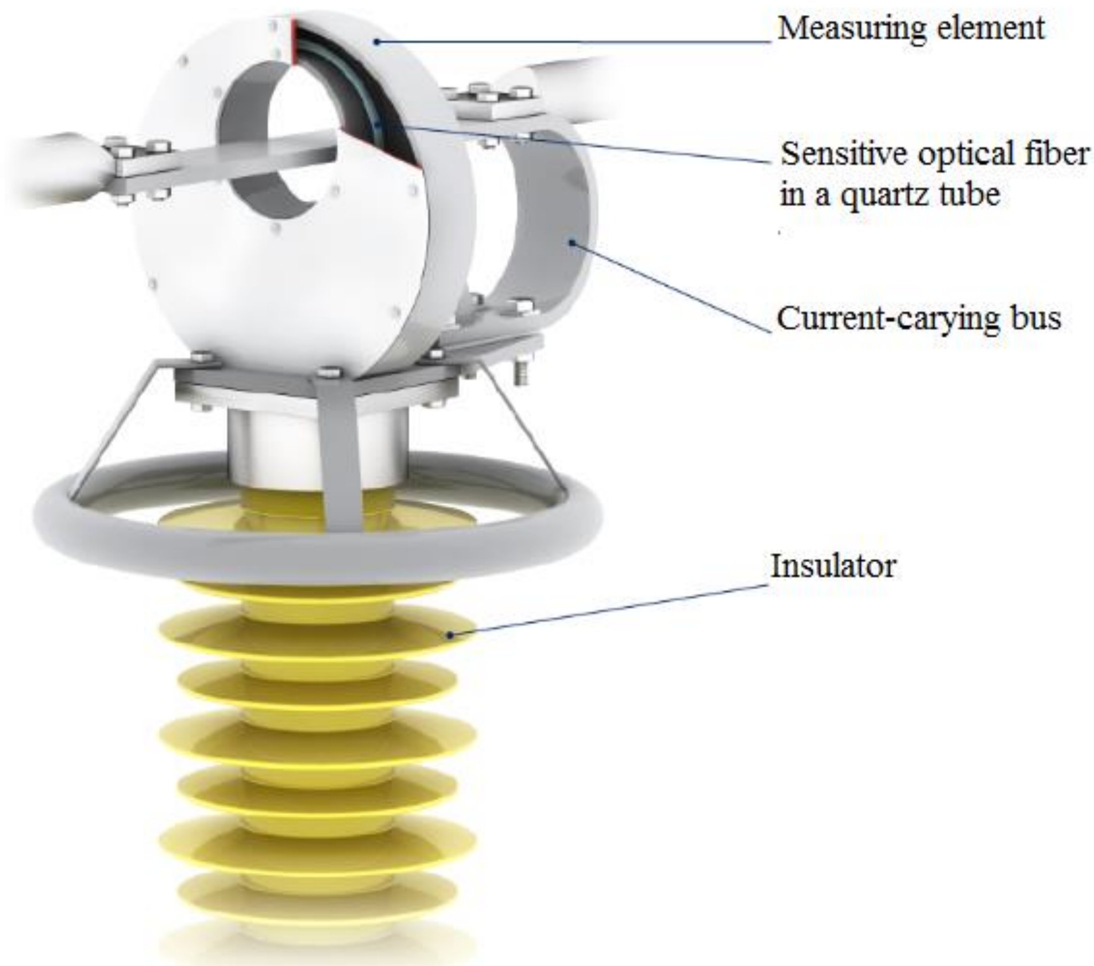


Figure 2.1 – FOCT manufactured by Profotech [30]

The manufacturer of FOCT by Profotech, speaking about design of this type of transformer, write in article, “a current sensor locates on the support insulator, and it consists of a measuring element, a sensitive optical fiber in a quartz tube and current-carrying bus. A linearly polarized light signal is supplied from the electro-optical unit, which enters the electron-optical unit through the optical fiber” [30]. The design of the FOCT in the support performance, by Profotech, is shown in Figure 2.2.

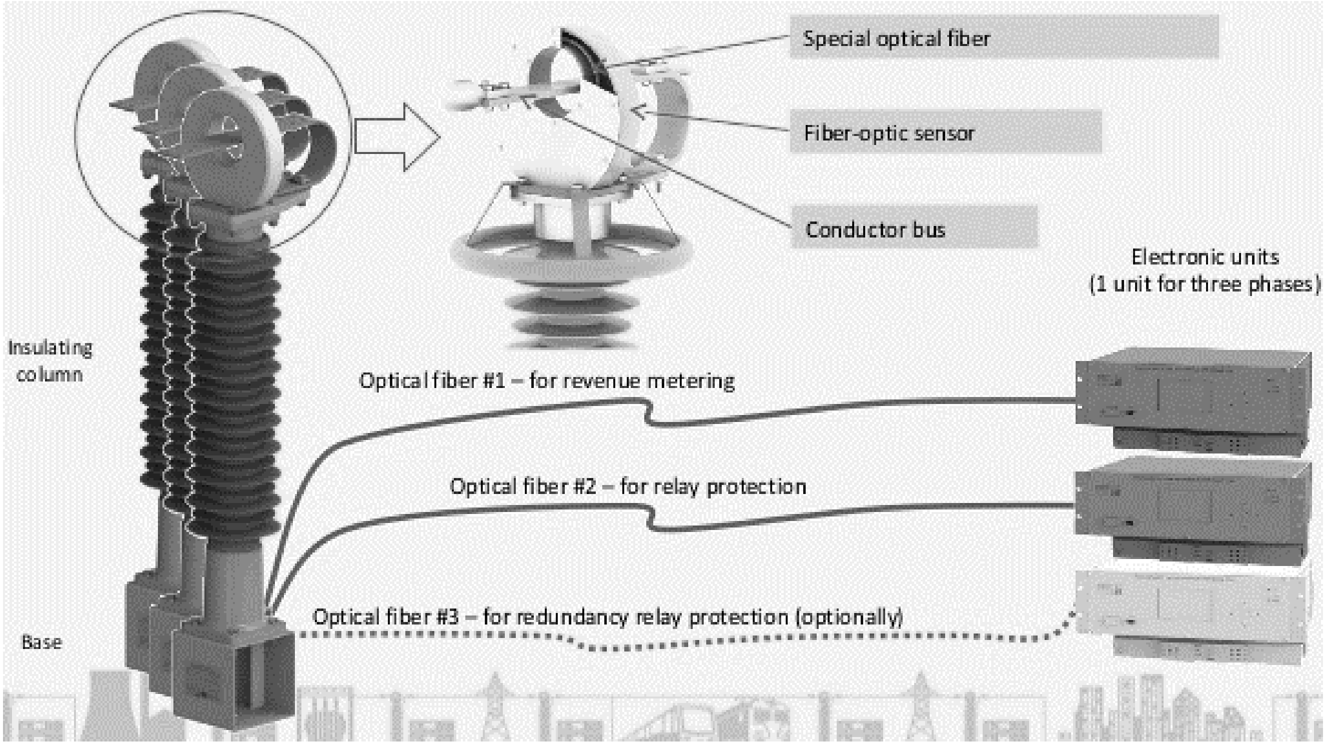


Figure 2.2 – The design of the FOCT manufactured, by Profotech [30]

As Kanevskiy [17], reports in his article, “the operating principle of the FOCT of the Canadian manufacturer NXT Phase is the same as the Russian one. It is worth noting that NXT Phase offers a new design of the FOCT with a breakable optical loop NXCT-F3, as in Figure 2.3 b. Optical current transformers can be used in information-measuring systems of technical and commercial metering and quality control of electrical energy. The transformer has a measuring sensor made in the form of several turns fiber optic loop covering a high voltage input, a generator bus, or a current conductor. Design features allow you to install the transformer in those places where the installation of traditional copper transformers is extremely difficult or simply impossible. The measuring loop of the sensor is a polarization-preserving optical fiber connected to a standard NXCT, as in Figure 2.3 an electronics kit with a standard set of output interfaces. This is an ideal solution that allows, in a short time and with a minimum amount of preparatory work, to organize the deployment of a measuring or verification complex”.

a – NXCT Measuring Fiber Optic Current Transformer;

b – NXCT-F3 Current Transformer with Opening Optical Loop.

Figure 2.3 – FOCT manufactured by NXTPhase

Figure 2.4 – GDGL manufactured by RHM International

The transformers manufactured by RHM International also allow a direct digitalization of the current sensing that is transmitted to the local control system. Existing optical CTs are based on a sensing configuration that needs to be installed on and powered by the primary line. The RHM solution uses the same primary HV winding around which a Rogowski coil is inserted. This combines the same long term reliability of the electrical insulation while allowing the benefits of an electronic configuration.

Different configurations can be offered that allow for different digital conversion time lines while maintaining the insulation system [48].

These current transformers have their own advantages.

Using these transformers, it is no need for a reconfiguration of old substation layout: the new optical CT can be installed in the exact place where a traditional CT was in operation before; the same support can be used and the user benefits from a "plug & play" experience.

Upgrade from traditional to digital/optical at minimum cost and time: if the user needs to replace some CTs today while knowing that eventually the system will evolve towards a digital configuration, RHM can provide CT equipped with the sensor needed to turn the CT into an optical version (when the rest of the station has been upgraded).

Operating the two options at the same time: Furthermore, dual CT provides both an analog and digital signal at the same time. This unique design allows a remarkable flexibility in introducing digitalization in current transformer operation at a minimum cost.

The ambient temperature at which the CT GDGL series can operate is -40℃ to +85℃. In addition, they provide unique benefits:

– high accuracy over wide dynamic range;
– wide bandwidth;
– no saturation;
– no noise;
– highly stable.

Let’s consider optical fiber in details. Optical fibers are made from either glass or plastic. Most are roughly the diameter of a human hair, and they may be many miles long. Light is transmitted along the center of the fiber from one end to the other, and a signal may be imposed. Fiber optic systems are superior to metallic conductors in many applications. Their greatest advantage is bandwidth [53].

Electrical Isolation — Fiber optics do not need a grounding connection. Both the transmitter and the receiver are isolated from each other and are therefore free of ground loop problems. Also, there is no danger of sparks or electrical shock.

Freedom from EMI — Fiber optics are immune to electromagnetic interference (EMI), and they emit no radiation themselves to cause other interference.

Low Power Loss — This permits longer cable runs and fewer repeater amplifiers.

An optical fiber consists of three basic concentric elements: the core, the cladding, and the outer coating (Figure 2.5).

The core is usually made of glass or plastic, although other materials are sometimes used, depending on the desired transmission spectrum.

The core is the light-transmitting portion of the fiber. The cladding usually is made of the same material as the core, but with a slightly lower index of refraction (usually about 1% lower). This index difference causes total internal reflection to occur at the index boundary along the length of the fiber so that the light is transmitted down the fiber and does not escape through the sidewalls.

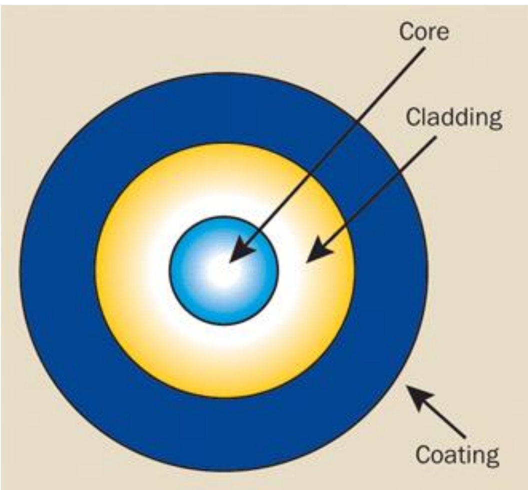


Figure 2.5 – Construction of fiber optic [54]

The coating usually comprises one or more coats of a plastic material to protect the fiber from the physical environment. Sometimes metallic sheaths are added to the coating for further physical protection.

Optical fibers usually are specified by their size, given as the outer diameter of the core, cladding, and coating. For example, a 62.5/125/250 would refer to a fiber with a 62.5-µm diam core, a 125-µm diam cladding, and a 0.25-mm diam outer coating.

There are basically three types of optical fiber: single-mode, multimode graded index, and multimode step-index. They are characterized by the way light travels down the fiber and depend on both the wavelength of the light and the mechanical geometry of the fiber. Examples of how they propagate light are shown in Figure 2.6.

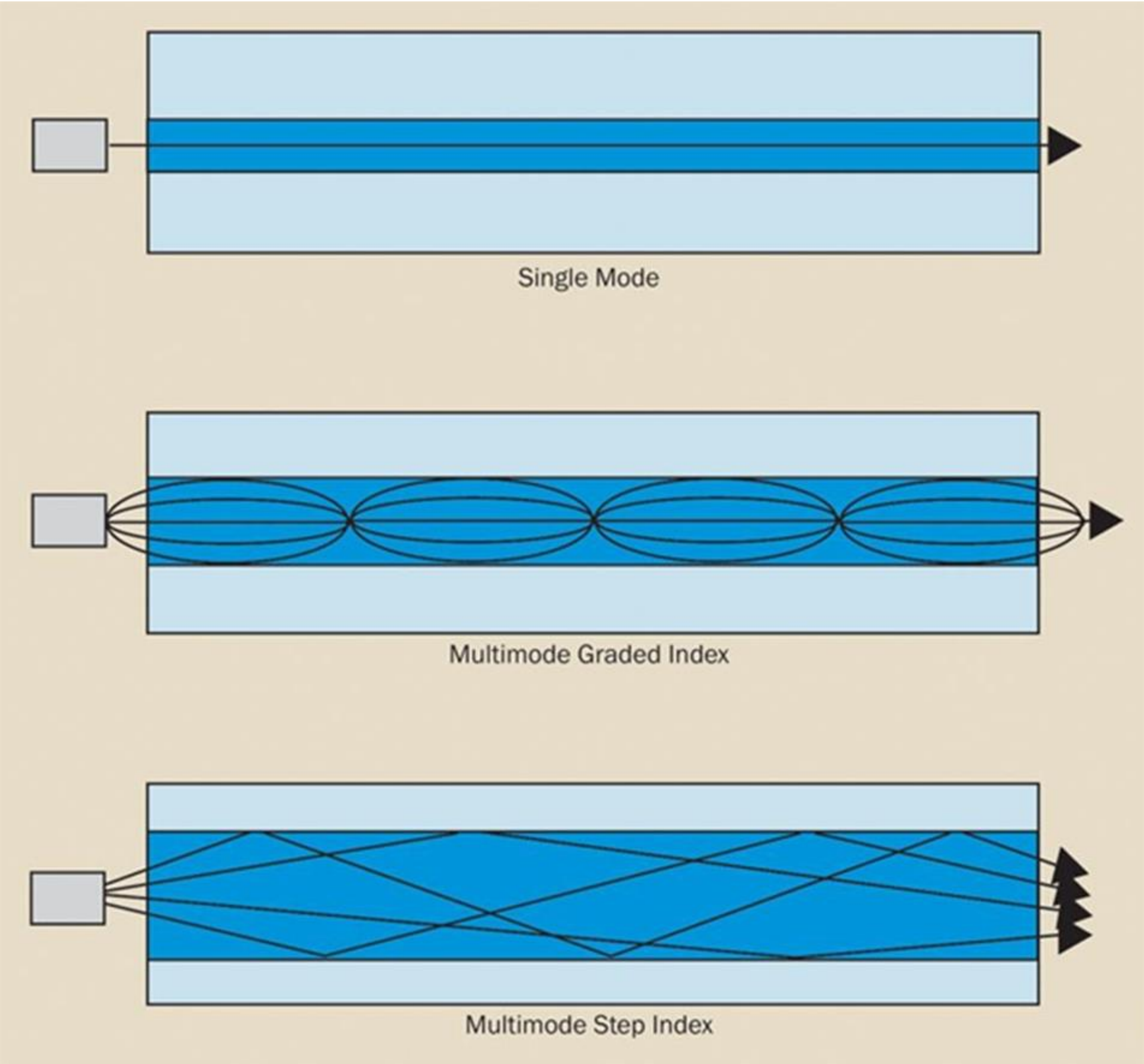


Figure 2.6 – Modes of fiber transmission

Only the fundamental zero-order mode is transmitted in a single-mode fiber. The light beam travels straight through the fiber with no reflections from the core-cladding sidewalls at all. Single-mode fiber is characterized by the wavelength cutoff value, which is dependent on core diameter, NA and wavelength of operation.

The core diameters of multimode fibers are much larger than single-mode fibers.

As a result, higher-order modes also are propagated.

The core in a graded-index fiber has an index of refraction that radially decreases continuously from the center to the cladding interface. As a result, the light travels faster at the edge of the core than in the center. Different modes travel in curved paths with nearly equal travel times. This greatly reduces modal dispersion in the fiber.

The core of a step-index fiber has a uniform index of refraction right up to the cladding interface where the index changes in a step-like fashion. Because different modes in a step-index fiber travel different path lengths in their journey through the fiber, data transmission distances must be kept short to avoid considerable modal dispersion problems.

2.2 Optoelectronic measurement methods

Laboratory and experimental samples have been created with various types of modulation of the light flux and various structural designs. All known OE methods are divided into two types: based on the methods of internal radiation modulation and on the methods of external radiation modulation. These two measuring systems are constructed according to two main structural schemes shown in Figure 2.7 and Figure 2.8.

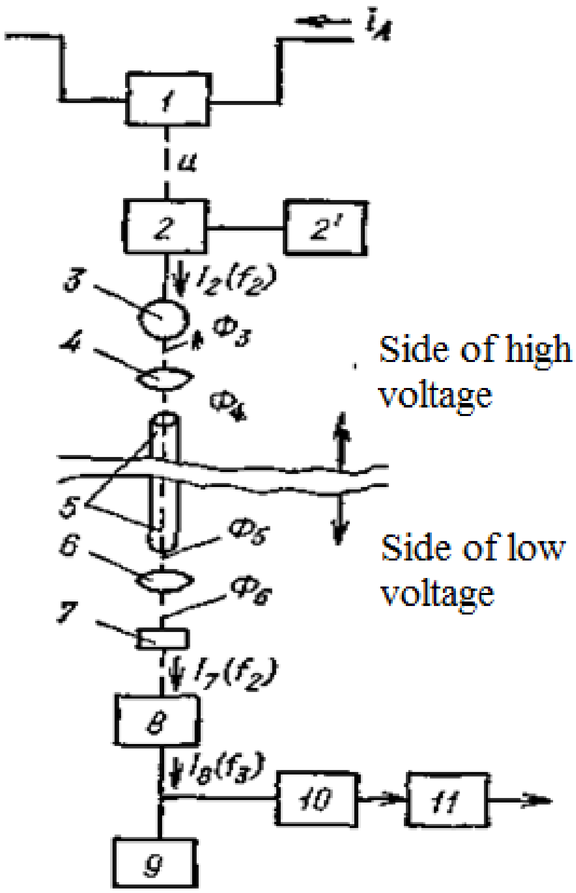


Figure 2.7 – Structural scheme of FOCT with internal modulation of light flux [15]

Chunikhin and Zhavoronkov [15], speaking about types of modulation, write in their work, “under internal modulation we mean the effect of the measured parameter on radiation in the light source itself. According to the Figure 2.7, the primary converter 1 usually emits a voltage proportional to the measured current. The intermediate Converter 2 modulates the signal.

At amplitude modulation, block 2 can be an amplifier; at frequency modulation, the current is converted into a variable frequency signal, which is proportional to the current. Power supply unit 2 is performed from a stabilized source 2’.

From block 2, the signal enters the photoconverter 3. For amplitude modulation, the linear part of the lumen-ampere characteristic of the light emitting diode is used. At a modulation frequency, the flash of a light-emitting diode is proportional to the current $i_{Л}$. Next, the light through the optical system 4, 6 and the optical fiber 5 is supplied to the photodetector 7. Photodiodes are used as the photodetector. The signal from the photodiode is fed to amplifier 8. A load 9 operating on a discrete signal is connected directly to amplifier 8. The load running on the analog signal is connected to the amplifier 11. The signal to the input of this amplifier is supplied from the frequency converter - analog, code - analog 10".

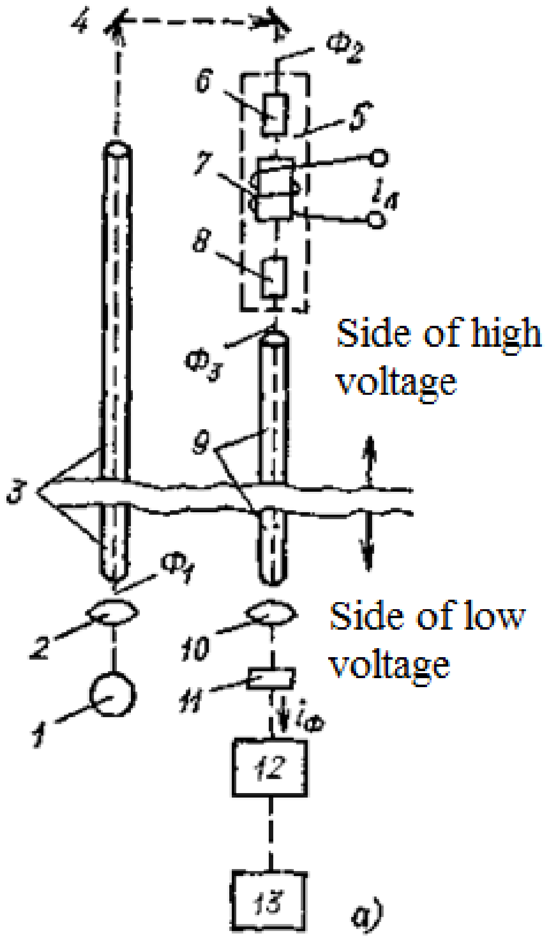


Figure 2.8 – Structural scheme of FOCT with external modulation of the light flux [15]

Under external modulation of the light flux we mean the effect of the measured parameter on radiation of constant intensity outside the source itself.

According to Figure 2.8, the source 1 and the optical system 2 create a stream of light F1, which is transmitted through the fiber 3 to a high potential. The most perfect should be considered fiber optic fibers.

This optical fiber is a bundle of individual fibers with a diameter of about 10 microns. Each fiber has a core made of glass or plastic with a specific refractive index n_1, and a cover is made of glass with its own refractive index n_2. The exponent n_2 is less than n_1, resulting in total internal reflection within the fiber. The efficiency of the optical fiber is approximately 15 % with a length of 10 m. Currently, optical fibers in the form of massive glass rods are being developed, which are easier to manufacture, operate, and more reliable.

After passing through the optical fiber, the light flux with the help of prisms 4 changes its direction (flux Φ_2) and is fed to a modulator 5, consisting of a polarizer 6, a transducer 7 and an analyzer 8. The light flux Φ_3 is transmitted through the optical fiber 9 to the blocks located on the LV side. Using the lens 10, the light beam is concentrated on the converter 11, in which a change in the light intensity causes a change in the photocurrent $i_ф$. An electrical signal is supplied to the amplifier 12 and then to the load 13.

That is, the modulation process occurs as follows. A beam of parallel rays of monochromatic light from a radiation source 1 is linearly polarized by a polarizer 6 and fed to a converter 7. A Faraday's cell can be used as a converter [15].

Some optical substances are used in the Faraday cell, for example, glass heavy flint, which have the property of rotation of the plane of polarization of light depending on the intensity of the magnetic field in which this substance is located. This phenomenon was discovered by Faraday. The angle of rotation of the plane of polarization is:

$$\theta = VlH, \tag{2.1}$$

where V is the Verdet constant, A/m;

l is the length of optical element, m;

H is the strength of magnetic field, A/m.

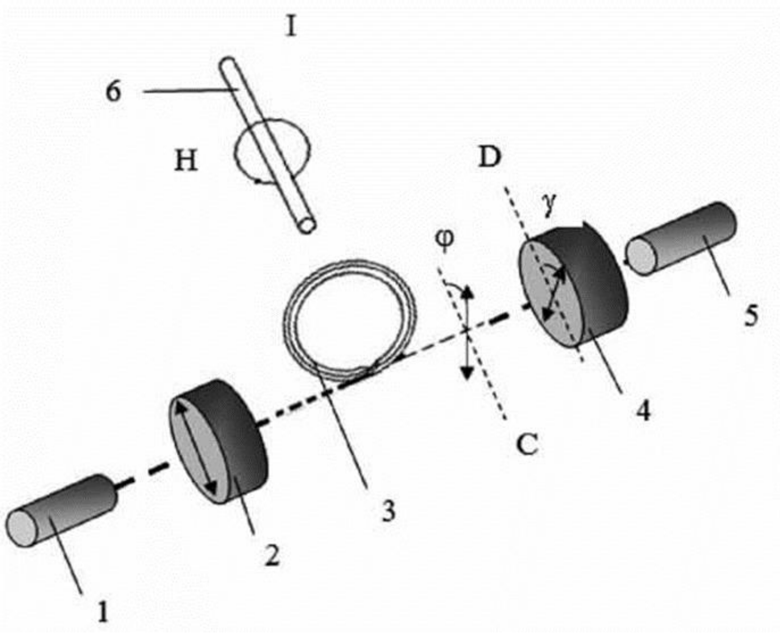
As Chunikhin A. A. and Zhavoronkov M. A. note in their work "a great advantage of external modulation of FOCT is the absence at high potential of complex and numerous converters requiring a stabilized power source. The disadvantages of FOCT is the dependence of the Verdet constant on temperature. The upper and lower

elements are in different temperature conditions and compensation is difficult. And also the disadvantage
of the Faraday sensor is the influence on its work of external magnetic fields created by other currents” [15].

2.3 Faraday's effect

Fiber optic current transformers using the Faraday's effect are universal devices designed to measure direct, alternating and impulse currents in installations and lines of any voltage [7]. The use of the magneto-optical Faraday's effect is a completely different, more promising approach.

Urakseev and Levina, speaking about the magneto-optical effect, write that “In 1845, Faraday discovered a phenomenon that became one of the main steps in the development of optical current converters — the phenomenon of rotation of the plane of polarization of linearly polarized light in a constant magnetic field” [19], as presented in Figure 2.9.



1 - laser diode; 2 - polarizer;

3 - Faraday's element (twisted optical fiber); 4 - analyzer;

5 - photodiode; 6 - electric current conductor.

Figure 2.9 – Schematic diagram of the Faraday's effect [19]

Based on the above, we can conclude that OETT could have been invented as early as 176 years ago, when the Fraday's optical effect was discovered. However, using these compelling optical properties for measuring currents would have required several key additional innovations before they could have become industrialized. Still today, further innovations are under way to advance the performance of these technologies, in order to help meet increasing customer specification demands [52].

The authors described the Faraday’s effect as follow, oscillations of the light wave at the output of the polarizer occur in the plane C. At the output of the analyzer the oscillations of the plane-polarized light wave occur in the plane D (taking into account the additional rotation of the plane of polarization in the Faraday element by the angle φ and the transmission angle of the pair of polarizers γ). Making a ring from many turns of optical fiber and wrap a wire around this ring, then by passing an electric current, you can get a magnetic field transducer with high sensitivity.

2.4 Comparative analysis of optoelectronic methods for measuring high voltage currents and analogue ones

Afanasiev and Zubko [8], speaking about opto-electronic measuring methods of currents of high voltages and analogue ones, make a comparative alalysis of these two methods.

Electromagnetic CTs can be rejected in the case that at the output of the FOCT there will be enough power to control the protection devices. In analogue CTs, the output power is consumed directly from the high-voltage network and can be quite large (100 VA or more in nominal mode). However, this is achieved simply, reliably and economically only for a certain range of the measured current and operating voltage: at high multiples of the measured currents and at ultrahigh voltages. The advantages of CTs in terms of power, lose their value, since the accuracy of transformers decreases with increasing of these parameters, and the apparatus itself becomes uneconomical. In the FOCT, information from a high potential to the earth is transmitted by a low power level, and the output power of this device is provided by an autonomous source located

on the earth's potential. Therefore, the output power of the FOCT does not determine its economy. The solution of the issue of the output power of the FOCT has become possible after powerful semiconductor triads have been developed, which allow to create the corresponding amplifiers. On the other hand, the power consumption of modern distance
protection is being gradually reduced due to the use of electronic devices, which allow matching protection requirements with the capabilities of a new type of CT.

In CTs, when transition to ultrahigh voltage, it is difficult to obtain a precisely mapped form of the primary current by the secondary during an asymmetric short circuit, since the transfer of DC components is quickly limited by saturation and residual induction. Magnetizing current, magnetic scattering, hysteresis, and loss in iron cause measurement errors that vary with the magnitude of the measured current and secondary load. The optoelectronic measurement system does not have these drawbacks and, with large multiples of the measured current, is capable to provide high measurement accuracy.

CT insulation is relatively simple up to 220 kV. Above this voltage, transformers become complex and expensive. The measuring properties of the FOCT are independent of the voltage between the line and the ground. Indeed, the information with a light beam can be transmitted to any necessary distances. FOCT are insensitive to voltage and currents of adjacent lines. At developing practical devices, the task is to select an insulating gap between the primary and secondary sides of the device, which has the necessary reserve of electric strength.

CTs do not allow large current overloads. But in it's turn some FOCT schemes, for example, based on the Faraday effect, allow almost any current overload by virtue of the cyclical effect.

The FOCT provide signal transmission in a wide frequency range. The above comparison of the properties of CT and FOCT indicates the proaspects of the latter in the transition to current measurements of ultrahigh voltages. The physical basis of OE measurement methods is constituted by the processes of conversion of the measured (input) electrical signal into a light signal and a light signal into an output electric signal. Specific conversion schemes differ from each other primarily by the way measured parameter affects the properties of the light beam (modulation method).

Conclusion from the above: FOCT undoubtedly surpass their predecessors in many ways. In Ukraine, a large number of analogue measuring CTs have reached the end of their service life (25 years) and their replacement are inevitable. With the growth of digital equipment introduction, the sense of replacing the old CT with a similar new ones is lost.

Along with the undoubted advantages listed above, FOCT in comparison with electromagnetic CTs have some disadvantages due to their operating principle. The main ones are:

- the conversion unit of the optical signal into electrical requires specialpowersources;
- the power of the output circuits is insufficient to drive the existing sets of protection on electromechanical relays, and its increase is associated with great technical and economic difficulties;
- the need to ensure high accuracy, reliability and stability at the time when changing operating temperatures in a wide range leads to significant complications of the circuit and, as a consequence, to a loss of competitiveness, especially in designs for lower voltage classes [15].

However, as Afanasiev and Adon'yev note in their work "these shortcomings should be considered as temporary, because as circuit designs and base elements are improved, they will be completely removable. There is no doubt about this, since OE methods have begun to develop relatively recently, scientists are doing everything possible to remove these shortcomings" [7].

2.5 Insulation design of FOCT

One of the main requirements for the operation of new generation transformers is reliable operation at voltages reaching many hundreds of kilovolts. Therefore, the issue of insulation is still of current interest, since only due to the choice of high-quality material, the correct shape of the ribs, the FOCT acquires such features as flexibility, insensitivity to external influences and are easy to mount [1].

The insulating structure during operation must withstand the long-term (tens of years) exposure to the highest operating voltage, as well as short-term repeated effects arising in the network of atmospheric (lightning) and internal (switching) overvoltages [30]. In modern apparatus engineering Polymer insulation account for a large proportion of manufactured FOCT. And this is due to the high level of electrical and mechanical strength (achieved by reinforcing them with fiberglass). However, Porcelain insulators, sometimes are being used as well.

The advantages of polymer insulators, according to ГОСТ 56737-2015 [21], are a higher electrical resistance during pollution, compared with similar porcelain insulators with an equal leakage path, this advantage is even more evident due to the use of the hydrophobicity of the material. The other important advantages of polymer insulators are: flexibility, which allows to install optical transformers in vertical, horizontal and tilted positions, and it does not affect the accuracy of measurements; compactness which allows them to be installed in conditions that are unacceptable for analog transformers; insensitivity to external electromagnetic fields does not require analysis of the relative position of the tires; light weight which allows installation without using of cranes.

According to the “Instructions for selecting insulation of electrical installations” [22], “having given a ribbed shape to the polymeric insulator, we will reduce the leakage current (by 1-2 orders of magnitude lower than that of porcelain insulators) to the required level over the surface of the insulator at dirty and moisture conditions. The profile of the ribs is an important component of the polymer insulator because it's a type of self-cleaning insulator. Depending on the growth of pollution, insulators with the same protrusion of ribs, require the length increasing (construction height), in order to obtain an increased length of the current leakage path. This solution cannot be used constantly, it is not economical and requires the development of new electrical equipment, especially for increased environmental pollution. The solution of the given problem is the new design of insulators with variable protrusion of ribs. An insulator with a variable protrusion of ribs at the same construction height allows an increased length of the leakage path. In addition, due to the variable overhang of the ribs, the dirt resistance is increased".

The company RHM International, proposes to use the most suitable internal insulation for the FOCT [48].

HV DryShield is a proprietary condenser finely-graded insulation using composite materials such as PTFE (Poly Tetra Fluoro Ethylene) as core insulation. A uniformly distributed electric field design eliminates stress points and is complemented with external silicone rubber insulation. A unique combination of design, materials and manufacturing know-how results in a very robust insulation with minimum flashover risk and very low partial discharge and tanδ values.

HV DryShield is used both in Current Transformers as well, Figure 2.10.

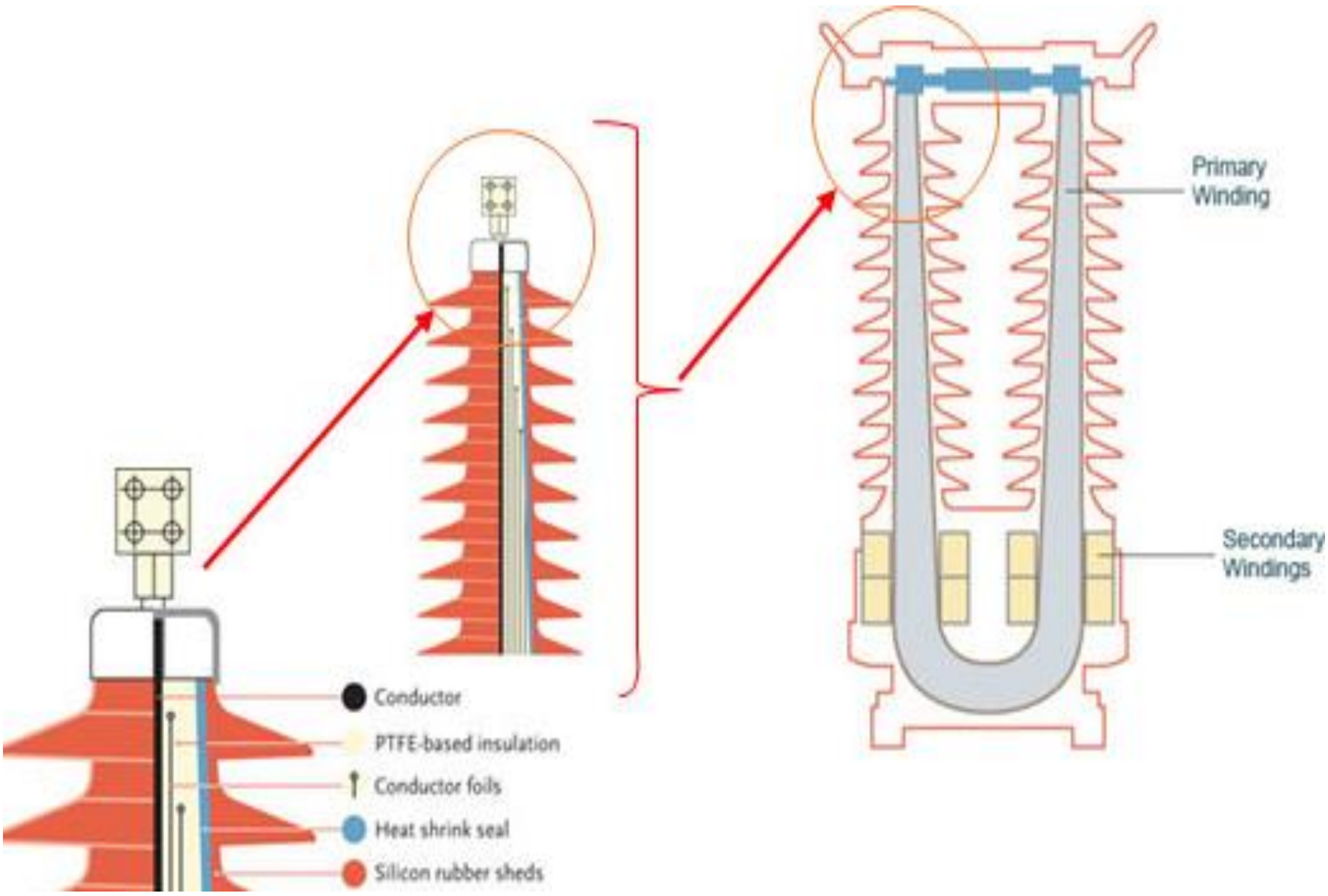


Figure 2.10 – HV DryShield insulation in current transformer

RIF is a proprietary paperless condenser graded insulation system composed of layers of fiberglass impregnated with epoxy resin between capacitive screens used to form a uniform core insulation, as it is shown in Figure 2.11. RIF – provides superior electrical, mechanical and thermal operational margins. It is impervious to humidity in a maintenance-free, leak-free and explosion-free package. As with all RHM International products a high quality silicone rubber is used as outer insulation; it provides superior pollution and climate resistance enabled by the uniformly controlled electrical field profile.

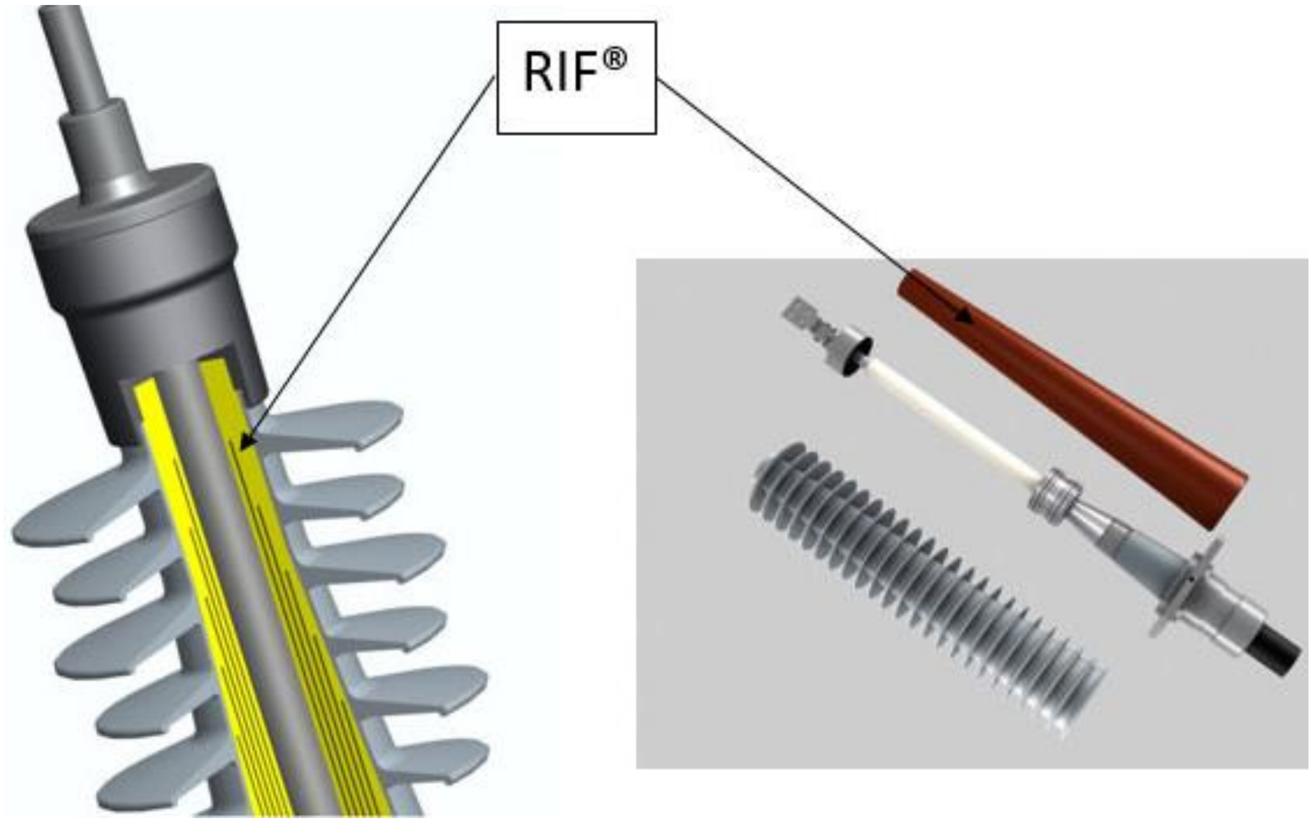


Figure 2.11 – RIF in Bushings and Cable Terminations

3 INSULATION OVERVIEW

Acording to the article “Advantages and disadvantages of various types of insulators for power transmission lines” [31], “in modern energy, electric power is transferred from the locations of its production to consumers via overhead power lines of voltage up to 750 kV and higher. Thus the great importance is the reliability of the power lines and the entire complex of equipment: transformers, generators, switching equipment, compensating devices, etc. In a large extent, the solution of this problem is ensured by the reliable operation of the insulation of electrical systems and equipment. In particular, the correct choice of the type of insulators that will be operated on the designed line in the future.

As noted in their work, Zhornyak, Afanasiev, Leonov, and Karpuk insist that “Insulation is an essential element in the design of electrical appliances and has a significant impact on both its design and operational reliability, especially in ultrahigh voltage devices” [18]. It is known that the trouble proof operation of networks, the service life of highvoltage equipment, the safety of maintenance directly depends on the quality of the insulators, and especially on their material, reliability, type and number of ribs. If to analyze the current state of the high-voltage equipment parks, one can be sure that they are in poor condition, as presented in Figure 3.1.

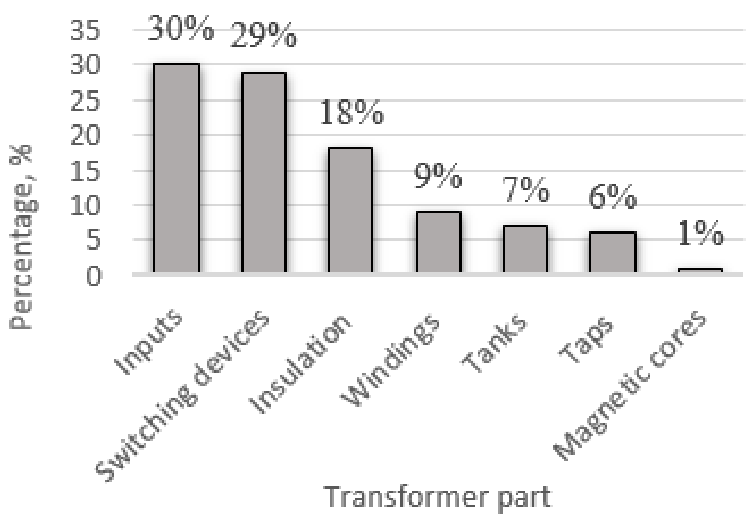


Figure 3.1 – Estimated damage of the analog transformers 110-150 kV in percent [1]

Due to long-term operation and the lack of necessary service conditions, the external insulation has lost its quality, has stopped to perform its functions, therefore, all these give a large measurement error. Thus, we can conclude that the parks of high-voltage equipment require urgent repair or replacement with completely new promising devices. But as practice shows, a complete replacement of old equipment is much more profitable than its repair [1].

The widest selection of insulators is presented on the market, and it often becomes difficult to understand all the nuances of their use, advantages and disadvantages. We have structured and analyzed the basic information in order to present it in the most understandable way [34].

Insulators can be classified by the following parameters: by the material from which they are made and by design. According to the material, the insulators that are currently used on overhead lines are divided into three types: glass, porcelain and polymer. How do they differ?

The overview of existing insulation constructions used for measuring current transformers in different environmental conditions and during different voltage loads are considered below.

3.1 Porcelain insulators

Speaking about porcelain, electrical porcelain for insulators, we recall that it is a product of inorganic chemistry, it is an artificial mineral based on clay, quartz and feldspar. Therefore, the chemical and physical properties of the material remain unchanged over time.

The use of porcelain insulators goes back to the 19-th century. At a time when glass production was in its infancy, and polymeric insulators were not even aware of, porcelain insulators successfully performed their task. Porcelain insulators can be called classics, they are the first insulators on power lines and have previously been used even for outdoor wiring in houses [40].

As noted on the website of production and trading company “Energomash” [32, 46] for the entire existence and usage of porcelain insulators, there are 6 different types:

Porcelain supporting insulators, as shown in Figure 3.2, are designed for indoor use (category of placement У3). It is allowed to use insulators in the open air under a canopy (category of placement УХЛ2).

Figure 3.2 – Porcelain supporting insulator

According to the article “Design of porcelain and glass insulators - structural elements of insulators” [36], “all types of outdoor porcelain insulators most often have umbrella-shaped ribs with droppers or recesses that prevent water from entering the surface below. In addition, the reliable operation of insulating structures under prolonged exposure to operating voltage is ensured by the selection of the appropriate leakage path, which depends on the number of ribs on the insulator [51]. Leakage path means the smallest distance along the surface of an insulating part between metal parts of different potentials”. The leakage path of insulators for different degrees of pollution is determined by the formula (3.1):

$$L_{l.p} = \lambda_{l.p} \times U_{ph}, \tag{3.1}$$

where U_{ph} is the largest phase voltage of the electrical installation;

$\lambda_{l.p}$ is specific leakage path along the insulator [15].

Consider all advantages for all types of porcelain insulators [34].

- throughout the life of the mechanical strength does not change;
- the material of the insulator is resistant to ultraviolet radiation and solar;
- radiation, to all aggressive chemical emissions from industrial enterprises;
- they have zero permeability and incombustibility;
- they withstand large compression loads;
- they have good dielectric properties;
- they are resistant to various atmospheric phenomena.

Porcelain insulators have significant disadvantages, as well [34]:

- significant weight – which complicates installation;
- high fragility – porcelain often bursts in on-off modes, especially during transition from cold to warm season;
- the surface of dish-shaped porcelain insulators is susceptible to the formation of a mud film – it creates the need of periodic washing of insulators.

As Golovin notes in his work, “Another generally recognized drawback of such insulators is the difficulties connected to the diagnosis of breakdowns and micro cracks. In addition, micro cracks arising in porcelain insulators are prone to accelerated aging due to temperature changes.

Nowadays a new generation of porcelain insulators appear, they are long-rod insulators. They are considered very reliable, but the production technology of such insulators is quite complicated and the price is correspondingly high. Therefore, they are not manufactured and practically not used in the Post-Soviet Union countries " [41].

The technical challenge when using fibre optic technology with porcelain insulators relates to manufacturing such an insulator with a straight 15 mm diameter 3 m long hole. The C-130 porcelain mass is extremely hard and would require special drilling heads. Keeping the hole straight across its entire length would be another challenge. This makes drilling time consuming as well as costly if relying only on conventional technologies. Moreover, manufacturing such a precise small hole with the plastic extrusion process for porcelain insulators is not feasible [44].

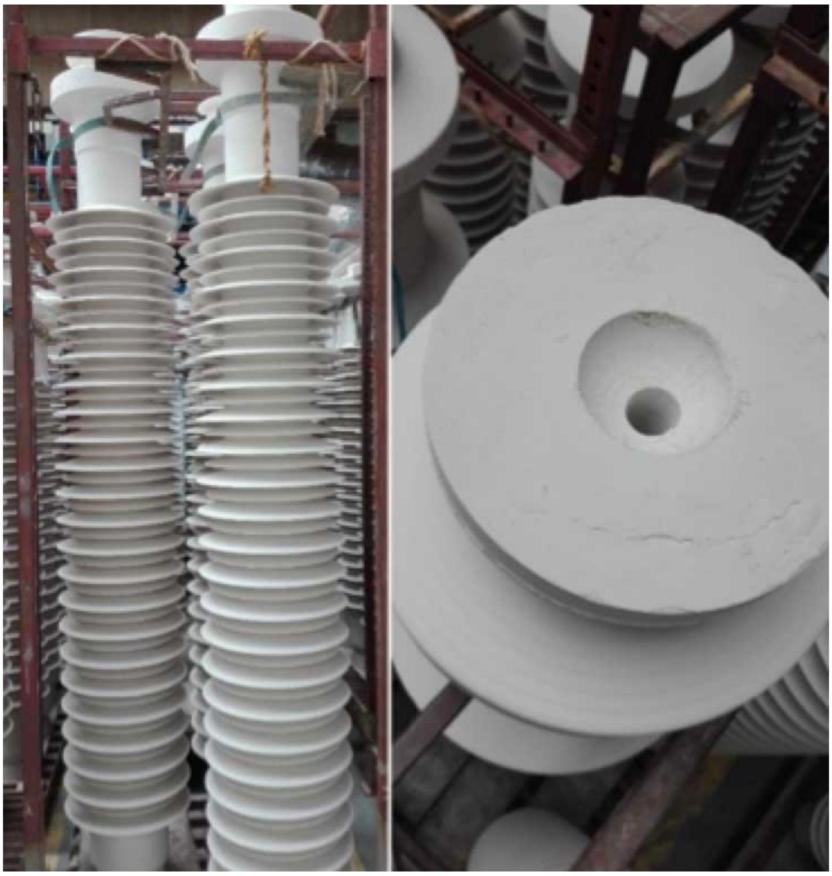


Figure 3.3 – Fibre optic hole support insulator insulator ready for glazing and firing [44]

Once the insulator has been fired, production continues following all the steps in conventional insulator manufacturing, i.e. cutting, grinding, assembly and testing. Figure 3.3 shows a fired C30-850 support insulator with a perfectly straight 20 mm wide hole on its central axis. The fittings must be pre-drilled and the hole and threads protected during the cementing process. Figure 3.10 shows completely assembled insulators.

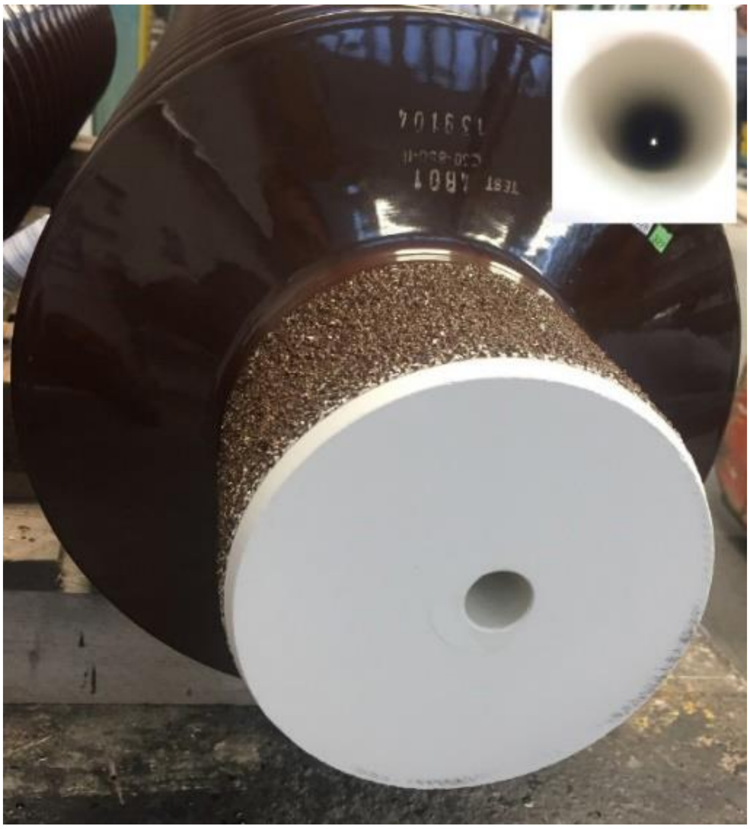


Figure 3.4– Support insulator with fiber optic hole after firing and cutting [44]

Figure 3.5 – Assembled C30-850 fiber optic support insulator ready for testing

Since the fiber optic hole is on the neutral axis, it does not affect mechanical strength of the insulator [44, 46]. Nonetheless, to verify this, samples of C30-850 support insulators have been manufactured with fiber optic holes for benchmarking bending tests performed at PPC's CAB plant in Slovakia. Figure 3.6 shows set-up of the bending test and Table 3.1 presents findings.

Figure 3.6 – Bending test [44]

Table 3.1 – Breaking Force of C30-850 Support Insulators [44]

Sample	C30-850 Standard Support insulator	C30-850 Fiber optic support insulator
1	41.03 kN	41.63 kN
2	40.48 kN	43.44 kN
3	38.90 kN	46.50 kN
4	40.59 kN	40.25 kN
5	40.48 kN	42.30 kN
6	40.70 kN	-
Average	40.36 kN	42.82 kN
Standard Deviation	0.680	2.108

These results confirm that the mechanical strength of a fiber optic post insulator is not affected by the hole in its neutral axis. In addition, this destructive test has allowed to observe whether or not the breaking mechanism was identical to that occurring with standard posts. All samples broke at the 2^{nd} or 3^{rd} shed from the bottom where cantilever forces are the greatest and breakage surface was identical to that of a standard post insulator. As such, it could be concluded that the hole does not affect strength, breakage mechanism or crack propagation of the porcelain.

3.2 Polymer insulators

Speaking about existing polymer insulators, the Forenergo Production Association in their article “Polymer insulators” [35] writes that, “the market of polymer insulators has existed since the last century, but active replacement of porcelain and glass insulation with polymer has been underway since 2005. Until 2006, the main barrier to the widespread introduction of polymer insulators was price. However, in 2006 the majority of manufacturers reached a technically new level of production and managed to put polymer insulators in the same price range with porcelain and glass. Thus, by 2011, the part of polymer insulators reached 14 % and continues to grow. This is primarily due to the improvement of the design of polymer insulators, a high level of electrical and mechanical strength (achieved by reinforcing them with fiberglass) and the use of more advanced materials”.

However, according to Kim Yong Dar [41], “I cannot say that the future belongs to polymer insulators, and I will not venture to say the opposite. It is easier to predict in which direction their production will develop in the Post-Soviet Union countries, especially since their direction coincides with the global one”.

Polymer (composite) insulators consist of a rod that determines the mechanical and electrical strength of the insulator. On this rod, metal terminators are being pressed, providing the connection of the insulator with wires and support elements of high-voltage lines using linear armature. Typically, the rod is made of resin reinforced by fiberglass. Besides, a special coating is applied to the rod, with an eye to protect the rod from the effects of various climatic factors and to create the required leakage path. This shell is made of epoxy compounds based on cycloaliphatic resins, from silicone rubber, from polyester resins with mineral filler and fluoroplastic additive. Outside, they are coated with a protective coating, for resisting an ultraviolet radiation and chemical influences, as well as waterproof varnishes for reducing hygroscopicity [32].

RHM International's proprietary dry-type Current Transformers are unique as they provide a rugged, reliable alternative for high-voltage insulation up to 252 kV. RHM bushings are of the category known as condenser, or capacitance-graded bushings, in which the desired voltage grading is obtained by an arrangement of conducting materials or semi-conducting layers incorporated in the insulating material [44].The manufacturer of RHM International company, insist, that: “An advancement of accepted principles, truly dry proprietary HV DryShield insulation uses proven materials like PTFE (polytetrafluoroethylene) and silicone rubber. HV DryShield high-voltage insulation provides unmatched uniform control of electric field distribution homogeneity between the conductor and the grounded outside structure in a genuine stress-free design that requires no insulating oil or gas, and needs no impregnated support up to 252 kV.

This provides a simple and robust construction that is completely stable, explosion-proof and that never needs maintenance” [44].

Customer benefits of HV DryShield:

- totally safe - no risk of explosion;
- totally maintenance free exceptionally low cost;
- environmentally friendly - no risk of toxic leak and insulation materials are recyclable;
- 2 to 3 times lighter than conventional oil- or gas-based products;
- mature yet innovative, with unmatched quality record - not a single failure in 20000 HV DryShield equipped products in the field;
- sealed and impervious to water and pollution.

The use of polymer insulators on power lines can significantly reduce the mass of insulators, and accordingly mass of the entire transformer. They allow to replace whole garlands of porcelain insulators, since they are much lighter [41].

Let's see A simple and rigorously controlled production process allowing design flexibility with consistent quality, Figure 3.7.

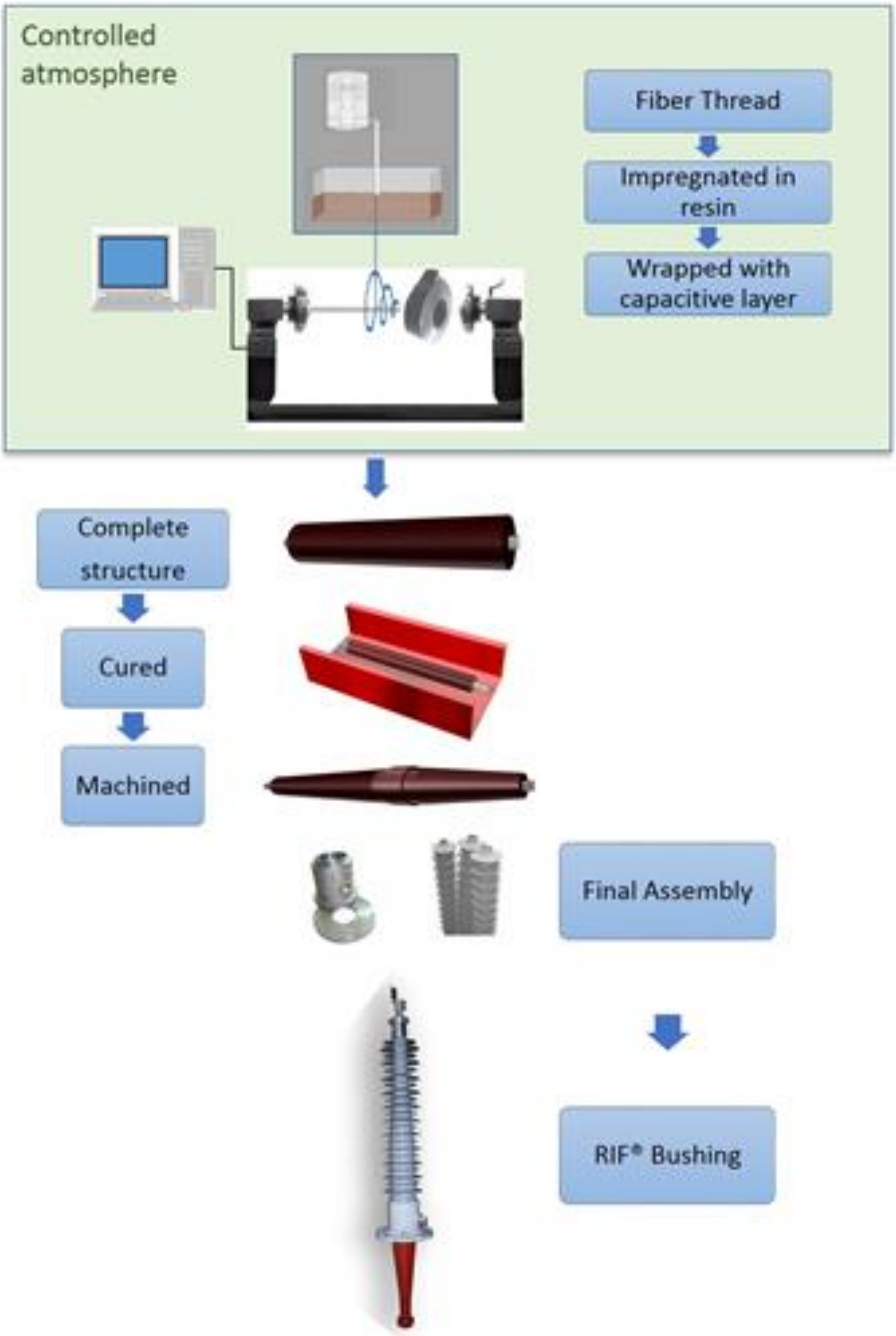
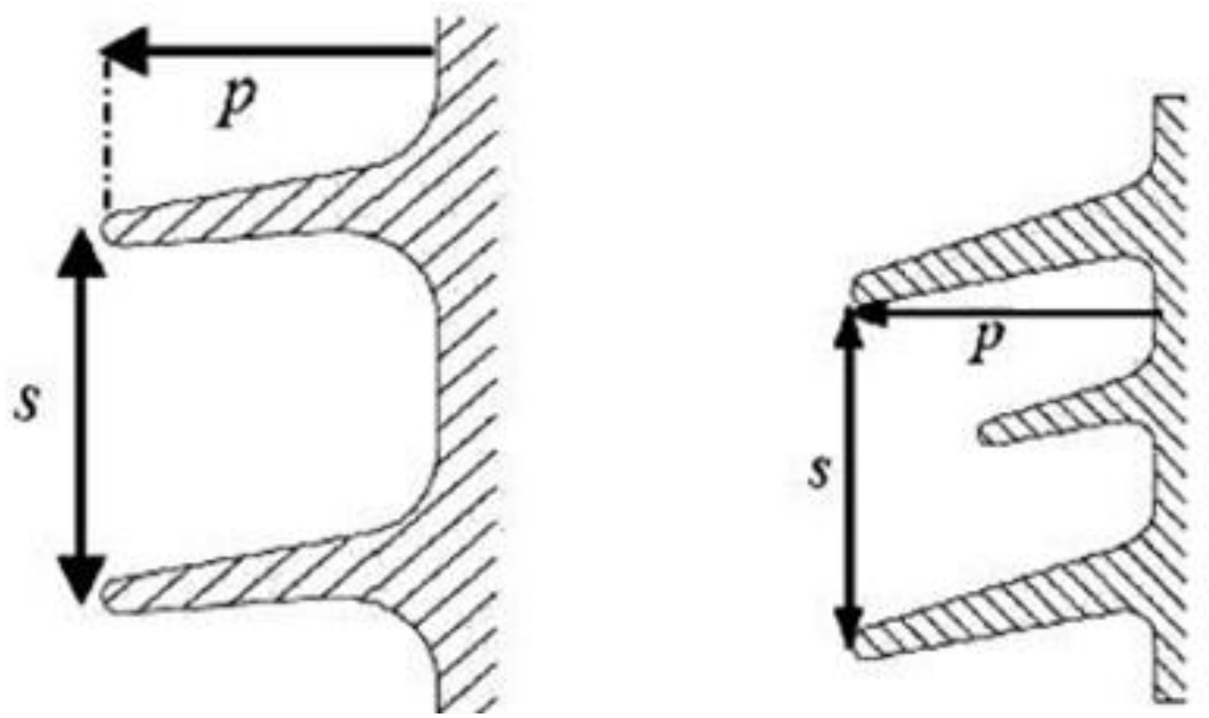


Figure 3.7 – Production process [44]

According to the “Instructions for selecting insulation of electrical installations” [22], “having given a ribbed shape to the polymeric insulator, we will reduce the leakage current (by 1-2 orders of magnitude lower than that of porcelain insulators) to the required level over the surface of the insulator at dirty and moisture conditions. The profile of the ribs is an important component of the polymer insulator because it's a type of self-cleaning insulator”.

According to ГОСТ 56735-2015, depending on the growth of pollution, insulators
with the same protrusion of ribs, as in Figure 3.8a, require the length increasing (construction height), in order to obtain an increased length of the current leakage path. This solution cannot be used constantly, it is not economical and requires the development of new electrical equipment, especially for increased environmental pollution. The solution of the given problem is the new design of insulators with variable protrusion of ribs, as in Figure 3.8b [21].



a – insulator with the same protrusion of ribs;

b – insulators with variable protrusion of ribs.

Figure 3.8 – Profile of ribs [21]

As Kustova reports in her article, “an insulator with a variable protrusion of ribs at the same construction height allows an increased length of the leakage path. In addition, due to the variable overhang of the ribs, the dirt resistance is increased. If you look at Figure 3.9, you can see the insulators of the outdoor installation with the same protrusion of the ribs, it is obvious that these insulators are not usable for areas with a cold climate, since all the ribs are covered with precipitation” [21].

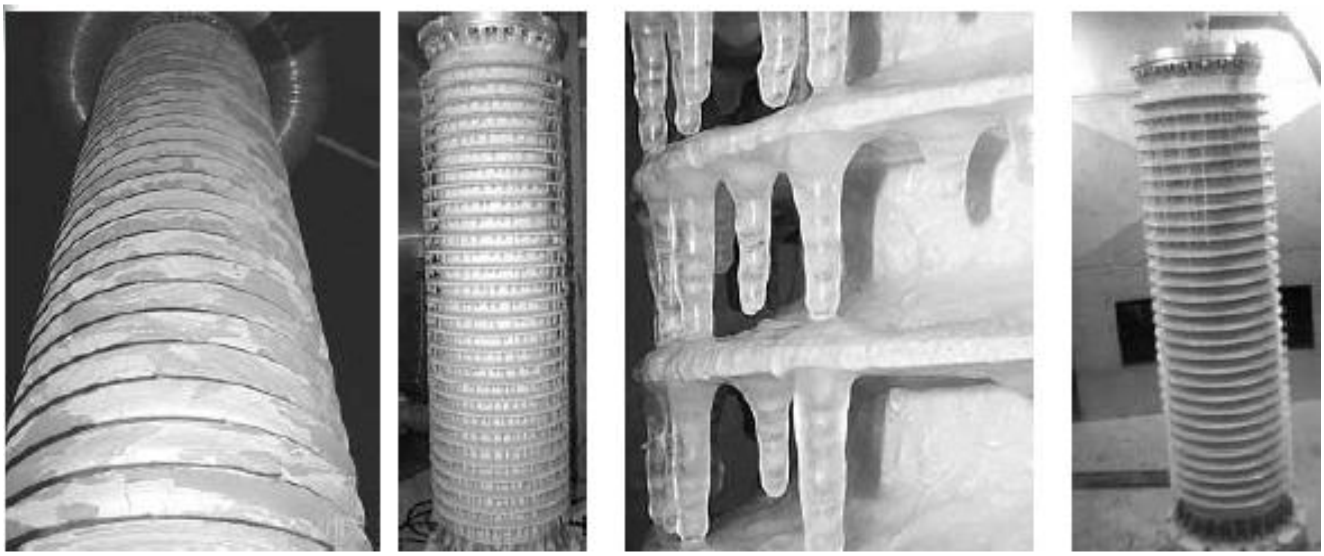


Figure 3.9 – External insulation with the same protrusion of ribs

There are 5 well-known types of polymer insulators, let’s consider them all [32].

Linear suspended polymer insulators, as shown in Figure 3.10, from 10 kV up to 750 kV are designed for insulation and fastening of wires of overhead power lines and in switchgears of power stations and AC substations.

The main structural elements of insulators:

- a fiberglass dielectric rod carrying a mechanical load;
- a polymer shell that protects the fiberglass from atmospheric impacts and forms the required length of the current leakage path. This shell is made of silicone rubber;
- metal terminators, fixed at the ends of the fiberglass rod, are designed to connect the insulator to the wires and support of the transmission line. Terminators are hot-dip galvanized;

– screen reinforcement, mounted on the terminators, provides equalization of the electric field strength and acts as an arcing element.

The service life of insulators is at least 25 years.

Figure 3.10 – Linear suspended polymer insulator

Polymeric support insulators, as presented in Figure 3.11, are designed for the assembly of various electrical equipment (high-voltage switches, switchboards, etc.), instead of porcelain insulators. The wares are manufactured in the climatic modification of УХЛ (NF), placement category 2 (closed premises), 3 and 4. It is allowed to use in areas with tropical and cold climates.

Figure 3.11 – Polymer support insulator

Polymer stick-pedestal insulators, as shown in Figure 3.12, of the outdoor installation are designed for insulation and fastening of live parts in electrical apparatus and switchgears of power electrical stations and AC substations, voltage up to 220 kV, frequency up to 100 Hz.

The main supporting element of the insulators is a fiberglass pipe or rod, protected from external atmospheric influences by an organosilicon finned coating. The inner surface of the pipe or rod is protected from breakdown by rubberizing. The internal cavity is sealed. The pipe is closed by flanges on both sides. Flanges are hot-dip galvanized.

Such insulators are designed for operation in areas with I-IV degree of pollution, according to regulations.

Figure 3.12 – Polymer stick-pedestal insulator

All types of polymer insulators used on high-voltage overhead lines have their own advantages [31, 34, 35, 47]:

– the greatest mechanical strength, which makes their use, especially at ultra-high voltages used in the electric power industry, very perspective;

– high resistance to atmospheric pollution;

– hydrophobicity;

– high resistance to overvoltage;

– high vandal resistance;

– low weight (more than 90 %), compared to glass and porcelain insulators, which allows installation without the use of crane;

– higher dielectric strength compared to similar porcelain and glass insulators with equal leakage path;

– flexibility, which allows to install optical transformers in vertical, horizontal and inclined positions, and this does not affect the accuracy of measurements;

– compactness, which allows the use of such insulators in conditions unacceptable for porcelain and glass insulators;

– reliability and convenience of transportation;

– insensitivity to external electromagnetic fields does not require analysis of the relative position of the tires.

Exept benefits all types of polymer insulators used on high-voltage overhead lines have some disadvantages [31, 34, 35]:

– there is no generally accepted unified production system, as the manufacturing technology is not sufficiently standardized yet;

– lack of material that would sufficiently satisfy the requirements for polymer insulators;

– lack of experience in the long-term operation of this type of insulators;

– the possibility of micro cracks occurrence during operation under the influence of internal stress in plastic rods at the terminators;

– the more complicated diagnostic procedure than in the glass insulators, that is, the condition of the rod during operation can only be determined by special devices, and this is a rather expensive procedure;

– during aging and exposure of high temperatures, mechanical and electrical strength decreases;

– aging due to ultraviolet radiation and solar radiation;

– high risk of breakdowns during depressurization.

Lev Vladimirskiy, speaking of the choice and use of insulators, writes that: "As you can see, the variety of types of linear insulators allows you to choose the most effective solutions for their use, depending on the voltage class of high-voltage lines, the requirements for their reliability and the conditions under which the insulators will be operated. The cost of insulators is a small fraction of the total cost of the overhead line (about 10 %). However, the reliability of the high-voltage lines, and, accordingly, the uninterrupted supply of electricity to consumers, largely depends on the quality of the used insulators and on the correctness of their choice (type and quantity). If insufficiently high-quality insulators are used (for example, due to economic considerations), concerns to maintain the required reliability of the overhead lines are transferred to operating organizations.

When choosing insulators for overhead lines, it is better to focus on the most reliable types of insulators that correspond to the “hung and forget” principle, that is, they require a minimum number of preventive measures and diagnostics [41] ".

After carrying out the most basic tests of external insulation, according to ГОСТ 1516.1-76 [51], all the results were entered in table 3.2.

Table 3.2 – Rated insulation level and partial discharge

Highest Equipment Voltage, kV	Rated Power Frequency Withstand Voltage, kV	Lightning Impulse Withstand Voltage, kV	Partial Discharge Measurement Voltage, kV	Partial Discharge level pC
40.5	95	185	28	5
72.5	140	325	50	5
126	230	550	87	5
252	460	1050	175	5

4 MAIN COMPONENTS CALCULATION OF FIBER OPTIC CURRENT TRANSFORMER

Aleksandrov G. N. in his work eapress opinion, that “each electrical apparatus operating in various power electrical installations has a current-carrying system (CCS). CCS is a part of an electrical apparatus, which is a combination of current-carrying elements, contacts, contact connections, and terminals forming one circuit or several parallel circuits.

The functional purpose of CCS is to conduct the operating current and short circuit current in the electrical circuit into which the apparatus is included, as well as its switching. In addition to the main function of CCS, system elements must perform additional functions that differ depending on the type of apparatus and its operating conditions” [5].

Afanasiev and Adon’yev, note in their work, that “current-carrying elements (CCE) are the main source of heat in electrical apparatus (EA). They emit heat during electric current flows, primarily as a result of the so-called Joul’s losses.

It should be noted that thermal phenomena in EA play a very important role. Moreover, it can be positive or negative.

Their positive role is, first of all, in the use of thermal phenomena for the functioning of electrical devices. And their negative role is, that EA, as a rule, are conductors of electrical energy, part of which is converted into thermal energy and goes to heat its elements” [6].

In adition Aleksandrov [5] writes, that “heat generation in elements of CCS leads to their heating and to heating of the adjacent parts of the apparatus, including insulating ones. In this regard, the problem of estimating the heating temperature of the apparatus and its limitation to an acceptable level arises. Thus, thermal design of current-carrying (and other heat-generating elements) elements is an important practical task to be solved in the process of designing electrical and electronic devices. To date, there are no exact methods of thermal calculation, therefore, in the design process, numerous and comprehensive tests are carried out, i.e. experimental verification of the calculations.

In general case, the task of thermal behavior analysis of any element of electrical apparatus is to determine the power of heat sources and calculate its temperature field. The thermal design is carried out, as a rule, in two consistent stages by numerical method [4, 9, 12, 13, 14, 25]:

– short-cut calculation, i.e. qualitative analysis of thermal conditions;
– precised thermal design, i.e. refined analysis of thermal conditions.

4.1 Short-cut calculation of the busduct

At this stage of calculation part, it is necessary, based upon predetermined current load and given cooling conditions, to determine geometrical parameters of apparatus' CCE, leaning predetermined structure of the busduct, its geometrical parameters, cooling conditions, current load and operating duty and required cross-sectional area of the current-carrier [9, 25].

On the basis of load current, the tubular conductor with outer diameter 85 mm and inner diameter 75 mm and cross-sectional area 1260 mm^2, according to the ПУЭ, is chosen.

During the calculation the following assumptions are accepted:

– the busduct has the infinite length;
– the specific heat of the conductor material, the coefficient of additional losses, the total heat transfer coefficient (and overall thermal resistance) are independent of temperature;
– in the plane of the cross section of the conductor, the temperature is constant, since the material has a sufficiently high thermal conductivity.

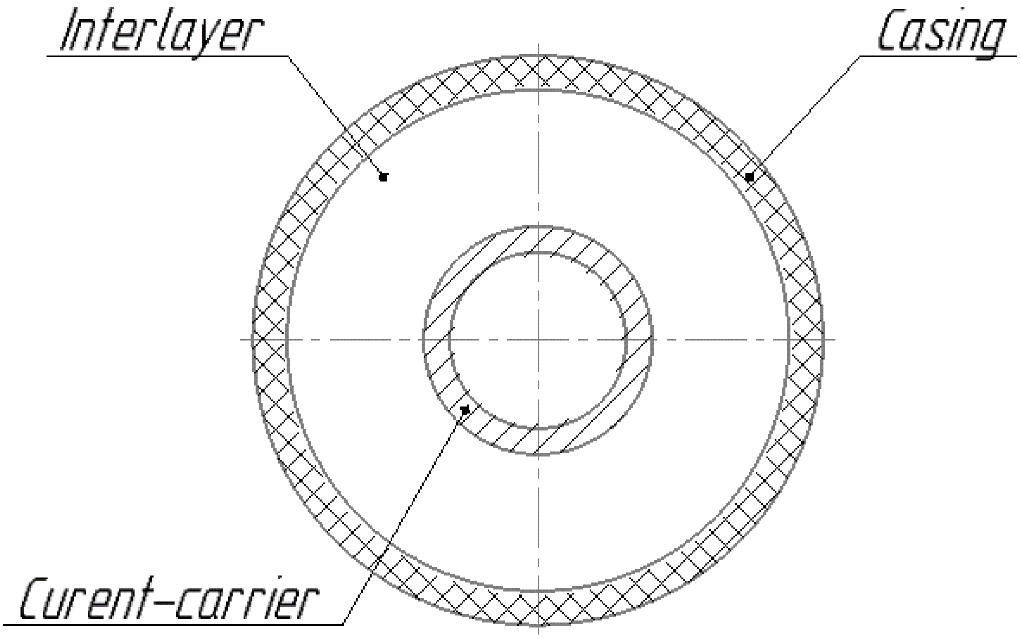


Figure 4.1 - Cross-section of the busduct [25]

Since the busduct is homogeneous, so for a unit of its length for a time interval dt it will have the following form:

$$dQ_1 = dQ_2 + dQ_3, \tag{4.1}$$

where dQ_1 is the amount of heat released per unit length of the conductor during the time interval dt, J;

dQ_2 is the amount of heat spent on heating the conductor;

dQ_3 is the amount of heat removed during dt from the side surface of the conductor.

These components are determined by the following expressions:

$$dQ_1 = \frac{{I_{rated}}^2 \rho_0 (1+\alpha\vartheta_{amb}) K_a}{q} dt, \tag{4.2}$$

where I_{rated} is the rated value of the current, A;

K_a is the additional losses coefficient;

ϑ_{cond} is the temperature of the conductor, °C;

α is the temperature coefficient of resistance, m^2/s;

ρ_0 is the specific electrical resistivity at 0 ° C.

$$dQ_2 = c\gamma q d\vartheta_{cond}, \quad (4.3)$$

where c is the specific heat capacity, kDj/(kg*K);

γ is the density of the material, kg/m^3.

$$dQ_3 = \frac{\vartheta_{cond} - \vartheta_{amb}}{r_{T\Sigma}}, \quad (4.4)$$

where ϑ_{amb} is the ambient temperature, °C;

$r_{T\Sigma}$ is the total thermal resistance between the surface of the conductor and environment per unit length, K/W.

Thus, the heat balance equation will have the following form :

$$c\gamma q \frac{d\vartheta_{cond}}{dt} + \left(\frac{1}{r_{T\Sigma}} - \frac{{I_{rated}}^2 \rho_0 K_a \alpha}{q}\right) \vartheta_{cond} = \frac{I^2 \rho_0 K_a}{q} + \frac{\vartheta_{amb}}{R_{Th.\Sigma}}, \quad (4.5)$$

From the heat balance equation (formula 4.5), the selected conductor cross-sectional area q was confirmed with calculation by the next way

$$q = \frac{{I_{rated}}^2 \cdot \rho_0 \cdot (1 + \alpha \cdot \vartheta_{cond}) \cdot R_{th.\Sigma}}{\vartheta_{cond} - \vartheta_{amb}}, \quad (4.6)$$

Firstly, it is necessary to find the total thermal resistance. Each component of these thermal resistances are consist of convectional and radiation components.

$$R_{th.\Sigma} = R_{th.air} + R_{th.amb}, \quad (4.7)$$

where $R_{th.air}$ is the thermal resistance of air, K/W;

$R_{th.amb}$ is the ambient resistance, K/W.

$$R_{th.air} = \frac{R_{th.air.conv} \cdot R_{th.air.rad}}{R_{th.air.conv} + R_{th.air.rad}}, \quad (4.8)$$

where $R_{th.air.conv}$ is the convective component of air thermal resistance, K/W;

$R_{th.air.rad}$ is the radiation component of air thermal resistance, K/W.

$$R_{th.amb} = \frac{R_{th.amb.conv} \cdot R_{th.amb.rad}}{R_{th.amb.conv} + R_{th.amb.rad}}, \quad (4.9)$$

where $R_{th.amb.conv}$ is the convective component of ambient thermal resistance, K/W;

$R_{th.amb.rad}$ is the radiation component of ambient thermal resistance, K/W.

To find the convectional component of the air for (4.8), it is necessary to applied the formula for convective heat transfer in limited space:

$$R_{th.air.conv} = \frac{1}{2\pi * \lambda_{eq}} \ln \frac{D}{d}, \quad (4.10)$$

where D, d are the external diameters of the case and conductor respectively, m;

λ_{eq} is the equivalent heat conductivity, W/(m2K).

$$\lambda_{eq} = \lambda_{air} \cdot \varepsilon_K, \quad (4.11)$$

where λ_{air} is the air heat transfer factor;

ε_K is the convection factor, defined from the dimensionless equation.

$$\varepsilon_K = \mathrm{A}[\mathrm{GrPr}]^{0.3}, \tag{4.12}$$

where A is the coefficient, chosen according to the configuration;

Pr is the Prandtl number (criteria, characterizing the properties of medium. It is defined by the ‘determining temperature’);

Gr is the Grashof number (criteria of pulling up force;).

$$\mathrm{Gr} = \frac{\beta_{air} \cdot \mathrm{g} \cdot L^3 \cdot (\vartheta_{cond} - \vartheta_{case})}{\nu^2}, \tag{4.13}$$

where β_{air} is the air volumetric thermal expansion coefficient, 1/ºC;

υ is the air kinematic viscosity factor, kg/(m·s);

ϑ_{case} is the temperature of the case, ºC;

L_{cond} is the characteristic dimension, in this case is defined by the diameter of conductor, m.

To find the radiative component of the air for (4.8), the next formula is used:

$$\mathrm{R}_{\mathrm{th.air.rad}} = \frac{\vartheta_{cond} - \vartheta_{case}}{\mathrm{P}_{\mathrm{rad}}}, \tag{4.14}$$

where $\mathrm{P}_{\mathrm{rad}}$ is the amount of radiated heat transferred from the conductor to the case, W.

$$\mathrm{P}_{\mathrm{rad}} = 5.67 \cdot \frac{[\left(\frac{\mathrm{T}_1}{100}\right)^4 - \left(\frac{\mathrm{T}_2}{100}\right)^4]}{\left(\frac{1}{\varepsilon_1}\right) + \left(\frac{\mathrm{F}_1}{\mathrm{F}_2}\right) \cdot \left(\frac{1}{\varepsilon_2 - 1}\right)}, \tag{4.15}$$

where T1, T2 are the absolute temperature of conductor and case, K;

ε1, ε2 are the degree of blackness of conductor and case, accordingly;

F1, F2 are the surface coefficient of conductor and case, accordingly, length of round in this case, m.

The next step is to find the convectional and radiative component of the ambient thermal resistance (4.9). Convective ambient thermal resistance is calculated by the nature convective in unlimited space.

$$\mathrm{R}_{\mathrm{th.amb.conv}} = \frac{1}{\mathrm{K}_{\mathrm{tk}} \cdot \pi \cdot \mathrm{L}_{\mathrm{case}}}, \quad (4.16)$$

where L_{case} is the characteristic dimension, in this case is defined by the diameter of case, m;

K_{tk} is the convective heat transfer coefficient for this case, found from the dimensionless equation.

$$\mathrm{K}_{\mathrm{tk}} = \lambda_{air} \cdot \frac{\mathrm{Nu}}{\mathrm{L}_{\mathrm{case}}}, \quad (4.17)$$

where Nu is the Nusselt number or criteria of heat similarity.

$$\mathrm{Nu} = \mathrm{C}(\mathrm{Gr}_1 \cdot \mathrm{Pr}_1)^{n}, \quad (4.18)$$

where C, n are the factors of the dimensionless equation, defined by the result of the multiplying of Gr by Pr.

$$\mathrm{Gr}_1 = \frac{\beta_{air} \cdot \mathrm{g} \cdot {\mathrm{L}_{\mathrm{case}}}^3 \cdot (\vartheta_{case} - \vartheta_{amb})}{{\nu_1}^2}, \quad (4.19)$$

where υ_1 is the air kinematic viscosity factor under the determining temperature, kg/(m·s).

The radiation thermal resistance component for (4.9) is determined in the next way:

$$R_{th.amb.rad} = \frac{\vartheta_{case} - \vartheta_{amb}}{P_{rad.1}}, \tag{4.20}$$

where $P_{rad.1}$ is the amount of radiated heat transferred from the case to the medium, W.

$$P_{rad.1} = 5.67 \cdot [\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_0}{100}\right)^4] \cdot \varepsilon_2, \tag{4.21}$$

where T_0 is the absolute temperature of the medium layer, K.

4.2 Precised thermal design

This part of calculations is necessary for finding the temperature of the busduct, with known current load, geometrical dimensions and known ways of cooling.

The first step at this part is to calculate the value of total heat losses in the conductor.

$$P = \frac{I_{rated}^2 \cdot \rho_0 \cdot (1 + \alpha \cdot \vartheta_{cond})}{q \cdot 10^{-6}}, \tag{4.22}$$

where q is the cross-section area of the conductor, m^2.

The temperature of the case is the simplest iteration method, carried out by the next way:

$$\vartheta_{case1} = \vartheta_{amb} + P \cdot r_{th.case.amb}, \tag{4.23}$$

where $r_{th.case.amb}$ is the result thermal resistance between the case and medium.

$$r_{th.case.amb} = \frac{1}{\alpha_T \pi \cdot L_{case}}, \tag{4.24}$$

where α_T is the resulted factor of heat transfer from the surface of conductor.

$$\alpha_T = \alpha_{conv} + \alpha_{rad}, \tag{4.25}$$

where α_{conv}, α_{rad} are the thermal diffusivity factor for convective and radiation processes.

$$\alpha_{conv} = \frac{\lambda_{air} \cdot \mathrm{Nu_{conv}}}{\mathrm{L_{case}}}, \tag{4.26}$$

$$\mathrm{Nu_{conv}} = \mathrm{C}(\mathrm{Gr_{coef}} \mathrm{Pr_{coef}})^n, \tag{4.27}$$

$$\mathrm{Gr_{coef}} = \frac{\beta_{air} \cdot \mathrm{g} \cdot \mathrm{L_{case}}^3 \cdot (\vartheta_{case} - \vartheta_{amb})}{\nu_1^2}, \tag{4.28}$$

$$\alpha_{rad} = 5.67 \cdot \frac{\left[\left(\frac{\mathrm{T_1}}{100}\right)^4 - \left(\frac{\mathrm{T_2}}{100}\right)^4\right] \cdot \varepsilon_2}{\mathrm{T_2} - \mathrm{T_0}}, \tag{4.29}$$

The results of the iteration process are applied in appendix A.

The next step is to determine the temperature of the conductor using the numerical method.

$$\vartheta_{cond1} = \vartheta_{case} + P \cdot \mathrm{r_{th.case.cond}}, \tag{4.30}$$

where $\mathrm{r_{th.case.cond}}$ is the resulted thermal resistance between the case and conductor

$$\mathrm{r_{th.case.cond}} = \frac{\mathrm{r_{conv}} \cdot \mathrm{r_{rad}}}{\mathrm{r_{conv}} + \mathrm{r_{rad}}}, \tag{4.31}$$

$$\mathrm{r_{conv}} = \frac{1}{2\pi \cdot \lambda_{eq}} \cdot \ln \frac{\mathrm{D}}{\mathrm{d}}, \tag{4.32}$$

$$\lambda_{eq} = \lambda_{air} \cdot \varepsilon_K, \tag{4.33}$$

$$\varepsilon_K = \mathrm{A}[\mathrm{Gr_{coef}Pr_{coef}}]^{0.3}, \tag{4.34}$$

$$\mathrm{Gr_{coef}} = \frac{\beta_{air} \cdot \mathrm{g} \cdot \mathrm{L_{cond}}^3 \cdot (\vartheta_{cond} - \vartheta_{case})}{\nu^2}, \tag{4.35}$$

$$\mathrm{r_{rad}} = \frac{\vartheta_{cond} - \vartheta_{case}}{P_{rad}}, \tag{4.36}$$

$$\mathrm{P_{rad}} = 5.67 \cdot \frac{\left[\left(\frac{\mathrm{T_1}}{100}\right)^4 - \left(\frac{\mathrm{T_2}}{100}\right)^4\right]}{\left(\frac{1}{\varepsilon_1}\right) + \left(\frac{\mathrm{F_1}}{\mathrm{F_2}}\right) \cdot \left(\frac{1}{\varepsilon_2 - 1}\right)}, \tag{4.37}$$

The results of the iteration process are applied in the appendix A.

4.3 Conductor’s temperature under the short-circuit mode

Using the adiabatic heating curves of the conducting materials [10] it is possible to determine the temperature under the short-circuit mode.

$$A(\vartheta_{sc}) = A(\vartheta_n) + j_{sc}{}^2 \cdot t_{sc}, \tag{4.38}$$

4.4 Electrical strength

As it mentioned by Procenko and Il’enko [49] “The purpose of the calculation of high-voltage fiber-optic current transformers is to ensure their reliable operation under various electrical influences that may occur during operation. It is necessary to exclude the possibility of:

– the occurrence of partial discharges that lead to breakdown of insulation
– development of thermal breakdown.

The design and dimensions of the insulator must be chosen so as to exclude the possibility of breakdown, as a result of the long existence of ionization processes that occur under the influence of an electric field on the surface or inside the insulation”.

There are the following ionization characteristics of insulation [49]:

– initial ionization voltage U_{rat}, i.e. the lowest voltage of occurrence of ionization processes of low intensity or corona, which do not lead to noticeable destruction of insulation or short-term influence of overvoltages, reduction of ionization voltage in case of short-term influence of overvoltages;
– critical ionization voltage U_{cr}, i.e. the lowest voltage of occurrence of ionization processes of significant intensity or sliding discharges capable of causing rapid appreciable destruction of insulation, is accompanied by a decrease in ionization voltage;
– minimum ionization voltage U_{min}, i.e. the smallest value to which the ionization voltage can decrease under the influence of critical ionization or other factors.

Taking into account the ionization characteristics can consist in choosing the operating electric field strength lower than the minimum voltage at which ionization will still take place. In this case, the impact on the insulation of overvoltages can cause partial discharges of varying intensity, but with a further decrease in voltage to the operating level, these discharges will stop and the insulation will remain suitable for further operation. However, this choice of field operating stresses causes an increase in the insulation size.

The phenomenon of unstable ionization for 110 kV class transformers operating in networks with grounded neutral should not occur in the case of the highest phase voltage:

$$U_{ph}=\frac{U_{rated}}{\sqrt{3}}, \qquad (4.39)$$

where U_{rated} is the rated voltage,

$$U_{ph}=63.51\ \text{kV}.$$

4.5 Electrodynamic calculation

According to the Ampere's Law

$$F = I_{sc} \cdot l \cdot B_b \cdot sin\, \gamma, \qquad (4.40)$$

where F is the electrodynamic forces acting on the conductors, N;

I_{sc} is the short circuit current, A;

l is the length of the conductor, m;

B is the magnetic induction, T;

sin γ is the angle between the current flow and induction vector.

$$B_b = \mu_0 \cdot H, \qquad (4.41)$$

where H is the magnetic field strength, A/m;

μ_0 is the magnetic permeability, H/m.

$$H = \frac{I_{sc}}{2\pi \cdot l}, \qquad (4.42)$$

Electrodynamic calculation results are represented in appendix A.

According to this method, the short-circuit temperature of the conductor will be 135 ^{o}C. The temperature of the conductor of the busduct to the end of the short circuit does not exceed 250 ^{o}C, and the time of reaching this temperature more than 4 seconds. Electrodynamic forces of the conductors under the short-circuit mode will be 320 N.

On the results of the calculation it can be concluded, that the busduct fully meets the requirements of the ГОСТ 617-90.

4.6 Insulation of FOCT

The main task of this part of calculation is to define the construction design of the insulator. The whole calculation of insulation is carried out by the well-known method described by V. V. Afanasiev [6].

4.6.1 Determination of the test voltages

Based on the rated voltage the next basic parameters were accepted according to the ГОСТ 1516.3.

Rated voltage of FOCT

$$U_{rated} = 110\ \text{kV}.$$

Short-time test voltage of industrial frequency 50 Hz of external insulation under dry condition

$$U_{short.time.dry} = 280\ \text{kV}.$$

Short-time test voltage of industrial frequency 50 Hz of external insulation under the rain

$$U_{short.time.rain} = 215\ \text{kV}.$$

Voltage of groom impulse (full impulse)

$$U_{gr.imp} = 460\ \text{kV}.$$

The length of leakage path is chosen from the table 3.10 “Leakage path length of external insulation” [6], for the insulation category A, $l_{leakage.path}$=190 cm, for the insulation category Б, $l_{leakage.path}$=280 cm, for the insulation category В, $l_{leakage.path}$=390 cm.

Calculational breakdown voltage U_{calc} is related to the insulators, that are tested separately. It must more, than test voltage U_{test} shown in the table 3.4 “Rational test voltages of current transformers with normal insulation” [6], in 1.6 times.

Calculational breakdown voltage under rain, kV

$$U_{calc.rain} = U_{short.time.rain} \cdot 1.1, \tag{4.43}$$

Calculational breakdown voltage under normal weather conditions, kV

$$U_{calc.dry} = U_{short.time.dry} \cdot 1.1, \tag{4.44}$$

Full lightning impulse breakdown voltage, kV

$$U_{calc} = U_{gr.imp} \cdot 1.1, \tag{4.45}$$

4.6.2 Calculation of the insulator

Calculation of the polymer insulation is performed for the purpose to determine its active height, amount and dimensions of ribs and the thickness insulator’s wall.

For the outdoor insulators, and for the insulation cathegory Б, (according to ГОСТ 9920-75) and leakage path the active height of this type of insulator is determined by the testing voltage of external insulation under the rain according to the next formula

$$U_{test.rain} = k_{save} \cdot k_v \cdot U_{calc.rain}, \tag{4.46}$$

where k_{save} is the safety factor;

k_v is the installation height factor, which is defined by the next way.

$$k_v = \frac{1}{1.1 - 10^{-4} \cdot H_{inst}}, \quad (4.47)$$

where H_{inst} is the installation height.

The active height of the outdoor insulator is determined by the method of Afanasiev V.V. [6], its value is calculated for each case and the largest of the obtained values is selected for the further calculations.

For the rated frequency voltage:

$$h_{act.fr} = 338.2 - \sqrt{111663 + 143 \cdot U_{calc}}, \quad (4.48)$$

$$U_{calc.fr} = 788.2 - 0.007 \cdot (338.2 \cdot h_{act.fr})^2, \quad (4.49)$$

Discharge voltage of industrial frequency, 50 Hz, under the rain:

$$U_{d.rain} = 2.25 \cdot h_{act.fr} + 22, \quad (4.50)$$

$$h_{d.rain} = 0.444 \cdot U_{d.rain}, \quad (4.51)$$

4.6.3 Configuration of the insulator

The profile of the ribs is an important component of the polymer insulator because it's a type of self-cleaning insulator. Depending on the growth of pollution, insulators can be with the same and with the variable protrusion of ribs. The amount of ribs providing the necessary leakage path.

$$n_r = \frac{l_{leakage.path} - h_{act}}{l_{ut} - l_2}, \quad (4.52)$$

where $l_{leakage.path}$ is the leakage path according to the ГОСТ 1516.3, cm;

l_{ut} is the leakage path length of one rib, mm;

l_2 is the height of the rib, mm;

h_{act} is the active height of insulator, cm.

The distance between the ribs:

$$l_r = \frac{l_2 \cdot (h_{act} - l_2 \cdot n_r - 2.5)}{(n_r - 1)}, \tag{4.53}$$

To confirm the calculation, the Fedorov L. I. empirical formula is used to determine the withstand voltage under the rain

$$U_d = 3.78 \cdot h_{act}^{0.77} + \frac{2.82 \cdot n_r \cdot l_r \cdot \alpha_p}{h_r}, \tag{4.54}$$

where h_r is the rib out length, mm;

α_p is the shortest distance between the ribs, cm.

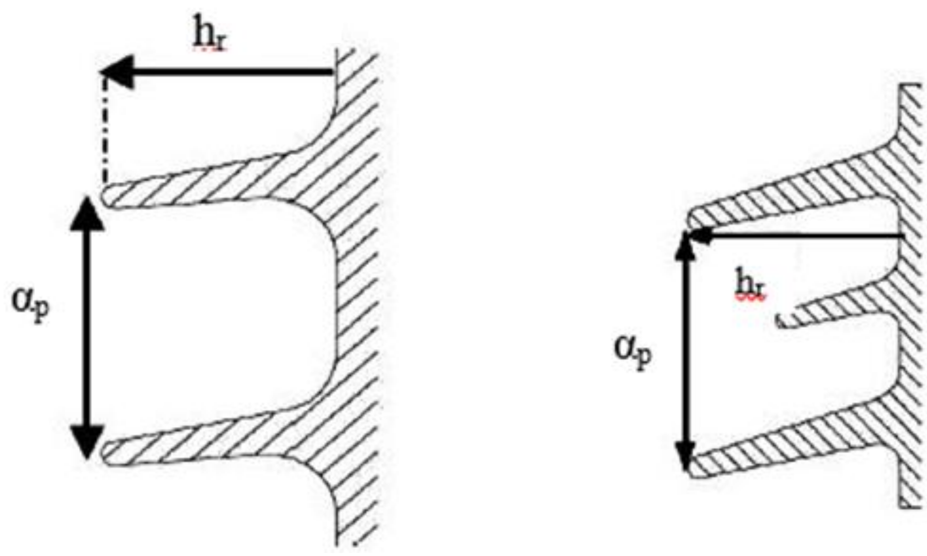


Figure 4.2 – Configuration of the insulator ribs [21]

The angle of the ribs should be in range of 5 – 25 degrees.

In order, to increase the efficiency of the insulator the length of the rib out should be performed with variable protrusion.

4.7 Bending moment from wind load

As mentioned earlier, FOCT can be both support and suspended, but in both positions it is subject to wind loads, which must be taken into account when the strength of the external insulation [50].

The force from the wind load is determined by the formula:

$$P_w = \alpha \cdot k \cdot F \cdot v^2 \cdot \cos\varphi / 1.6, \quad (4.55)$$

where α is the coefficient taking into account the non-uniformity of wind speed, α=1;

k is the aerodynamic coefficient, k=0.7;

F is the estimated area, m^2;

v is the wind speed, v=40 m/s;

φ is the angle of inclination of the input in the vertical, $\varphi = 45°$.

All calculation results are represented in the appendix B. According to that method, for the insulation category «Б» the withstand voltage value under the rain is 257.5 kV, active height is 170 cm and there are installed 17 ribs under the angle of 16 degrees on the insulator surface and the force from the wind is 3.13 N.

It should be noted that the material of the insulators, regardless of environmental pollution conditions, does not change, but the number of ribs increases and the distance between them decreases, so as to increase the leakage path [51].

5 OCCUPATIONAL SAFETY AND SAFETY IN EMERGENCY SITUATIONS

Since the topic of the diploma project is “Investigation of the external insulation of fiber-optic current transformers”, therefore, let’s consider measures to ensure safety, industrial sanitation, occupational health and fire safety when operating a fiber-optic current transformer in a testing station.

Based on the analysis of the operation of the existing equipment and technological processes of the testing station, according to GOST 12.0.003-74 (1999) “Occupational safety standards system. Dangerous and harmful production effects. Classification" [54], the following hazardous and harmful production factors were identified, that can lead to injury, to health issues of workers and damage the environment:

- physical;
- chemical;
- biological;
- psychophysiological.

Let's consider each of the listed factors in more detail using several examples.

Physical hazardous and harmful production factors are divided into:

- destruction of the measuring unit of the FOCT (electromagnetic bus), due to violation of the rules of installation work, which can lead to personal injury or death;
- electric shock, due to violations of electrical safety rules, malfunction of electrical equipment, which can lead to electrical injuries or death;
- failure to wear special clothing, due to violations of the protection rules of the straight line, can lead to cuts with sharp edges of parts, and injury to the lower extremities when the tool or parts fall.

Chemical hazards and harmful production factors are divided into chemical substances and industrial dust. The degree and nature of the disturbances in human body caused by them depends on the route of entry into the human body, dose, exposure time, concentration of the substance and its solubility, the state of the receiving tissue and the body as a whole, atmospheric pressure, temperature and other characteristics of the environment.

- Industrial dust due to inefficient ventilation and lack of regular ventilation can lead to respiratory diseases and mucosal irritation.
- Biological hazards and harmful production factors include the following biological objects:
- unsatisfactory parameters of the air environment in the production premises, which is due to inefficient operation or lack of heating systems, air exchange and can lead to general diseases.

Psychophysiological hazardous and harmful production factors by the nature of the action are divided into the following:

- unsatisfactory organization of work, associated with the acceleration, increase plans, can lead to excessive physical and nervous overload of workers;

5.1 Labor protection measures

5.1.1 Safety measures

The considered and projected current transformer is a fiber-optic current transformer (FOCT), which is a new class of electric current meters that has appeared on the market relatively recently. FOCT was designed and will be operated in accordance with GOST R IEC 60044-8-2010 "Instrument transformers. Part 8. Electronic current transformers" [55]. FOCT is equally applicable to both AC and DC current measurements. The noted features are extremely important at facilities whose operation requires monitoring and control of technological processes with the flow of significant quasi-constant electric currents. This situation takes place, in particular, at non-ferrous metallurgy enterprises. FOCT can also be used in information and measurement systems for technical and commercial accounting and quality control of electrical energy. The design features allow the transformer to be installed in places where the installation of traditional copper transformers is extremely difficult or simply impossible. At the moment, five fiber-optic current converters of CJSC "Profotech" have been used for a year at the Krasnoyarsk aluminum smelter to perform similar functions.

According to Arrangement of Electrical Installations (PUE), "Rules for safe operation of electrical installations" and "Rules for safe operation of electrical installations of consumers" [56] FOCT can be operated in premises with high humidity level and dust, at low and high temperatures, since the external insulation of the transformer is resistant to different conditions, thus the research result remains accurate.

The testing station where FOCT operates, according to p.1.1.13 Arrangement of Electrical Installations (PUE) [56] is characterized as premises of an increased risk, i.e. there is a large number of metal constructions that is under voltage. Maintenance staff has the IV qualification group of the electrical safety, according to NPAOP 40.1-1.01-97 «Rules of safe operation of electrical installations» [78]. Work is carried out under the decree, order, and in the manner of the current operation. Organization of work corresponds to p.6.1 NPAOP 40.1-1.01-97 «Rules of safe operation of electrical installations» [78].

Electrical equipment, sensitive optical fiber, current-carrying bus, insulators, measuring element are selected and installed in accordance to p.4.2.17 Arrangement of Electrical Installations (PUE) [56].

According to p.1.7.51 Arrangement of Electrical Installations (PUE) [56], FOCT provides a protective ground. Resistance of protective ground is 0.5 Ohms. The place for connection of the ground wire to ground is denoted by the sign of grounding by DSTU 3335-96 (GOST 12.2.007.4-96) "Cabinets of unsealed complete switchgear and complete transformer substations. Security requirements" [79]. According to GOST 12.2.007.0-75 «Occupation safety standards system. Electrical equipment. General safety requirements» [59] diameter of the grounding bolt thread is M10, the diameter of the contact area is 25 mm.

Distances between non-isolated current carrying parts of different phases, distances from non-isolated current carrying parts to earthed structures and fences, ground and floor are chosen according to the p.4.2.86 Arrangement of Electrical Installations (PUE) [56].

When operating FOCT, personnel injury via electric shock is possible if there is accidental contact with non-isolated current carrying parts, or approaching them at a close distance when overlap of the air gap is possible and the defeat via electric spark (electric arc). Defeat is also possible when touch of the metal chassis of the panel, that has as a result of damage of the insulation short to ground in the event of poor ground conditions, according to NPAOP 40.1-1.01-97 «Rules of safe operation of electrical installations» [78]. To avoid the above, in FOCT, appliances, current carrying parts, insulation are chosen in such a way that:

– when removing the voltage from any circuit current carrying parts, machines and structures related to it could be subjected to inspection, replacement and repair in conditions that ensure safety, without disturbing the normal functioning of neighboring chains in FOCT;
– electric arcs or sparks, caused by the normal conditions of operation, could not cause harm to operating personnel and did not cause overlapping of insulation of FOCT.

Assembly clamps, contacts of auxiliary circuits of breaker and devices of auxiliary circuits in the relay cabinet are installed in such a way that their secure service without removing of the main circuit voltage is ensured.

Electrical equipment installed in the sliding element is available for repairs and maintenance only after removing the sliding element in the repair position.

Moreover, disabled plug-in contacts result in isolation of the breaker, and creation of visible break the chain.

All current carrying parts of the main circuits that can be under voltage after rolling out of the sliding element in the repair position are locked automatically by closing blinds. There is warning signs "Attention! Energized" at the blinds in accordance with GOST 12.4.026-76 (1987) "Signal colors and safety signs" [57].

Exterior compartment door of the sliding element is completely closed in the operating and control provisions of the sliding element.

The FOCT includes indices "controlling" and "working" position of sliding element.

According to GOST 12.1.009-76 (1999) “Occupation safety standards system. Electrical safety. Terms and Definitions” [58] the investigated transformer is made using polymer insulation. And this is due to the high level of electrical and mechanical strength.

By way of protection of people from electric shock, SGP refers to the class I, according to GOST 12.2.007.0-75 (2001) “Occupation safety standards system. Electrical products. General safety requirement” [59].

In the FOCT are hold all the locks for protection and secure operation of the product in accordance with GOST 14693-90 (2003) «Unsealed metal-enclosed switchgear and control gear for voltages up to 10 кV. General specifications» [60], namely:

– lock, preventing movement of the sliding element with the breaker from the operational position to the control one, as well as from control position to the operational one when the breaker is turned off;
– lock, preventing turning on of the breaker that is installed on the sliding element, when sliding element is between the working and control provisions;
– lock, preventing movement of the sliding element from control position to the operational one at the grounded knives and grounding of the knives in the operational position of sliding element;
– lock, preventing the grounding of knives in the panel of sectional disconnector at operational position of sliding element of the sectional breaker;
– lock, that does not permit turning on of the input or section switch at grounded knives at assembly buses of the section;
– lock, preventing turning on of main blades of stationary disconnector at earthed grounding knives or turning on of grounding knives at main knives of the stationary disconnector turned on;

- lock, preventing the opening of doors at the major knives of the stationary breaker turned on, or preventing of turning on of the main knives of stationary disconnector at opened doors;
- lock, preventing the doors opening in the presence of stress on the tires of cable assemblies;
- lock, preventing rolling out of sliding element when the circuit breaker at the side of low voltage is turned on.

5.1.2 Measures to ensure industrial sanitation and occupational hygiene

Measures to ensure occupational health and hygiene for the FOCT testing stations designed in accordance with the requirements of DSN 3.3.5-8.6.6.1-2002 "Hygienic classification of labor on the indicators of harmfulness and danger of factors of the production environment, the severity and intensity of the labor process" [61].

According to DSP 173-96 "State sanitary rules of planning and development of settlements" [62] FOCT is the electrical equipment of the IV class sanitary (Highly dangerous), with sanitary-protective zone of 100 m. Meteorological conditions in the work zone area shall be in accordance with the requirements of DSN 3.3.6.042-99 "Sanitary norms of microclimate of industrial premises" [63], GOST 12.1.005-88 "Occupational safety standards system. General sanitary requirements for working zone air" [64]. These parameters are used in warm, cold, and the transitional period of the year, based on the categories of hardness of work.

The work performed at the testing station area, refer to the work of moderate hardness, category Iб with energy loss 141-175 Wt. For this category of work are established the following weather conditions:

- in the cold and the transition period, the temperature of (18…20) º C, relative humidity (40…60) %, the rate of air movement of 0.2 m/s;
- in the warm season temperature of (21…23) º C, relative humidity (40…60) %, the rate of air movement of 0.2 m/s.

The parameters of the microclimate in the workplace are provided through rational planning of production facilities of the testing station, the maximum mechanization, automation and remote control of the testing process, as well as heating, air conditioning and ventilation, according to DSN 3.3.6.042-99 "Sanitary norms of microclimate of industrial premises" [63] and GOST 12.1.005-88 " Occupational safety standards system. General sanitary requirements for working zone air" [64].

Since rational lighting of workplaces and premises creates a certain psychological tone in employees, prevents visual and general fatigue, promotes highly productive work. Insufficient lighting of workplaces can be an indirect cause of accidents at work. If we consider a lightning in testing station, it should be noted, that there are certain hygienic requirements for lighting. In accordance with DBN V.2.5-28:2018 "Engineering equipment of buildings and constructions. Natural and artificial lighting" [65], the lighting in premise is even and sufficient to quickly and easily distinguish objects, it provides contrast between the object and the background. The light source doesn't blind the person, and doesn't create glare on the testing object.

The lighting is natural, artificial and combined (using both natural and artificial light). In testing station in the daytime combined type of lightning is used, at night - the total artificial lighting is used. During natural lighting, only side light is used, it is the lighting of the premis with light that penetrates through the windows in the walls of the building.

As for artificial lightning, then it is divided into general, local and combined. In testing station used a combine type. Combined lighting is a combination of general and local lighting. At the same time concentration of a light stream on separate workplaces is reached, according to DBN V.2.5-28:2018 "Engineering equipment of buildings and constructions. Natural and artificial lighting" [65]. It is not allowed to use open lamps for lighting of premises and workplaces. Luminaires are used for this purpose - devices that consist of a light source (lamp) and fittings. All lamps in the premise are gas-discharge (mercury-vapor lamp type "MVL"), which are powered from the net with a voltage not exceeding 220 V and suspended at a height of at least 4 m from the lighting area.

On testing station area noise and vibration are generated by mechanical tools and conveyor for moving the crane, only. The permissible level of noise in the workplace does not exceed 60 dB, according to DSN 3.3.6.037-99 “Sanitary standards of production noise, ultrasound and infrasound” [66] and GOST 12.1.003-2014 “Occupational safety standards system. Noise. General safety requirements” [67]. The value of the noise level in the area does not exceed the permissible level. Control of noise level in the workplace is provided at least once a year.

At testing station, there is some vibration, due to working of conveyor for moving the cranes and these cranes. It is a general vibration transmitted through the supporting surfaces of the body in a sitting position (buttocks) or standing (soles of the feet). In terms of frequency composition, it is classified as a mid-frequency vibration of 16 Hz, this is permissible rate of vibration affecting people at testing station for the duration of the work shift 8 hours, according to the DSN 3.3.6-039-99 “State sanitary norms of industrial general and local vibration” [68] and GOST 12.1.012-90 «Occupational safety standards system. Vibration safety. General requirements» [69].

To reduce the exposure to vibration at the testing station, the following actions are envisaged for employees:

– two adjustable breaks;
– the use of vibration damping, dynamic vibration damping, active and passive vibration isolation;
– use of personal protective equipment.

In the FOCT construction there is electromagnetic busbar, which is involved in measurements. Thus, during it’s working process the busbar creates an electromagnetic field, of low frequency 50 Hz. According to DSN 3.3.6-096-2002 "State sanitary norms when working with sources of electromagnetic fields" [70] and GOST 12.1.006-84 “Occupational safety standards system. Electromagnetic fields of radio frequencies. Permissible levels at work-places and requirements for control” [71] this level of frequency an acceptable level.

To measure the level of electromagnetic radiation at the enterprise, the П3-41 device is used - a meter for the levels of electromagnetic radiation, which determines the magnetic component in the frequency band 0.01-50 MHz.

However, even at an acceptable level, the following protection rules should be adhered to:

– people's access to dangerous places should be limited to sanitary zones;
– limit the time of exposure to EMF;
– move away from the radiation source to the maximum distance;
– reduce the number of simultaneously operating household appliances.

In the testing station area, the collection and disposal of waste is provided: chemicals, oil, garbage, industrial water, etc. are collected in the appropriate containers, according to p.1.1.25 of Arrangements of Electrical Installations (PUE) [56]. In the assembly area the revolving cycle of water is provided, therefore the possibility that the waste contaminates water, storm drain system, ravines is excluded. The ventilation system provides the filtering properties of the plant that provides air defense of the environment.

The plant, where the testing station is located, provides sanitary and domestic premises: dressing rooms, showers, washrooms, toilets, smoking area, placed according to the SNiP 2.09.04-87 "Administrative and domestic buildings". The distance from the workplace to the sanitary facilities do not exceed 100 m near the dressing room area of open type for staff recreation during working hours, according to p.2.44 SNiP 2.09.04-87 "Administrative and domestic buildings" [87].

5.1.3 Fire safety measures

Fire safety of industrial enterprises is an important set of measures to ensure the preservation of the health of industrial workers. Such rules are developed and approved by special commissions whose activities are aimed at preventing accidents in the workplace.

Measures for fire proof of FOCT testing station area are designed in accordance with the requirements of NAPB A.01.001-2004 "Rules of fire safety of Ukraine" [73].

Since FOCT does not apply to either dry transformers or oil transformers, respectively, it does not have oil-filled tanks and paper insulation. FOCT considered non-explosive and non-fire hazardous for workers. In accordance, with NAPB B.03.002-2007 "Standards for determining the categories of premises, buildings and outdoor installations for explosion and fire safety" [74] the testing station of FOCT belongs to the premises of the production category "D". Speaking about fire safety measures, should be noted fire sabe of the building where testing station located. The safe operation of buildings and structures depends on many factors. This is the observance of technology during construction, and the use of high-quality materials.

It depends, first of all, on the degree of fire resistance of the building or structure. Depending on what materials are taken during construction, a structure can be, to varying degrees, resistant to adverse factors such as open fire, lightning, and electric shock. In accordance with DBN V.1.1.7-2002 "Fire safety of construction objects" [75], the degree of fire resistance of building is “IIIa”, it means that the building with frame elements made of metal. The enclosing structures are sheathed with sheets that do not support combustion. The insulation inside the building frame also non-combustible.

According to DBN V.1.1.7-2002 "Fire safety of construction objects" [75], evacuation of people from the building in case of fire is provided through emergency exits that lead directly to the exterior of the premises. The width of stairs and walkways is 0.9 meters according to п. 2.29 SNiP 2.09.02-85* "Industrial buildings" [76] the distance from the most remote workstation to the nearest evacuation exit at the density of the human flow in the passage of 3 or higher humans per m^2 does not exceed 65 m.

At the site of FOCT testing station the equipment that meets the requirements of fire safety is used, according to NAPB A.01.001-2004 "Rules of fire safety of Ukraine" [73]. All of the equipment has marked signs that indicate the degree of protection equipment in accordance with p.5.1.6 NAPB A.01.001-2004 "Rules of fire safety of Ukraine" [73].

Equipment, power and lighting networks correspond to fire safety requirements as they are made in accordance with the requirements of NPAOP 40.1-1.32-01 "Rules for the construction of electrical installations. Electrical equipment of special installations" [77], and have a degree of protection of covers IP44 and of fixtures IP54.

For a quick notice of the Fire Service about fire arisen in the room there is an automatic fire alarm and manual alarm. Manual alarms of type have push-button control and are located on the prominent places - in the corridors at the exit doors, etc. To call the fire brigade it’s necessary to break the glass on the body of the sensor and press a button.

The testing station provides for the installation of a modular fire extinguishing system. It has a high level of reliability, is characterized by the use of a minimum amount of extinguishing substance, quickly and effectively extinguishes fire and does not harm the equipment in the premises.

However, we should not forget about the primary means of fire extinguishing. At the first sign of a fire, proper use of primary extinguishing agents can help prevent the spread of flames and prevent major disasters. To the the primary means of fire extinguishing we can can be attributed:

- fire extinguishers;
- blankets made of non-combustible heat-insulating cloth, coarse-woolen fabric or felt;
- sandboxes;
- barrels of water;
- fire buckets;
- dyes;
- scraps;
- hatchet.

Of all the types of primary fire extinguishers, fire extinguishers are the most common and most effective. Due to features such as efficiency and ease of use, the ability to quickly actuate and supply fire extinguishing agent to the fire, as well as relatively low cost, fire extinguishers play an important role in fire protection (reducing the number of fires and damage from them).

As well at the testing station water supply system is provided, which is a source of water supply for mobile fire equipment and fire extinguishing systems. According to SNiP 2.04.02-84 and SNiP 2.04.01-85 [80, 81], the amount of water required for firefighting depends on the volume of the test station area. The volume of the considered territory is 5000 m^3.

The water consumption for external fire extinguishing is determined by the formula.

$$Q_{ext} = 3600 * q_1 * T_1, \quad (5.1)$$

where q_1 is the water consumption for one firefighting, q_1=10;

T_1 is estimated duration of external firefighting, T_1=3h.

Q_{ext}=108000 liters.

Calculation of the flow rate of water for internal extinguishing.

$$Q_{int} = 3600 * n * q_2 * T_2, \quad (5.2)$$

where n is the number of streams, n=2;

q_2 is the minimal water consumption for one stream, q_2=2.5;

T_2 is the estimated operating time of fire hydrants, T_2=3h.

Q_2=54000 liters.

The total estimated water consumption for internal and external fire extinguishing of the specified building is:

$$Q_{tot} = Q_{ext} * Q_{int},$$

Q_{tot}=162000 liters.

5.2 Safety measures during emergencies

Site workers should provide for emergency control. In order to ensure human safety in emergencies the management strategy must involve the realization of 3 goals:

- prevention of causes of occurrence;
- prevention of extreme situations themselves;
- attenuation, maximum reducing of consequences of the emergencies.

The strategy of prevention of causes of occurrence of emergencies includes the avoidance of such acts or processes that carry a threat for the population. This strategy is realized through either refusal from building dangerous sites or the destruction or the reorientation of production sites that are the sources of increased risk.

The second strategy of prevention of emergency itself includes the avoidance of the dangerous process to run beyond control by using reliable emergency systems, alarms, automation and other measures to enhance reliability and stability of the enterprises operation as well as by taking measures of preventive evacuation etc.

The third strategy of attenuation of consequences includes the orientation on reducing, localization of consequences of the emergencies. This strategy is of priority in managing natural disasters and “combined” type situations.

In management practice the most effects are achieved through the use of all three strategies especially in case of industrial accidents. In case of emergencies attributable to natural disasters the second and the third strategies are of priority. For the realization of each management strategy is necessary to develop and to adopt a complex of preventive and operative measures.

Preventive:

- analysis and establishment of external and internal reasons that lead to the catastrophe;
- forecasting of centers of destruction, losses and damage at the enterprise;
- measures to increase stability;
- justification of forces and means to localize centers of destruction and search and rescue operations;
- training of forces and citizens in safety methods;
- preparation of a reliable command control center.

Operative:

- notification about the emergencies;
- all types of reconnaissance and situation forecast;
- emergency safeguards (refuge in protective shelters, evacuation, use of individual protective gear);
- use of permanent readiness forces for the localization of the catastrophe;
- medical and premedical first aid;
- increase of forces and means in the centers of destruction by involving advanced readiness forces;
- urgent supply of the victims with food and other life-saving means;
- introduction of emergency restoration works.

In the event of emergencies, the emergency control is organized, which consists of four stages of consequence management.

1) The goal is to use the mechanism of emergency control and timely respond to emergencies. The main objectives of the initial stage are: the determination of a fact of emergency, preliminary assessment of the situation in the disaster zone and the scale of consequences, mobilization and establishing of operational tasks of emergency management, orders to bring the fire protection AMF, ambulance, public order and other services to help the victims, assistance to local authorities in organizing rescue and localization of the disaster zone with their own forces;

public and higher authorities awareness about the emergencies and the actions taken. The duration of the initial stage is 1-10 hours.

2) Stage of mastering the situation and the organization of emergency management mechanism in the area of disaster, planning and conducting of the appropriately scaled rescue operation. Objectives are: to assess the situation in detail, immediately take the reasonable decisions and clarify the plan of liquidation of consequences of the emergency; to calculate the required capacity, resources for all the works in the disaster zone, to organize a clear interaction of all involved forces and emergency services. The duration of the second stage is from several hours to several days.
3) The main and decisive stage. The goal is to overcome the urgency of the situation, restore public safety in the disaster zone, eliminate the threat to life and health of all victims, establish minimum conditions for the life of the population left. Objectives are: to deploy as soon as possible the facilities to rescue the victims in the disaster zone, to assist the victims to protect their lives, health and vital functions under extreme conditions; to evacuate the victims from the zone of disaster and their sustenance; emergency rescue and recovery operations on systems of water, heat, gas, electrical power supply and communications in the disaster zone. The duration is from several days to several weeks.
4) The stage of recovery, i.e. economic, social, cultural and environmental rehabilitation of the disaster zone. Emergency management authorities have accomplished their role and transfer functions to the permanent local government. A special program is developed with the sequence of measures for the rehabilitation of disaster areas.
5) The set of measures to ensure safety, industrial sanitation, occupational health and fire safety provided for the testing station provides safe and comfortable working conditions for the stuff, eliminate dangerous and harmful effects and correspond to the requirements of normative documents.

6 COST AND PRICE OF PRODUCTS

6.1 Product characteristics of innovation project. Market assessment

The considered design of FOCT is almost similar to analog current transformer. However, there is one main difference between the developed design of transformer and analog one, it is that new generation transformers has completely different working principle, which is based on Faraday's effect. Thus, fiber optic current transformers are more improved than electromagnetic ones and replace them worldwide. This enhancement increases the technical characteristics of the device, more reliable and more efficient to operate and maintain. Using optical methods for measuring current allows to get the measured values immediately in digital form, and the applied voltage measurement circuit makes it possible to significantly increase the accuracy of measurements and reduce errors [24].

An important, advantages of this equipment are the safe operation, easy control, safe and convenient installation. The device is manufactured by leading companies around the world (USA, Germany, Canada, China, Japan, Russia). This device complies with the customer on all technical and economic parameters of products.

At the table 6.1 lists all the main technical and economic indicators of FOCT and analog transformers.

Table 6.1 – Technical and economic indicators of FOCT and analog transformers.

Parameters	New choice	Base choice
Type	Fiber optic current transformers	Current transformers
Rated voltage, kV	AC – 35-1150 BC – 25-800	0.66 – 1150
Rated current, A	100 – 4000	1 – 40000

Continuation of the Table 6.1

Maximum thermal stability current, kA	63	40
Maximum electrodynamic stability current, kA	20 – 170	10 – 212
Power consumption, W	no more than 60	no more than 60
Height, m	1.5 – 6.3	0.6 – 7.9
Weight, kg	Power Amplifier and Power Supply – 10; Electro-optical unit – 7; Insulator– from 34 to 80	9 – 100
Accuracy class	0.2s – for measurements; 0.5p – for protection	0.5; 0.5s; 0.2; 0.2s; 1; 3; 5; 10 – for measurements; 5p; 10p – for protection
The overhaul period, years	6	6
Production volume of new product, units per year	5	5
Service life, years	No less than 30	No less than 30

Due to long-term operation of the transformer in HV equipped parks, and taking into consideration all parameters of analog and fiber optic transformers it can be concluded that the old equipment, require an urgent repair. But as it shown on practice the installation of FOCT is expedient for the radical reconstruction of existing electrical substations or the construction of new ones. In this case, a complex meter of electrical energy parameters, built into optical transformers, will produce data directly for АИИС КУЭ, telemechanics systems and measurement of electricity quality parameters.

Table 6.2 – Description of the idea

The content of the idea	Directions of application	Benefits for consumers (users)
Replacement of oil-filled and gas-filled electromagnetic current transformers with digital, fiber-optic current transformers	Energy-intensive production	Measurement accuracy
	Control measurements, calibration	High stability
	Generation	Speed
	High voltage power lines	Wide dynamic range
	Electricity quality control	Small dimensions and ease of installation
	Measurement of direct, alternating and impulsive currents, at any voltage	Minimal error
	Information and measuring systems	Fire resistance

At the present stage of development of the Ukrainian electric power industry, classical measurement methods based on electromagnetic principles have reached their limit and cannot meet new requirements. But despite this, they are still very popular among buyers and occupy a large part of the market.

Table 6.3 – Preliminary description of the potential market

№	Market indicators (name)	Characteristic
1	The main competitors	Electromagnetic current transformers
		SF6 current transformers
2	Market dynamics (qualitative assessment)	is growing

Continuation of Table 6.3

3	Presence of entry restrictions (specify nature of restrictions)	Lack of funds and opportunities for global change throughout the system
		Lack of digital equipment
		Lack of highly qualified staff
4	Specific requirements for standardization and certification	Use of innovative technologies and solutions
		Full transition to digital networks and digital substations
		Setting up digital control in production

Hence, it should be noted, that at the present stage of development of the electric power industry of Ukraine, classical measurement methods based on the electromagnetic principles have reached the limit of their capabilities and cannot satisfy new requirements. They have arisen due to technological revolution of the last several decades. Therefore, the modern development of electrical complexes and systems requires the introduction of the latest designs of instruments and equipment. Let’s consider potentional costumers of the innovative product.

Table 6.4 – Preliminary description of the potential costumers

№	Demand that mold the market	Target audience (target market segments)	Requirements of consumers (users)
1	Energy insecurity of the country's regions	Energy services	Stable operation of transformers and avoidance of emergency situations
2	Improving the quality of population's life	Population	Constant supply, without interruptions
3	High reliability and accuracy of measurements	Production enterprises	Error reduction, work at any voltage and in different weather conditions
4	Ease of installation	Groups of installers	Installation without useing auxiliary tools and cranes, avoidance of damage during transportation

In the conditions of changing market relations and the current competition it is necessary to keep a hand on pulse. This is aided by a variety of analytical tools, including SWOT analysis. It provides an opportunity to learn about the internal strengths and weaknesses of the equipment, as well as its external capabilities and threats.

Table 6.5 – SWOT analysis

Strengths:	Weak sides:
- wide frequency and dynamic range; - no effect of short circuits; - small dimensions and ease of installation; - high overload capacity; - innovation in the Ukrainian energy market.	- lack of qualified staff; - special power supplies are required; - great technical and economic difficulties; - significant complications of schemes due to high accuracy; - high costs for the purchase of new equipment.
Opportunities:	**Threats:**
- high demand for new vacancies; - improving the energy situation in the regions; - new infrastructure for energy stations; - the use of innovative technologies that will significantly improve the energy and economic situation.	- quite large competition with analog transformers; - there are no alternative suppliers of spare parts in case of breakage; - lack of advanced training courses.

6.2 Cost and product price

As it was mentioned above for the exploitation of this type of transformer a high qualified staff should be on the enterprise. Let's consider the salary and the award of such workers. The statistics of the Ukrainian labor market in the field of engineering shows the following average monthly amounts received by engineers, you can see it in Table 6.6. But except salary workers get an awards in the amount of 17% and pay Single social contribution (SSC) to the government’s coffers, in our country this contribution is 22%.

Calculation of the awards

$$S_{aw}=S \cdot Pr, \tag{6.1}$$

where S_{aw} is the sum of awards, UAH;

S is the monthly salary of the workers, UAH;

Pr is the premium percentage to salary, %.

Calculation of the Single social contribution (SSC)

$$SSC = W \cdot C, \tag{6.2}$$

where W is the Annual fund wages, UAH;

C is the contribution to the government's coffers, %.

All the calculation's results indicated in Table 6.6, for each worker at the enterprise.

Table 6.6 – Composition, number and salary fund of administrative staff

Position	Numb-er of people	Salary, UAH	Premium percentage to salary, %	Sum awards, UAH	Monthly salary, UAH	Annual fund wages, UAH	SSC, UAH
1	2	3	4	5	6	7	8
Chief Engineer	1	30000	17%	5100	35100	421200	92664
Chief Power Engineer	1	30000	17%	5100	35100	421200	92664
Fire Safety Engineer	1	20000	17%	3400	23400	280800	61776
Engineer constructor	1	11353	17%	1930	13283	159396	35067.12
Accountant	2	15350	17%	2609.5	17959.5	215514	47430.8
Electrician	3	12467	17%	2119.39	14586.39	175036.68	38508.07
Equipment maintenance engineer	3	12548	17%	2133.16	14681.16	176173.92	38758.26
Mechanic	3	12010	17%	2041.7	14051.7	168620.4	37096.49
Total of managerial staff	15	143728	X	24433.75	168161.75	2017941	443964.74

The cost of raw materials and basic materials is given in Table 6.7.

Table 6.7 – Calculation of material costs

Material costs	Volume of raw materials	Price, UAH	Sum UAH
1	2	3	4
Insulator	1	7000	7000
Optical sensor	1	13547	13547
Optoelectronic unit	1	12300	12300
Current amplifier	1	13660	13660
Power supply unit	1	4350	4350
Fiber Optic Cables	2	42,75	85,5
Software on CD	1	200	200
Cable system	1	3024	3024
Interconnect cable PSU	2	114,75	229,5
Trunk Temp Sensor cable Belden 9512	1	242,55	242,55
Optical trunk cable Belden 1037A	1	105,75	105,75
Modulator cable Belden 1118A	1	37,8	37,8
Electrotechnical steel , ton	0.07	12792	895,44
Polymer, kg	50	125	6250
Fiber Optic Cables: Zip Cord	5	42,75	228,75
Paint and varnish production, kg	9.3	500	4650
Non-ferrous metal hire, kg	26	200	5200
Cable products, kg	8	108	864
Transportation and procurement costs			4870
Total			77740,14

The cost of packaging of products are also calculated on the basis of consumption rates and prices.

The cost of raw materials, basic materials and cost of purchasing components is calculated on the basis of usage rates, prices, and consumption rates. Transportation and procurement costs are taken into account as well, the waste should be deducted. The value of transportation and procurement costs depends on the location of enterprises-suppliers of raw materials and basic materials, as well as the types of transportation.

Monthly operating costs are calculated taking into account each type of electrical equipment.

Operating costs for high-voltage devices accommodate the following costs:

– of electricity;
– for actual repairs (cost of materials and spare parts, salary);
– the cost of maintaining the production area required for installation and maintenance of transformers;
– depreciation of total capital investments consumer.

Electricity (Cel) costs are determined by the formula 6.4.

$$C_{el} = P \cdot T \cdot D \cdot Pr_{el} \cdot K_{los.el}, \text{ UAH} \quad (6.3)$$

where P is the used power, W, P=50W;

T is the working time of electrical equipment, hours, T=16 hours;

D is the working days per month, D=20 days/month;

Pr_{el} is the price of 1 kW*h of electricity, UAH,

Pr_{el} = 2,92 UAH;

$K_{los.el}$ is the losses coefficient in electrical networks, $K_{los.el}$ = 0.83.

The calculation results of power supply, is shown in Table 6.8.

Table 6.8 - Calculation of the cost of consumed services

Type of services	Standard per one product (services), W/hour	Production program, hours/day	Scope of services, W /month	Tariffs, UAH/kW	Electricity losses coefficient	Sum UAH/month
1	2	3	4	5	6	7
Power supply	50	16	16000	2,92	0.83	38777.6
Total						38777.6 UAH

Since all equipment has a tendency to wear out after its operation for a long period, and the transformer under consideration, is no exception, it is necessary to calculate the depreciation cost. Depreciation is the process of periodically transferring the initial cost of a fixed asset or intangible asset to production, commercial or general expenses. Voltage transformers belong to the seventh group of operation with a service life of 15-30 years. For calculation we will take the period of operation of 30 years. The annual depreciation rate for this period is 3.3%. The total cost of FOCT is 911640.50 UAH.

Before depreciation calculation it is necessary to indicate the salvage value of old equipment. Salvage value – the amount of funds or value of other assets that the company expects to receive from the sale (liquidation) of non-current assets after the end of their useful life (operation), less costs associated with the sale (liquidation) [82].

After analyzing the market for old equipment, it was decided to give 10 pieces of old transformers for scrap. So, the salvage value calculates by the following formula:

$$C_{liq} = Q * P, \tag{6.4}$$

where Q is quantity of old equipment, kg, Q=300kg;

P is price for one kg, P=7.8UAH.

Let's calculate the depreciation amount for each year. For the first year of exploitation the depreciation is,

$$A_1=P_{total}*D_y*2, \quad (6.5)$$

where P_{total} is total price of FOCT, UAH;

D_y is the annual depreciation rate, %

$$D_y=\frac{100\%}{n}, \quad (6.6)$$

where n is the number of years of useful life of the equipment, n=30 years.

Residual value

$$V_{r1}= P_{total}- A_1, \quad (6.7)$$

For the second year of exploitation the depreciation is,

$$A_2= V_{r1}*D_y*2, \quad (6.8)$$

Residual value

$$V_{r2}= V_{r1}- A_2, \quad (6.9)$$

For the third year of exploitation the depreciation is,

$$A_3= V_{r2}*D_y*2, \quad (6.10)$$

Residual value

$$V_{r3}= V_{r2}- A_3, \tag{6.11}$$

For the fourth year of exploitation the depreciation is,

$$A_4= V_{r3}*D_y*2, \tag{6.12}$$

Residual value

$$V_{r4}= V_{r3}- A_4, \tag{6.13}$$

According to the calculations for the 10 years of exploitation the depreciation is,

$$A_{10}=34435.31 \text{ UAH},$$

Residual value

$$V_{r10}=396006.11 \text{ UAH}.$$

According to the calculations for the 20 years of exploitation the depreciation is,

$$A_{20}=14958.3 \text{ UAH},$$

Residual value

$$V_{r20}=172020.48 \text{ UAH}.$$

According to the calculations for the 30 years of exploitation the depreciation is,

$$A_{30}=V_{r29}-C_{liq}, \tag{6.14}$$

Recoupment for actual repairs per the period of exploitation is calculated by the formula 6. 4.

$$C_{rep} = S_{rep} \cdot n_{rep} \cdot Y, \quad (6.15)$$

where S_{rep} is the cost of one actual repair, UAH, S_{rep}=5250;

n_{rep} is the number of actual repairs per year, n_{rep}=6;

Y is the period of exploitation, Y=30 years.

The cost of maintaining the production area per the period of exploitation is calculated by the formula 6.6.

$$C_{area} = C_m \cdot S \cdot K_{area}, \quad (6.16)$$

where C_{area} is the specific cost of maintaining 1m^2 of production area, per month UAH, C_{area}=115 UAH;

S is the area occupied by the transformers, 200m^2;

K_{area} is the coefficient taking into account the additional area, K_{area} = 1,15.

The calculation results of operational expenses, are shown in Table 6.9.

Table 6.9 – Calculation of depreciation and other recoupments per the exploitation period

Group of fixed assets	Depreciation rate	Initial cost of equipment on 01.01	Start of exploitation		End of exploitation		Amount for the period of operation UAH
			date	Price per month	date	Price per year	
1	2	3	4	5	6	7	8
Annual depreciation	3,3	911640,50	01.01.2021	6077.6	01.01.2051	72931.24	78881.42
Costs for the maintenance of production area, UAH	-	911640,50	01.01.2021	26450	01.01.2051	317400	9522000

Continuation of table 6.9

Recoupment for actual repairs, UAH	-	911640,50	01.01.2021	5250	01.01.2051	31500	945000
Total				37777.6		356191.24	1975881.42

Except costs the transformers should bring the profit. Let's consider which profit will be and whether it is advisable to introduce this novelty into operation.

The transformer substation calculated by me supplies electricity to 3 residential buildings with built-in-attached non-residential premises and a shopping center. The power of the substation is 110 kW. Approximately 50,000 kW are consumed per month. according to electricity tariffs in Ukraine, For individual household consumers, the tariff is 144 UAH per 1 kW.

Thus the profit from the FOCT substation is:

$$P=C*T*n, \tag{6.17}$$

where C is the consumption per month, kW;

T is the tariff for the electricity, UAH;

n is the amount of working months.

But when making a profit, there is necessary to pay Value Added Tax (VAT) to the government, and in Ukraine the VAT on profit is 22%.

$$VAT=P-22\%, \tag{6.18}$$

In accordance with all the tables and calculation it will be rational to complete the cost estimates for one year of exploitation of one and all 10 FOCTs. The table 6.10 displays all indicators.

Table 6.10 – Cost estimates

Costing articles	Costs	
	per unit of equipment, UAH	based on the total volume of equipment, UAH
Raw materials	77740,14	777401,40
Power supply	38777.6	387776
Wages of workers	2017941	2017941
Single social contribution	443964.74	443964.74
Depreciation	72931.24	729312.4
Recoupment for actual repairs	31500	315000
Costs for production area	317400	317400
VAT	19000800	19000800
Estimates for FOCT	22008254.72	23989595.54

Since in the first year of operation, funds were spent on the purchase of transformers (the cost for 10 new transformers is 9,116,405.00 UAH), all expenses during the year increased by this amount (one-time). Thus, in the first year, the cost of maintaining the substation of fiber-optic transformers amounted to 33,106,000.54 UAH. While the income for the year, according to formula (6.17), amounted to 67,392,000.00 UAH. Based on the figures received, I can say that the first year before the costs of the substation will pay off, and besides, the substation will bring profit in the amount of 34,285,999.46 UAH

According to the cost and price of new product in the field of high-voltage apparatuses, it can be said that replacement of analog transformers is a good choic. Its characteristics are better and price is quite acceptable.

CONCLUSION

At this master's thesis, I have analised the pools of high voltage equipment, compared measuring methods of current by analog transformers and fiber optic ones. So, to sum up it can be said, that at the present stage in the electric power industry, the development of optoelectronic current transformers is promising and expedient. To date, their further development is not hindered by anything and in a number of countries the work on creating new current transformers is gaining popularity.

According to the result of all calculations it can be summed, that the temperature of the conductor of the busduct to the end of the short circuit does not exceed 250 ^{o}C, and the time of reaching this temperature is more than 4 seconds. Electrodynamic forces of the conductors under the short-circuit mode will be 320 N.

Based on the analysis of different materials of insulators and on calculation results of external insulation, it can be bringing to the end that it is rational and profitable to produce FOCT with polymer insulators. Today polymer insulators are economical and easy to install, they have high vandal resistance and much lower weight compared to porcelain one. As it is indicated above, FOCT with polymer insulators can be used under any environmental conditions. The design and dimensions of the insulator must be chosen so as to exclude the possibility of breakdown, as a result of the long existence of ionization processes that occur under the influence of an electric field on the surface or inside the insulation. The considered FOCT has enough force to withstand wind load. Also it should be noted that the material of the insulators, regardless of environmental pollution conditions, does not change, but the number of ribs increases and the distance between them decreases, so as to increase the leakage path.

According to the cost and price of new product in the field of high-voltage apparatuses, it can be said that this is a good choice and the best replacement of analog transformers. Their chsracteristics are beter and price is quite acceptable. Line on the calculations the first year before the costs of the substation will pay off, and besides, the substation will bring profit.

REFERENCES LIST

1. Fylymonenko, A. V. Fiber Optic 110 – 150 kV Current Transformers [Текст]: / A. V. Fylymonenko, S. Y. Yatsura, L. B. Zhorniak // Електромеханічні та енергетичні системи. Методи моделювання та оптимізації. Збірник матеріалів XVIII Міжнародної науково-практичної конференції молодих учених і спеціалістів 04 –06 листопада 2020 року. – Кременчук, КрНУ, 2020. – С. 69-73.

2. Fylymonenko A. Fiber optic current and voltage sensors / A. Fylymonenko, V. Vasilevskiy. // Збірник наукових праць національного університету «Запорізька політехніка». – 2020. – №95. – С. 23–25.

3. Zubia J. Design and Deve- lopment of a Low-Cost Optical Current Sensor / J. Zubia, L. Casado, G. Aldabaldetrek. – 2013.

4. Адоньев Н. М. Справочник по расчету и конструированию контактных частей сильноточных электрических апаратов [Текст] / Н. М. Адоньев, В. В. Афанасьев. – Ленинград: Энергоатомиздат, 1988. – 384 с

5. Александров Г. Н. Проектирование электрических аппаратов [Текст]: Учебник для П 79 вузов / Г. Н. Александров. – Л.: Энергоатомиздат, 1985. – 448 с.

6. Афанасьев В. В. Справочник по аппаратам высокого напряжения [Текст] / В. В. Афанасьев, Н. М. Адоньев, И. М. Бортник. – Л.: Энергоатомиздат, 1989. – 544 с.

7. Афанасьев В. В. Трансформаторы тока [Текст] / В. В. Афанасьев, Н. М. Адоньев, В. М. Кибель и др. – Л.: Энергоатомиздат, 1989. – 416 с. – (2).

8. Афанасьев В. В. Оптико – электронные трансформаторы тока [Текст] / В. В. Афанасьев, В. П. Зубков., 1970. – (Электричество). – (7).

9. Близняков О. В. Конспект лекцій дисципліни Основи теорії електричних Апаратів [Текст] / О. В. Близняков. // Національний університет «Запорізька політехніка». – С. 94.

10. Буткевич Г. В. Задачник по электрическим аппаратам [Текст], учебное пособие для вузов / Г. В. Буткевич, В. Г. Дегтярь. – М.: Высшая школа, 1987. – 232 с. – (2).

11. Гречухин В. Н. Электрические трансформаторы тока и напряжения. Состояния, перспективы развития и внедрения на ОРУ 110-750 кВ станций и подстанций систем [Текст] / В. Н. Гречухин. // Вестник ИГЭУ. – 2006. – №4. – С. 5.

12. Крючков И. П. лектрическая часть электростанций и подстанций [Текст]:
Справочные данные для курсового и дипломного проектирования / И. П. Крючков, Н. Н. Кувшинский. – М.: Энергия, 1978. – 465 с.

13.Никитенко, А. Г. Программирование и применение ЭВМ в расчетах электрических аппаратов [Текст]: Учеб. пособие для вузов / А. Г. Никитенко, В. П. Гринченков, А. Н. Иванченко. – М. : Высш.шк., 1990. – 231 с.

14. Сахаров П. В. Проектирование электрических аппаратов [Текст] / П. В. Сахаров. – М.: Энергия, 1971. – 560 с.

15. Чунихин А. А. Аппараты высокого напряжения [Текст] / А. А. Чунихин, М. А. Жаворонков. – М.: Энергоатомиздат, 1985. – 432 с.

16. Актуальные проблемы энергетики//Материалы 70й научно-технический конференции студентов и аспирантов. Электронное издание. // Белорусский национальный технический университет. – 2014. – С. 15

17. Каневский Д. Оптические трансформаторы / Д. Каневский. // Энергознание. – 2018.

18. Можливості компенсації напруженості електричного поля зовнішньої ізоляції високовольтних газонаповнених трансформаторів струму / Л. Б.Жорняк, О. І. Афанасьєв, Р. С. Леонов, А. В. Карпук. // Збірник наукових праць національного технічного університету «ХПІ». – 2017. – №34. – С. 14–18.

19. Ураксеев М. А. Оптоволоконные трансформаторы как элементы современных электротехнических комплексов и систем: Электротехнические комплексы и системы / М. А. Ураксеев, Т. М. Левина. – 2013.

20. ДСТУ 3008:2015 Інформація та документація. Звіти у сфері науки і техніки. Структура і правила оформлення. – К.: ДП «УкрНДНЦ», 2016. – 31 с.

21. ГОСТ 56737-2015 Изоляторы высокого напряженя для работы в загрязненных условиях, выбор и определение размеров: часть 3. – М.: Стандартинформ, 2016. – 18 с.

22. Стандарт организации ОАО «ФСК ЕЭС» Инструкция по выбору изоляции электроустановок переменного тока классов напряжения 6-750 кв. – М.: СТО56947007-29.240.068 – 2011. – 21 с.

23. Методичні вказівки до підготовки і захисту магістерських робіт для студентів усіх форм навчання другого (магістерського) рівня вищої освіти спеціальності 141 – Електроенергетика, електротехніка та електромеханіка (освітня програма «Електричні та електронні апарати»)/ Укл.: П.Д. Андрієнко, О.В. Близняков. – Запоріжжя: НУ «Запорізька політехніка», 2021. – 17 с.

24. Методичні рекомендації щодо виконання економічного розділу дипломного проекту здобувачами вищої освіти технічних спеціальностей за освітнім ступенем «магістр» спеціальності 141 «Електроенергетика, електротехніка та електромеханіка» освітніх програм: «Електричні машини та апарати», «Електромеханічне обладнання енергоємних виробництв» /Автор: Р. Г. Бобровнікова, –Запоріжжя: ЗНТУ, 2020. – 12 с.

25. Методичні вказівки до розрахунково-графічного завдання з дисципліни: "Основи теорії електричних апаратів" для студентів спеціальності 141 – Електроенергетика, електротехніка та електромеханіка усіх форм навчання / уклад.: О. В. Близняков, Л. С. Скрупська – Запоріжжя : ЗНТУ, 2017. – 14 с.

26. Методичні вказівки до виконання розділу «Охорона праці та безпека у надзвичайних ситуаціях» в магістерських дипломних роботах зі спеціальності 141 - «Електроенергетика, електротехніка та електромеханіка» з спеціалізації – «Енергетичний менеджмент»/ Укл.: М. О. Журавель, С. М. Журавель – Запоріжжя: ЗНТУ, 2018 – 32 стор.

27. Методичні вказівки до курсової та самостійної робіт з дис-ципліни «Електричні апарати» для студентів денної форми навчання спеціальності 6.092204 – «Електромеханічне обладнання енергоємних виробництв» / Укл. О.Г. Стаценко – Запоріжжя: ЗНТУ, 2010. – 42с.

28. АББ Измерительные трансформаторы — Справочник покупателя. [Електронний ресурс] // 4.1. – 2006. – Режим доступу до ресурсу: https:// library.e.abb.com/public/96196f045e55d 13ec1257cfc0024470b/Buyers%20Guide%20 Outdoor%20Instrument%20Transformers%20Ed%204.1%20Ru%20(IEC).pdf.

29. Актуальные проблемы энергетики и пути их решения [Електронний ресурс] // 5 (23). – 2008. – Режим доступу до ресурсу: https://market.elec. ru/nomer/22/aktualnye-problemy-energetiki-i-puti-ih-resheniya/

30. Вся правда об оптических трансформаторах: часть 1: Цифровая подстанция [Електронний ресурс]. – 2020. – Режим доступу до ресурсу: http://digitalsubstation.com/blog/2017/ 08/23/vsyapravda-ob-opticheskih-transformatorah-chast-1/

31 Достоинства и недостатки различных типов изоляторов для ЛЭП [Електронний ресурс] // Энергетика оборудование, документация – Режим доступу до ресурсу: https://forca.ru/stati/vl/dostoinstva-i-nedostatki-razlichnyh-tipov-izolyatorov-dlya-lep.html.

32. Изоляторы всех типов [Електронний ресурс] // Производственно – торговая компания ООО «ПТК «Энергомаш». – 2020. – Режим доступу до ресурсу: http://www.em.dn.ua/iz/steklo/izs_shtur. htm..

33. Изоляторы для ВЛ [Електронний ресурс] // Производственная компания «Астнон-электротехника». – 2016. – Режим доступу до ресурсу: http://www.aston-e.ru/products/izolator/.

34. Изоляторы из стекла, фарфора, полимера: преимущества и недостатки [Електронний ресурс] // Росэнерго ресурс. – 2020. – Режим доступу до ресурсу: https://rernsk.ru/articles/izolyatori-iz-stekla-farfora-polimera-preimyshestva-i-nedostatki.

35. Изолятор полимерный [Електронний ресурс] // Форэнерго производственное объединение. – 2016. – Режим доступу до ресурсу: https://www.uik.ru/productions/179/izolyatorpolimer/.

36. Конструкция фарфоровых и стеклянных изоляторов – конструктивные элементы изоляторов [Електронний ресурс] // Энергетика оборудование,

документация – Режим доступу до ресурсу: https://forca.ru/spravka/vvody-i-izolyatory/konstrukcii-farforovyh-i-steklyannyh-izolyatorov-2.html.

37. Назначение и классификация трансформаторов тока [Електронний ресурс] // Электрические сети. – 2020. – Режим доступу до ресурсу: https://leg.co.ua/info/podstancii/naznachenie-i-klassifikaciya-transformatorov-toka.html.

38. Ограничение перенапряжений [Електронний ресурс] // Электрические сети. – 2020. – Режим доступу до ресурсу: https://leg.co.ua/knigi/oborudovanie/ogranichenieperenapryazheniy.html.

39. Описание конструкции трансформаторов тока 110-150 кВ [Електронний ресурс] // Система электротехническая компания. – 2019. – Режим доступу до ресурсу:http://eks.com.ua/opisanie-konstrukczii-transformatorov-toka-110-150-kv.html

40. Производство и продажа изоляторов фарфоровых [Електронний ресурс] // Форэнерго производственное объединение. – 2016. – Режим доступу до ресурсу: https://www.uik.ru/productions/179/farforizol/.

41. Фарфор, полимер, стекло – кто победит [Електронний ресурс] // Энергетика и промышленость. – 2006. – Режим доступу до ресурсу: https://www.eprussia.ru/epr/75/5217.htm.

42. GLASS INSULATORS FOR 10–1150 kV OVERHEAD LINES AND SUBSTATIONS. // Global insulator group. – 2021. – С. 20.

43. GE Grid Solutions [Електронний ресурс] // COSI-CT Optical Current transformer. – 2016. – Режим доступу до ресурсу: grid-ga-l3-cosi_ct-0907-2016_07-en.pdf

44. INMR Enriching Technical Knowledge of T&D Professionals [Електронний ресурс] // Engineering Porcelain Post Insulators to Assist Digitalization at Substations. – 2021. – Режим доступу до ресурсу: https://www.inmr.com/engineering-porcelain-post-insulators-to-assist-digitalization-at-substations/

45. Buric M. Optical Fiber Sensor Technology Development and Field Validation for Distribution Transformer and Other Grid Asset Health Monitoring / M. Buric, P. Lu. // final. – 2020. – №4. – С. 68.

46. PORCELAIN INSULATORS FOR 0.22–110 kV OVERHEAD LINES AND SUBSTATIONS // Global insulator group. – 2020. – С. 32.

47. HIGH-VOLTAGE COMPOSITE INSULATORS GIG POLYMER // Global insulator group. – 2020. – С. 52.

48. RHM International [Електронний ресурс] // Go Paperless: A real High Voltage reliable Dry type insulation. – 2020. – Режим доступу до ресурсу: https://rhmintl.com/technology/

49. Проценко Р. О. Методичні вказівки "Основи проектування високовольтної ізоляції" / Р. О. Проценко, О. С. Ільєнко. // Київ "Політехніка". – 2002. – С. 56.

50. Определение ветровой нагрузки и изгибающего момента. Проверка прочности корпуса колонного аппарата. [Електронний ресурс]. – 2021. – Режим доступу до ресурсу: https://studfile.net/preview/2180918/page:8/.

51. ГОСТ 1516.1-76 ЭЛЕКТРООБОРУДОВАНИЕ ПЕРЕМЕННОГО ТОКА НА НАПРЯЖЕНИЯ ОТ 3 ДО 500 кВ Требования к электрической прочности изоляции. // Издательство стандартов. – 1978. – С. 94.

52. Digital Substation Evolution through Optical Transformer Revolution [Електронний ресурс] // Think Grid. – 2019. – Режим доступу до ресурсу: https://www.think-grid.org/digital-substation-evolution-through-optical-transformer-revolution

53. Fiber Optics: Understanding the Basics [Електронний ресурс] // Photonics marketplace. – 2021. – Режим доступу до ресурсу: https://www.photonics.com/Articles/Fiber_Optics_Undrstanding_the_Basics/a25151.

54. ГОСТ 12.0.003-74 Система стандартов безопасности труда. Опасные и вредные производственные факторы. Классификация. // 1974. – С. 20.

55. ГОСТ Р МЭК 60044-8-2010 ТРАНСФОРМАТОРЫ ИЗМЕРИТЕЛЬНЫЕ. Часть 8. Электронные трансформаторы тока. – 2010. – С. 8.

56. Правила улаштування електроустановок (ПУЕ). – 2006. – С. 617.

57. ГОСТ 12.4.026-76 «Сигнальные цвета и знаки безопасности». – 1976. – С. 27.

58. ГОСТ 12.1.009-76 «Система стандартов безопасности труда. Электробезопасность. Термины и определения». – 1976. – С. 35.

59. ГОСТ 12.2.007.0-75 (2001) «Система стандартов безопасности труда. Электротехническая продукция. Общие требования безопасности». – 2001. – С. 12.

60. ГОСТ 14693-90 (2003) «Распределительные устройства и аппаратура управления закрытые в металлическом корпусе на напряжение до 10 кВ. Основные Характеристики". – 2003. – С. 14.

61. ГН 3.3.5-8.6.6.1-2002. «Гігієнічна класифікація праці за показниками шкідливості та небезпечності факторів виробничого середовища, важкості та напруженості трудового процесу» - 2002. – С. 55.

62. ГСП 173-96 «Государственные санитарные правила планирования и застройки населенных пунктов». – 1996. – С.24

63. ДСН 3.3.6.042-99 «Государственные санитарные нормы микроклимата производственных помещений». – 1999. – С. 12

64. ГОСТ 12.1.005-88 «Система стандартов безопасности труда. ОБЩИЕ САНИТАРНО-ГИГИЕНИЧЕСКИЕ ТРЕБОВАНИЯ К ВОЗДУХУ РАБОЧЕЙ ЗОНЫ». – 1988. – С. 95

65. ГН В.2.5-28: 2018 «Инженерное оборудование зданий и сооружений. Естественное и искусственное освещение». – 2018. – С. 157

66. ДСН 3.3.6.037-99 «Санитарные нормы производственного шума, ультразвука и инфразвука». – 1999. – С. 34

67. ГОСТ 12.1.003-2014 «Система стандартов безопасности труда. ШУМ. Общие требования безопасности». – 2014. – С. 27

68. ДСН 3.3.6.039-99 «Державні санітарні норми виробничої загальної та локальної вібрації». – 1999. – С. 39.

69. ГОСТ 12.1.012-2004 «Система стандартов безопасности труда. ВИБРАЦИОННАЯ БЕЗОПАСНОСТЬ. Общие требования». – 2004. – С. 20.

70. ДСНіП 3.3.6-096-2002 «Державні санітарні норми при роботі з джерелами електромагнітних полів». – 2002. – С. 36.

71. ГОСТ 12.1.006-84 «Система стандартов безопасности труда. Электромагнитные поля радиочастот. Допустимые уровни на рабочих местах и требования к проведению контроля». – 1984. – С. 170.

72. СНіП 2.09.04-87 «Адміністративно-побутові будівлі». – 1987. – С. 20.

73. НАПБ А.01.001-2004 «Правила пожежної безпеки України».– 2004.– С. 86

74. НАПБ В.03.002-2007 «Стандарти визначення категорій приміщень, будівель і зовнішніх установок з вибухо- та пожежної безпеки». – 2007. – С. 27.

75. ДБН В.1.1-7-2002 «Защита от пожара. Пожарная безопасность объектов строительства». – 2002. – С. 36.

76. СНіП 2.09.02-85* «Промислові будівлі». – 1985. – С. 115.

77. НПАОП 40.1-1.32-01 «Правила будови електроустановок. Електрообладнання спеціальних установок». – 2001. – С. 89.

78. НПАОП 40.1-1.01-97 «Правила безопасной эксплуатации электроустановок». – 1998. – С. 75

79. ДСТУ 3335-96 (ГОСТ 12.2.007.4-96) «Система стандартов безопасности труда. Шкафы негерметизированных комплектных распределительных устройств и комплектных трансформаторных подстанций. Требования безопасности». – 1996. – С. 112.

80. СНиП 2.04.02-84*. Водоснабжение Наружные сети и сооружения — М: ФГУП ЦПП, 2006. — 128 с

81. С Н и П 2 .0 4 .0 1 -85* . Внутренний водопровод и канализация зданий. –

М: ФГУП ЦПП, 2006 — 60 с.

82. Метод ускоренного уменьшения остаточной стоимости [Електронний ресурс]. – 2021. – Режим доступу до ресурсу: https://www.buhoblik.org.ua/uchet/uchet-osnovnyx-sredstv/1072-metod-uskorennogo-umensheniya-ostatochnoj-stoimosti.html

83. ГОСТ 1.0-92 «Межгосударственная система стандартизации. Основные положения». – 2014. – С. 27.

APPENDIX A

Table A.1 – Results of the scoping calculation of the busduct cross-section

Conductor - Case		Case - Ambience		Result	
Designation	Result	Designation	Result	Designation	Result
L_{cond}	0.085	L_{case}	0.489	$R_{th.\Sigma}$	0.374
Gr	2777212.5	Gr1	291511919.4	q	1217
ε_k	7.264	Nu	64.747	m	11.3
λ_{eq}	0.206	K_{tk}	3.747		
$R_{th.air.conv}$	1.355	$R_{th.amb.conv}$	0.174		
F_1	267.04	$P_{rad.1}$	7.65		
F_2	1536	$R_{th.amb.rad}$	2.614		
P_{rad}	180	$R_{th.amb}$	0.163		
$R_{th.air.rad}$	0.25				
$R_{th.air}$	0.211				

Table A.2 – Results of the precised calculations for busdact

Conductor - Case		Case - Ambience	
Iteration	Result, $\theta_{case,}$ °C	Iteration	Result, $\theta_{cond,}$ °C
1	66.86	1	88.46
2	65.153	2	82.2
3	65.53	3	78.75
		4	76.53
		5	74.95
		6	73.76
		7	72.84
		8	72.087

Table A.3 – Result of the short-circuit calculations

Thermal calculation		Electrodynamic forces	
Designation	Result	Designation	Result
$A(\theta_н)$	$1.55 \cdot 10^{16}$	H, A/m	666.2
Sr_0, mm^2	4418	B, T	$8 \cdot 10^{-3}$
Sr, mm^2	5675	F, N	320
$A(\theta_{sc})$	$2.06 \cdot 10^{16}$		
θ_{sc}, ^oC	135		

APPENDIX B

Table B.1 – Results of the external insulation calculation for «A» cathegory

Designation	Value	Unit of measure
U_{rated}	110	kV
$U_{calc.dry}$	308	
$U_{calc.rain}$	236.5	
U_{calc}	506	
k_v	1.09	
$l_{leakage.path}$	190	cm
$h_{act.fr}$	139.9	cm
$U_{calc.fr}$	513.4	kV
$U_{d.rain}$	336.88	kV
$h_{d.rain}$	149.57	cm
n_r	11	
l_r	29	cm
U_d	207.7	kV
α_p	19	degree

Table B.2 – Results of the external insulation calculation for «Б» cathegory

Designation	Value	Unit of measure
U_{rated}	110	kV
$U_{calc.dry}$	308	
$U_{calc.rain}$	236.5	
U_{calc}	506	
k_v	1.09	
$l_{leakage.path}$	280	cm
$h_{act.fr}$	139.9	cm
$U_{calc.fr}$	513.4	kV
$U_{d.rain}$	336.88	kV
$h_{d.rain}$	149.57	cm
n_r	17	
l_r	23.9	cm
U_d	226.3	kV
α_p	16	degree
U_{ph}	63.5	kV
P_w	3.3	N

Table B.3 – Results of the external insulation calculation for «B» cathegory

Designation	Value	Unit of measure
U_{rated}	110	kV
$U_{calc.dry}$	308	
$U_{calc.rain}$	236.5	
U_{calc}	506	
k_v	1.09	
$l_{leakage.path}$	390	cm
$h_{act.fr}$	139.9	cm
$U_{calc.fr}$	513.4	kV
$U_{d.rain}$	336.88	kV
$h_{d.rain}$	149.57	cm
n_r	34	
l_r	4	cm
U_d	323.8	kV
α_p	2.7	degree