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ABSTRACT

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OPTIC FIBER, TRANSFORMERS, CURRENT, INSULATOR, SENSORS, FARADAY'S EFFECT.

Object design is Fiber Optic 35 kV Current Transformer.

Purpose is to design the external insulation and primary current carrying contour for 35 kV Fiber optic Current Transformer.

Research method are analytical and numerical techniques for calculation of insulation and current-carrying contour proposed by G.N. Alexandrov, V.V. Afanasiev, A.G. Nikitenko [6, 7, 14].

The result of this work is external insulation transformer calculation and primary current carrying contour with specified parameters, within acceptable limits of deviation and development of transformer design. External insulation transformer calculation contains the following sections: electric calculation of the insulator, design of the rib's configuration of the transformer. Busbar calculation contains the following sections: scoping calculation of the conductor cross-sectional area, precise calculation of the current carrying contour temperatures, thermal analysis under the short-circuit mode and electrodynamic analysis under the short-circuit mode.

Based on all materials and conclusions of this diploma project the scientific thesis "Analysis of external insulation of optic- fiber 35 kV current transformer" for Збірник наукових праць національного університету «Запорізька політехніка» №95, 2020, was published [2].

Based on all calculations and theory information of this diploma project the scientific thesis "Analysis of External Insulation of Optic- Fiber 35 kV Current Transformer" Easy chair preprint #3396, May 14, 2020, has been published [1].

CONTENT

Abstract.....	4
Introduction.....	7
1 View of measuring current transformers design	10
1.1 Purpose of current transformers.....	10
1.2 Current Transformer Classification.....	11
1.3 Main parameters and operational characteristics of CT.....	11
1.4 Advantages and disadvantages of conventional CT.....	14
1.5 Current requirements for CT. Comparative analysis of conventional and fiber optic current transformers.....	17
2 Fiber optic current transformer	20
2.1 Principle of operation.....	21
2.2 Opto–electronic measurement methods.....	23
2.3 Comparative analysis of optoelectronic and analogue methods of high voltage currents measurement.....	25
2.4 Design features.....	25
2.5 Insulation design.....	28
3 Review of external insulation calculation methods	30
3.1 Insulators overview.....	30
3.1.1 Porcelain insulators.....	34
3.1.2 Polymer Insulators.....	36
3.2 Contamination Flashover Comparison.....	39
3.3 Factors that influence the electric field distribution along the height of polymer Insulator.....	40
3.4 Calculation practice in the US.....	41
3.4.1 Deterministic Method.....	43
3.4.2 Probabilistic (Statistical) Method.....	44
3.5 Application of insulation coordination according to IEC 71–2 Insulation Coordination.....	45

3.5.1 Insulation Coordination for Power–Frequency and Temporary Overvoltages.....	48
3.5.2 Insulation Coordination for Slow–Front Overvoltages.....	49
3.5.3 Insulation Coordination for Fast–Front Overvoltages.....	49
4 Optic fiber current transformer main nodes calculation.....	50
4.1 Thermal behavior analysis.....	50
4.1.1 Scoping calculation.....	51
4.1.2 Precise thermal design.....	56
4.1.3 Determination of the conductor temperature under the SC mode.....	58
4.1.4 Determination of the electrodynamic forces under the SC mode.....	59
4.2 Calculation of the external insulator.....	60
4.2.1 Determination of the testing voltages.....	61
4.2.2 Electrical calculation of the insulator.....	62
4.2.3 Insulator configuration.....	63
5 Occupational safety.....	66
5.1 Occupational safety measures.....	68
5.2 Fire safety measures.....	72
6 Cost and price of products.....	74
6.1 Product characteristics of innovation project. Market assessment.....	74
6.2 Cost and product price.....	75
6.3 Operational expenses.....	82
6.4 Economic efficiency of innovation project.....	84
Conclusion.....	88
References.....	89
Appendix A.....	93
Appendix B.....	94

INTRODUCTION

Current transformers (CT) are designed for reducing alternating current to controlled level in proportion to the corresponding original values. They provide galvanic isolation of measuring devices, counters, relays, etc. from the high-voltage (HV) circuit. Principle of their operation is based on the electromagnetic induction law.

Digital (microprocessor) systems of relay protection, automation, automatic control, measurement and dispatching systems are modern trends in the world power industry, along with the existing traditional systems of relay protection, emergency control, measurement and metering at power plants and substations. And this situation leads to an increase in the load on CT and, as a result, to a deterioration in the accuracy class of CT.

Grechukhin V.N. [13] analyzed the economic conditions for the functioning of power energy enterprises and energy systems in his work "Electronic current and voltage transformers". According to this work, it is necessary to increase the accuracy of electricity monitoring signals. Digital metering systems can achieve it, but, the insufficient accuracy class of conventional CTs is a barrier on this path.

World leading companies' designers strive to develop CTs of a higher accuracy class (better than accuracy class 0,2S and 0,2) with greater load capacity. Meeting these requirements will inevitably lead to an increase in weight and size indicators (larger amount of electrotechnical steel, copper and other high-cost materials), which is undesirable under the conditions of current economy situation. The identified problems have led to more intensive use of insulation, and according to international regulations, this question remains open and relevant.

At the modern stage of the HV technology development conventional transformers have reached the limit of their capabilities and can hardly meet new requirements and tendencies, such as digitalization, safeness, and compactness.

Search for an alternative technical solution measuring current and voltage of high voltage electric power plants started a long time ago both in our country and abroad.

These researches have become more relevant considering the intensive process of introducing microprocessors into control systems, measurement, relay protection, emergency control at substations.

Fiber optic Current Transformer (FOCT) is following-generation transformers. In our country many transformers are approaching deadline of service life. Implementation of modern technologies makes senseless replacing the old current transformers (CT) with the similar new ones, as they can be hardly paired with digital communication methods.

Among the requirements for high-voltage current and voltage transformers, the main ones can be singled out:

- electrical safety of personnel and secondary circuits of all systems on the control panel of the station or substation, i.e. ensuring high-voltage isolation between the primary and secondary circuits of CT and VT;

- accuracy of measurement of primary current and voltage.

These requirements determine the construction features of the CT and VT.

The economic conditions for the functioning of energy enterprises require improving the accuracy of electricity metering.

The magnetic system of traditional transformers results in such flaws, as phenomena of saturation, hysteresis, resonance, residual magnetization, as well as large weight and dimensions. To surpass these drawbacks the FOCT was developed.

To the main advantages of this transformers Urakseev M.A. and Levina T.M. in their work “Fiber optic components transformers as modern electrical and complex systems” [24] include the following:

- fast installation process;
- small size and weight;
- multifunction: metering & protection in one device;
- self monitoring;
- high precision control and metering of electricity;
- transmission without distortion of all information in short circuit modes, including aperiodic SC current component;
- digital communications;

- FOCTs have analog and digital outputs, and, therefore, compatible with existing secondary circuits as well as with advanced information systems;

- spark, explosion proof;
- versatility in production;
- lower operating costs;
- economic viability.

Research of FOCT is ongoing in order to accomplish the following tasks:

- improve accuracy;
- improve temperature and time stability;
- suppress the vibration sensitivity;
- ensure the transformation of the aperiodic component of the short-circuit current;
- create more cost-effective technology of the current sensor.

1 VIEW OF MEASURING CURRENT TRANSFORMERS DESIGN

This chapter gives the classification, basic parameters, advantages and disadvantages of traditional current transformers, substantiation of relevance and prospects of the development of fiber optic current transformers (FOCT).

1.1 Purpose of current transformers

Current transformer (CT) is a measuring device used to convert current. The primary winding of CT is sequentially switched on the circuit. The secondary circuit is closed to some load (measuring instruments and relays), ensuring the passage of current through it proportional to the current in the primary winding.

High-voltage (HV) measuring CT is the main measuring device in the electric power industry. 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 HV current devices on low voltage ones for availability, direct observation by personnel, and reduce of measurement of any primary current.

Instrument CT differs from power transformer by the following features:

- the measuring CT works in conditions close to a short circuit, since the resistance in the secondary circuit is very small. This is rated mode, while for power transformers short circuit operation mode is an emergency;

- induction in the measuring CT is not constant. It is determined by the measured current and operating mode of the transformer. But power transformer induction is constant;

- the current in the secondary circuit of the measuring current transformer within a certain range does not depend on the load resistance and mainly changes in accordance with the change in the primary current. In a power CT, the primary current varies depending on the load of the secondary winding.

1.2 Current Transformer Classification

All current transformers – both for measurements and for protection – can be classified according to the following main criteria:

- by rated voltage;
- by type of installation. Transformers that are working in the open air (placement category 1 according to ГOCT 15150–69) and that are working in enclosed spaces and built-in;
- according to the installation method. Passing CTs, that are intended for use as an input and installed in the openings of walls, ceilings, mechanical structures, supporting CTs, built-in CTs, etc.;
- by the number of transformation ratios. There are single-stage and cascade (multi-stage) types;
- by primary windings (single-turn, multi-turn);
- by type of insulation between the primary and secondary windings of CTs. They are made with solid (porcelain, cast insulation, pressed insulation, polymer, etc.), viscous (casting compounds), combined (paper-oil, condenser type) or gaseous insulation (air, SF₆);
- according to the principle of CT current conversion (electromagnetic and optoelectronic).

1.3 Main parameters and operational characteristics of CT

In accordance with ГOCT 7746–2015 "Current transformers. General specifications" the main parameters and operational characteristics of CTs are:

- rated voltage is the effective value of the linear voltage at which the CT is intended to operate, indicated in the CT rating sheet;
- rated primary current I_r (indicated in the passport) passing through the primary winding at which continuous operation of the CT is provided;

– rated secondary current $2I_r$ (indicated in the CT rating sheet) passing in the secondary winding. The rated secondary current is taken equal to 1 A (with a rated primary current of up to 4000 A) or 5 A;

– rated secondary load of CT Z_{2l} corresponding to the total resistance of its external secondary circuit, expressed in Ohms, with an indication of the power factor $\cos(\varphi)=0.8$. The established accuracy class of CTs or the maximum ratio of the primary current is relative to its rated value and called the rated secondary CT load Z_{2lr} , it is expressed in volt–amperes (VA). The value of the rated secondary load Z_{2lr} is determined by the formula:

$$Z_{2lr} = S_{r2} / I_{r2}^2,$$

where S_{r2} is the rated value of the secondary load, VA;

I_{r2} is the rated value of the secondary current, A.

– the CT transformation ratio, that is equal to the ratio of the primary current to the secondary current;

– accuracy class;

– rated frequency;

– resistance of CTs to mechanical and thermal influences is characterized by current of electrodynamic resistance and current of thermal resistance. Electrodynamic resistance current is equal to the largest amplitude of the short–circuit current for the entire time of its flow, which the CT can withstand without damage, preventing it from further proper operation. The electrodynamic resistance can also be characterized by the ratio of the electrodynamic resistance current to the amplitude of the rated primary current. The requirement of electrodynamic resistance extends to busbar, built–in and split CTs.

The thermal resistance current I_t is equal to the largest effective value of the short–circuit current for a period of time t_D , which the CT can withstand during this period of

time without heating current-carrying parts to temperatures exceeding those allowable for a short-circuit current, and without damage that impedes its further operation.

Thermal resistance characterizes the ability of a CT to withstand the thermal effects of a short-circuit current. To judge 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 number of heat released, which is proportional to the product of the square of the current I_t and its transit time t_T . This time, in turn, depends on the parameters of the network in which the CT is installed, and varies from one to several seconds. In accordance with ГОСТ 7746–2015, the following thermal resistance currents are installed for domestic CTs:

- one second I_1 for current transformers with a rated voltage of 330 kV and higher;
- three second I_3 for rated current transformers voltage 110; 150 and 220 kV;
- four second current I_4 for current transformers for rated voltages up to and including 35 kV.

There must be the following ratio between currents of electrodynamic and thermal resistance:

- for current transformers with a rated voltage of 330 kV and higher

$$I_D \geq 1.8 \cdot \sqrt{2 \cdot I_1}.$$

- for current transformers with rated voltage of 110 kV, 150 kV and 220 kV

$$I_D \geq 1.8 \cdot \sqrt{2 \cdot I_3}.$$

- for current transformers for rated voltage up to 35 kV

$$I_D \geq 1.8 \cdot \sqrt{2 \cdot I_4}.$$

- temperature of the current-carrying parts of the CT with the passage of current thermal resistance should not exceed 200 ° C for live parts made of aluminum and 250°C for live parts of copper and its alloys, accompanied by organic insulation or oil;
- mechanical loads determined by wind pressure at a speed 40 m/s on the surface of the CT and the tension of the supply wires, which must be at least 500 N for current transformers up to 35 kV inclusive, 1000 N for current transformers from 110 kV up to 220 kV and 1500 N for current transformers 330 kV and higher.

1.4 Advantages and disadvantages of conventional CT

Electromagnetic high voltage current transformers have the following advantages:

- 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 from 6 kV up to 35 kV;
- the temperature stability of the characteristics of the CT.

And their disadvantages are:

- the saturation of the magnetic circuit of the electromagnetic CT aperiodic component of the short circuit current (short circuit) and the lack of transmission of information about the primary current in the first periods of the emergency transient, when this information is mostly needed for relay protection and automation systems for successful localization and liquidation of an accident (errors in the transformation of current by electromagnetic CTs reach 90% in this mode);
- problems with HV insulation, as indicated by unfavorable accident statistics of from 110 kV up to 750 kV current transformers at power plants and substations of the world in recent years;
- the explosion and fire hazard of current transformers of existing structures are fundamentally unavoidable, not only in oil-filled current transformers. In SF₆ CTs, an explosion is also inevitable when a breakdown of the main insulation occurs.

Due to the importance of the first drawback of electromagnetic CTs, it will be dealt in more detail. Short circuit current as an emergency mode can be in one of the phases of

the line periodic and contain an aperiodic component, as shown in Figure 1.1, in at least one of the other two phases, according to ABB information [36].

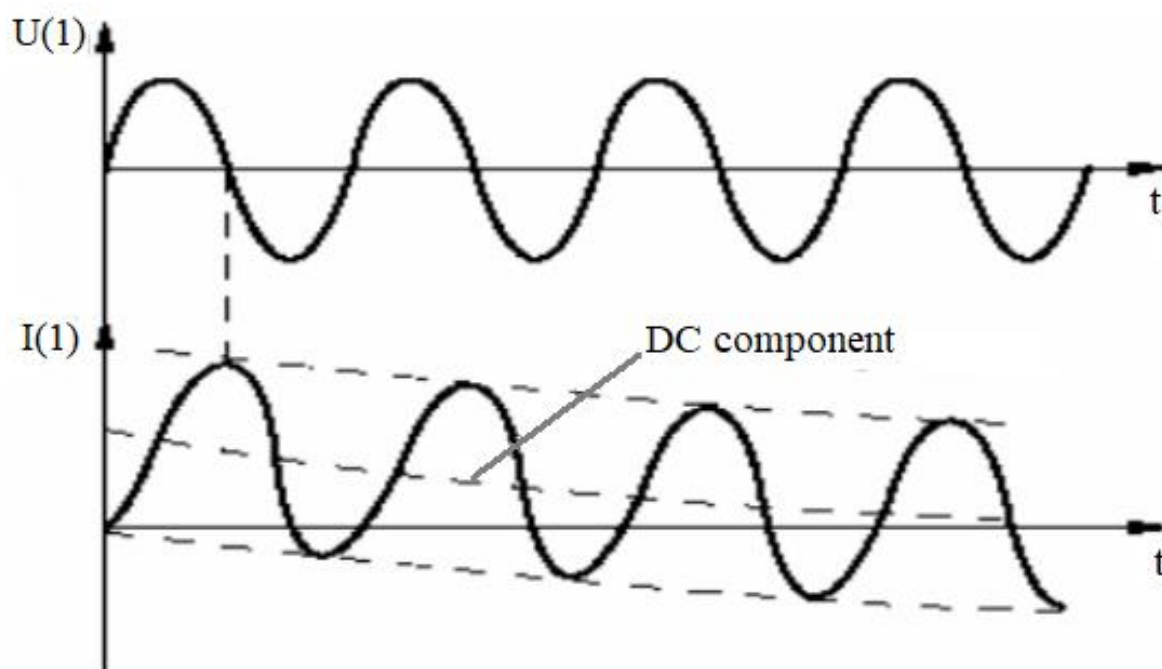


Figure 1.1 – Oscillogram of the primary short circuit current with a periodic and aperiodic component decaying exponentially [36]

The aperiodic component decays exponentially with a time constant determined by the power of the power system and the reactance to the accident site. This component can be approximately interpreted as direct current, taking into account the power and time constant of the power system. A change in flux linkage in the magnetic core of the current transformer in the presence of an aperiodic component in the primary short circuit current, as represented in Figure 1.2 [36]. Inevitably leads to saturation of the CT magnetic circuit.

And saturation of the magnetic circuit leads, in turn, to an asymmetric distortion of the shape of the curve of the secondary current of the current transformer, while with a periodic primary short-circuit current, the distortions of the secondary current are symmetric, as shown in Figure 1.3 [36].

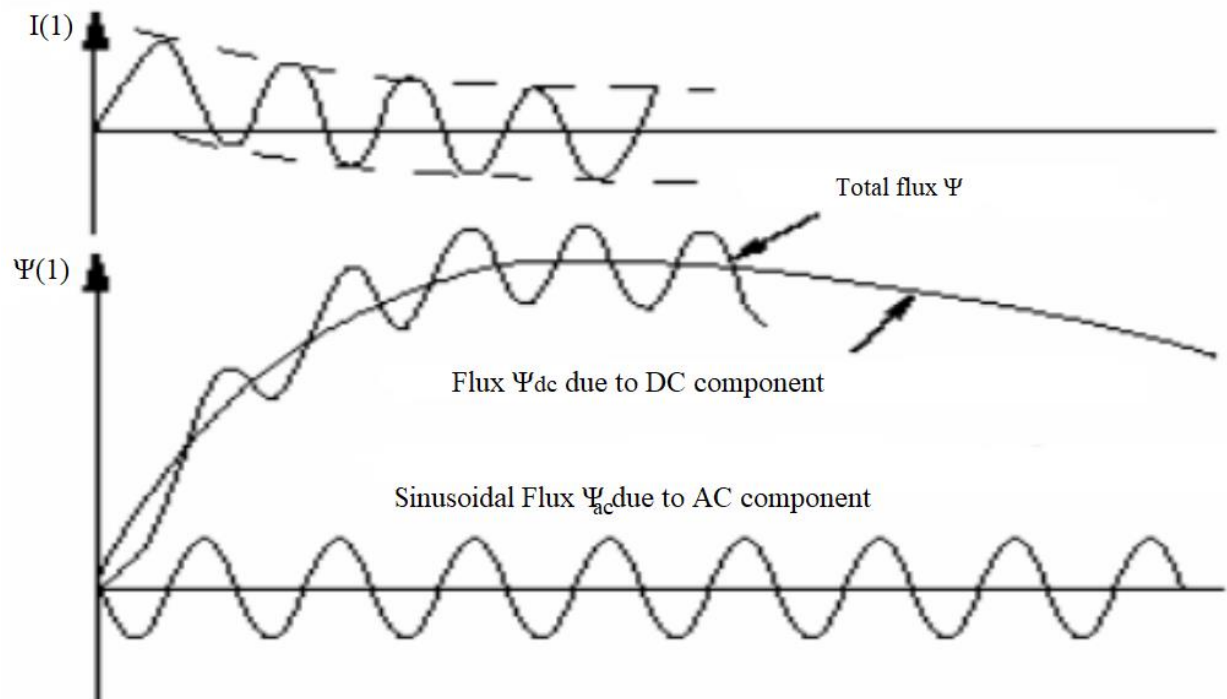
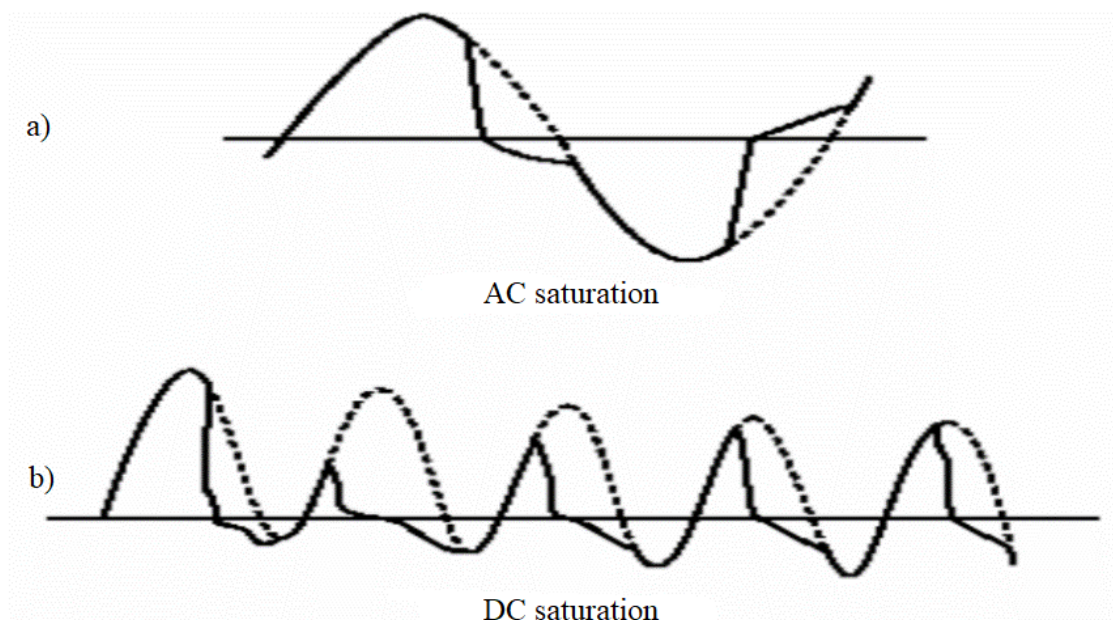


Figure 1.2 – Oscillogram of flux linkage in the transformer magnetic circuit current during the flow of the primary short circuit current with an aperiodic component that decays exponentially [36]



a – with a periodic short circuit current;

b – if there is an aperiodic component of the short-circuit current in the primary current.

Figure 1.3 – Oscillograms of the secondary current of the transformer current [36]

The asymmetric distortion of the shape of the CT secondary current curve under the action of an aperiodic component in the primary short-circuit (SC) current has three important consequences:

- information, about the primary current, actually ceases to flow through the secondary circuits to the relay protection and automation systems 10 milliseconds after the start of the accident, and not only the aperiodic component of the short-circuit current is strongly distorted, but also periodic, about 90% in the second period (after from 5 up to 10 periods the transformation of the primary current is restored);

- information about the primary processes is virtually absent or severely distorted. Protection systems (both microprocessor and old) either do not work, work falsely, or they simply drag out the process until information appears under these conditions. Although according to the rules of the relay protection and automation system the place of the accident should be determined in one or two periods to issue commands to the appropriate HV circuit breakers. Which are localize and eliminate the accident in the initial stage;

- delaying the liquidation of an accident is fraught with the loss of synchronism of large electric motors and generators in factories and power plants, which turns a simple accident into a systemic one. Since the saturation of the CT magnetic circuit with the aperiodic component of the short-circuit current follows from the physical principle of the transformer (direct current does not transform), this defect cannot be corrected.

1.5 Current requirements for CT. Comparative analysis of conventional and fiber optic current transformers

Grechukhin V.N. [13] analyzed in his work “Electronic current and voltage transformers” the conditions for the functioning of power energy enterprises and energy system. According to this work, the trends in the electric power industry in the world are such that, along with the existing traditional systems of relay protection, emergency automation, measurement and metering at stations and substations, digital (microprocessor) relay protection and automation systems, emergency automatic control,

and an automated system of commercial electricity metering are being introduced and dispatched. This leads to an increase in the load on current transformers and, as a result, to a deterioration in the accuracy class of current transformers used in the world energy sector.

The economic conditions for the functioning of energy enterprises and energy systems are such that it is necessary to increase the accuracy of electricity metering, and digital (microprocessor) systems allow this to be done, however, the CT accuracy class that is not high is a drag on this path.

Known shortcomings of CTs led to intensive research work with the goal of creating explosion-proof, high-voltage, with the best metrological characteristics of primary current information sensors for use at power switchgear stations and substations.

In the descriptions of new types of current transformers, the rationale for choosing the opto-electronic method as the main one for measuring high voltage current is given:

– electromagnetic current transformers can be rejected in the event that at the output of the Fiber Optic CT (FOCT), sufficient power is received to control the protection devices. In conventional CTs, the output power is consumed directly from the high-voltage network and can be quite large (100 VA or more in rated 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 increase of these parameters, and the device becomes uneconomical. In FOCT, information from a high potential to the earth will be transmitted by a low power level, and the output power of this device is provided with an autonomous source located on the potential of the earth [37]. Therefore, the output power of the FOCT does not affect its efficiency. The solution of the issue of the output power of the magnetron transistor becomes possible after the development of powerful semiconductor triads that makes it possible to create appropriate amplifiers. On the other hand, the power consumption of modern distance protection is gradually reduced due to the use of electronic devices, which allow matching protection requirements with the capabilities of a new type of current transformers;

– in CT, when switching to ultra-high voltages, 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 iron loss cause measurement errors that vary with the magnitude of the measured current and secondary load. The opto-electronic measurement system does not have these drawbacks and, with large multiples of the measured current, can provide high accuracy of measurement;

– 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, information by a light beam can be transmitted at practically any distance; FOCT are insensitive to voltage and currents of adjacent lines. In developing practical devices, the task is to select an insulating gap between the primary and secondary sides of the device, which has the necessary margin of electrical strength;

– CTs do not allow large current overloads. Some FOCT schemes, for example, based on the Faraday effect, allow almost any current overload due to the cyclical effect;

– FOCT provides signal transmission in a wide frequency range. The above comparison of the properties of CT and OETT indicates the prospects of the latter in the transition to measurements of ultrahigh voltage current. The physical basis of Opto-Electronic measurement methods is the conversion of the measured (input) electrical signal into a light signal and a light signal into an output electric one. Specific conversion schemes differ from each other primarily by the way the measured parameter affects the properties of the light beam (modulation method).

So, FOCTs undoubtedly surpass their predecessors in many ways. In our country, a large number of traditional measuring CTs have exceeded their life span (25 years) and their replacement is inevitable. With the growth of newly introduced digital equipment, the sense of replacing the old CT with a similar new one is lost.

2 FIBER OPTIC CURRENT TRANSFORMER VIEW

On the modern stage of the HV technology development conventional transformers have reached the limit of their capabilities and can hardly meet new requirements and tendencies, such as digitalization, safeness, and compactness.

Search for an alternative technical solution measuring current and voltage of high voltage electric power plants started a long time ago both in our country and abroad.

These researches have become more relevant considering the intensive process of introducing microprocessors into control systems, measurement, relay protection, emergency control at substations.

Fiber optic Current Transformer (FOCT) is following-generation transformers[13]. In our country many transformers are approaching deadline of service life. Implementation of the modern technologies makes senseless replacing the old current transformers (CT) with the similar new ones, as they can be hardly paired with digital communication methods.

Implementation of FOCT to the electric power industry mainly depends on success in the development of automation system, relay protection, and measuring instruments of analog and digital computing with low power consumption from their output circuits. Thus, quite a lot of attention is paid to this direction [13].

Nowadays, FOCT are gaining more popularity today. World-leading countries are rapidly replacing analog transformers with FOCT. And it is well-known that a fiber optic current transformer is characterized by very high stability in an increased frequency bandwidth, as well as a wide dynamic range and perfect transient processes characteristics.

The most famous companies, that produce or develop FOCT's are: Canadian NXT-Phase, Russian Profotech and Mars-Energo, Spainian Arteche, Shanghai Condis and so on.

2.1 Principle of operation

According to Silva M., Martins H., Nascimento I., Baptista J. M. “Review Optical Current Sensors for High Power Systems” [18], the work of the FOCT is based on a non-contact optical method for measuring electric current. The method uses the magneto-optical Faraday effect in a quartz fiber. Qualitatively, the principle of FOCT operation is illustrated at Figure 2.1.

Michael Faraday discovered this magneto-optical effect in 1845. Physical essence of this effect was the following – due to the presence of the external magnetic field, a circularly polarized light had a difference in glass refractive index for left-handed and right-handed polarization. This effect found its application in fiber optic current sensors.

The polarization vector of the light beam, passing through a medium with intensive magnetic field, changes its value, according to the equation 2.1, which was researched by Pedrotti F.L. and Bandettini P. in “Faraday rotation in the undergraduate advanced laboratory” [23].

$$\varphi = V \oint B \, dl, \quad (2.1)$$

where V is the material Verdet constant;

B is the magnetic flux density vector,

dl is the differential vector along the direction of propagation.

The Verdet constant has positive values for diamagnetic materials and negative values for paramagnetic materials. The magnetic field B produced by the current of a metallic wire is

$$B = \frac{\mu_0 * i}{2\pi R}, \quad (2.2)$$

where R is the distance from the wire axis;

i is the electric current;

μ_0 is the permeability of free space.

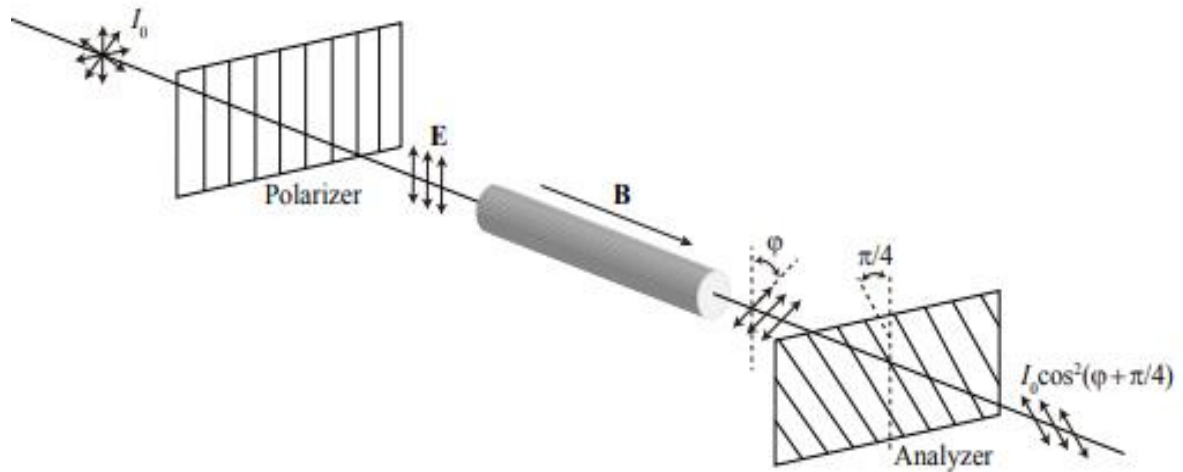


Figure 2.1 – Faraday effect

Two light waves with orthogonal circular polarizations are introduced into the multi-turn circuit from a special optic fiber and a current conductor is located inside the circuit. If there is no current in the conductor, light waves propagate along the fiber circuit with the same phase velocity and come to the output of the circuit with a zero relative phase difference.

If there is an electric current in the conductor, the light guide is in the longitudinal magnetic field of the flowing current. In this case, the optical properties of the fiber change, and the speed of propagation of light waves along the contour becomes different. Accordingly, a time delay and a relative phase shift arise between the waves at the exit from the circuit.

The light fluxes are converted by the optoelectronics into two alternating current voltages with a frequency by the formula 2.3

$$\omega = 2\pi C / \lambda, \quad (2.3)$$

where C is the speed of light in an optical fiber;

λ is the wavelength of optical radiation.

The received electrical signals are fed to the input of an analog–digital converter of the electronic unit, which converts the angle Δj into a digit with further processing in a Digital signal processor (DSP).

The digital unit is equipped with high–level (5A) and low–level (1A) analog interfaces and an additional digital interface, that supports the IEC 61850 standard, which has paved the way for the creation of a fully digital protection and measurement system.

2.2. Opto–electronic measurement methods

All known Opto–electronic (OE) methods are divided into two types [16], based on the methods of internal radiation modulation and on the methods of external radiation modulation:

- by internal modulation is meant the effect of the measured parameter on radiation in the light source itself;

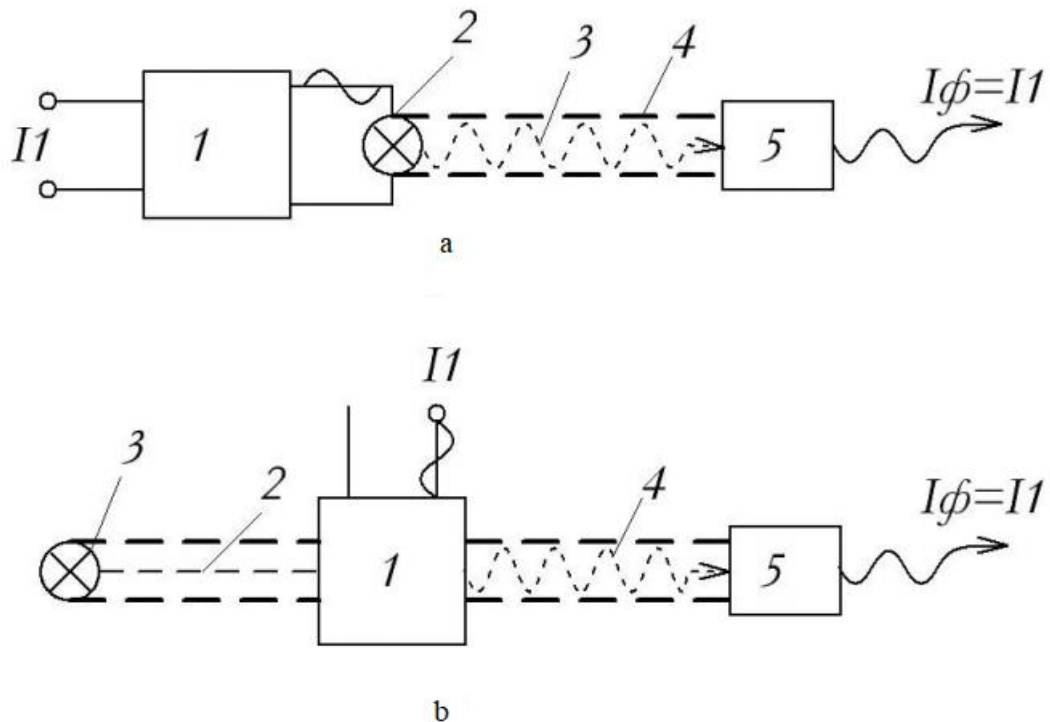
- by external – the effect of the measured parameter on radiation of constant intensity outside the source itself.

Based on this classification, all OE measuring systems are constructed according to the two main functional schemes shown in Figure 2.2.

On scheme, in Figure 2.2 – a internal modulation of the radiation intensity is used, in which the measured parameter (current) through the primary transducer 1 (current sensor) acts on the light source 2, causing corresponding changes in the radiation intensity. The radiation 3 thus modulated is transmitted via an optical communication channel 4 to a photosensitive device 5, which converts the light signals into electrical signals. After appropriate amplification the electrical signals are fed to the input of the measuring device or automation device.

The scheme, in Figure 2.2 – b, is based on the external modulation. The measured parameter (current), acting on the modulator 1, causes corresponding changes in the intensity of the light flux 2 passing through it from an external light source 3. The

amplitude of the light flux 4, modulated by amplitude, is converted into electrical signals using a photosensitive device 5. A value of the measured parameter in both schemes is the change in the photocurrent at the output of the photodetector.



a – based on the principles of internal modulation of light;

b – based on the principles of external light modulation;

I_1 – measuring current; I_ϕ – photo stream.

Figure 2.2 – Scheme of OE measurement methods

Internal modulation occurs in a result of changes in the nature of light emission. Recently, semiconductor LEDs of coherent and incoherent radiation has been used as a light source.

External modulation of light is achieved by changing the transparency of a special element of the optical system that serves as a light modulator. Controlled transparency light modulators include devices based on the use of the physical connection of the electrical and magnetic properties of certain substances with their optical properties. FOCT measuring systems use modulators based on the Faraday magneto–optical effect.

2.3 Comparative analysis of optoelectronic and analogue methods of high voltage currents measurement

According to the Bazyl, I.M. and Dudarenko, A.D., “The use of optical current transformers” [26] the main advantages of FOCT in comparison with their electromagnetic counterparts are as follows:

- ability to measure alternating (up to 100 kA) and direct or pulsed (up to 600 kA) current wound voltage levels (up to 800 kV);
- optoelectronic low–inertia conversion of light signals with the absence of a hysteresis loop, magnetic saturation and residual magnetization, characteristic of electromagnetic analogs and restraining their dynamic range and measurement accuracy;
- large dynamic range (0.1...200% I_{rated}) and high accuracy (0.1 ... 0.2%) for measurements and protection of current circuits, achieved through the use of polarized light signals and their digital processing. At the same time, the same product, unlike to the conventional electromagnetic analogs, can be used at absolutely different primary rated currents due to electronic retuning of transformation ratios;
- wide bandwidth of signals (up to 10 kHz), allowing a complete analysis of the quality of electricity in terms of harmonics (up to 100 harmonics) and transients (for relay protection).

2.4 Design features

The major components of the FOCT are the following:

- input electric busbar;
- measuring Unit. Optic Current Sensor;
- insulation construction;
- external opto–electronic device.

As the FOCT operation principle is based on the magneto–optical Faraday effect, as represented in Figure 2.3, these transformers are free from a magnetic system and its shortcomings [24].

It follows that the design assumes a simplified execution of external and internal insulation, because the fiber optic cable is made of dielectric material and transformer overall dimensions are much less. And block with opto–electronics can be remote from the operating FOCT to a distance up to 1 km, without signal distortion.

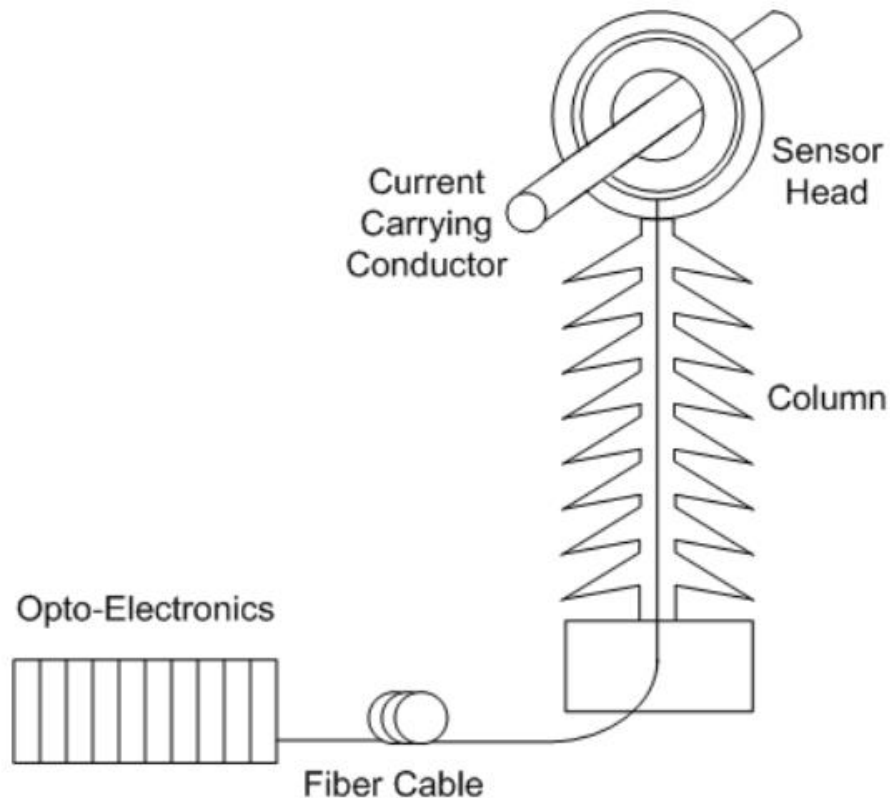


Figure 2.3 – Common view of optical current transformer.

This opto–electronics contains a linearly polarized light source, which is connected through the fiber optic fiber made of fiber optic to the beginning of the polarization–sensitive photodetector, the end of which is connected to the measuring and computing unit. Functional scheme of FOCT is shown on the Figure 2.4.

The minor drawback of this installation is that the opto–electronics requires external low–power energy source (50W) for their operation.

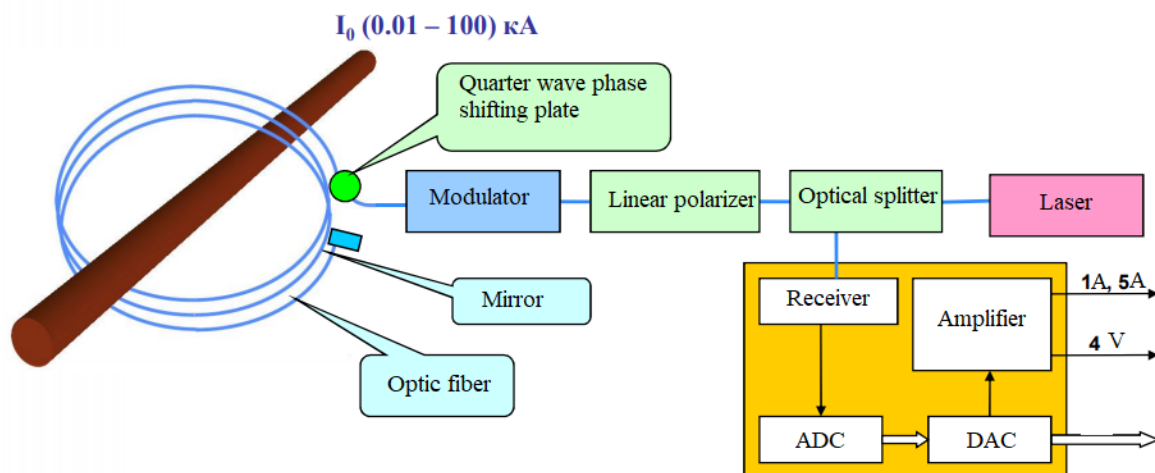
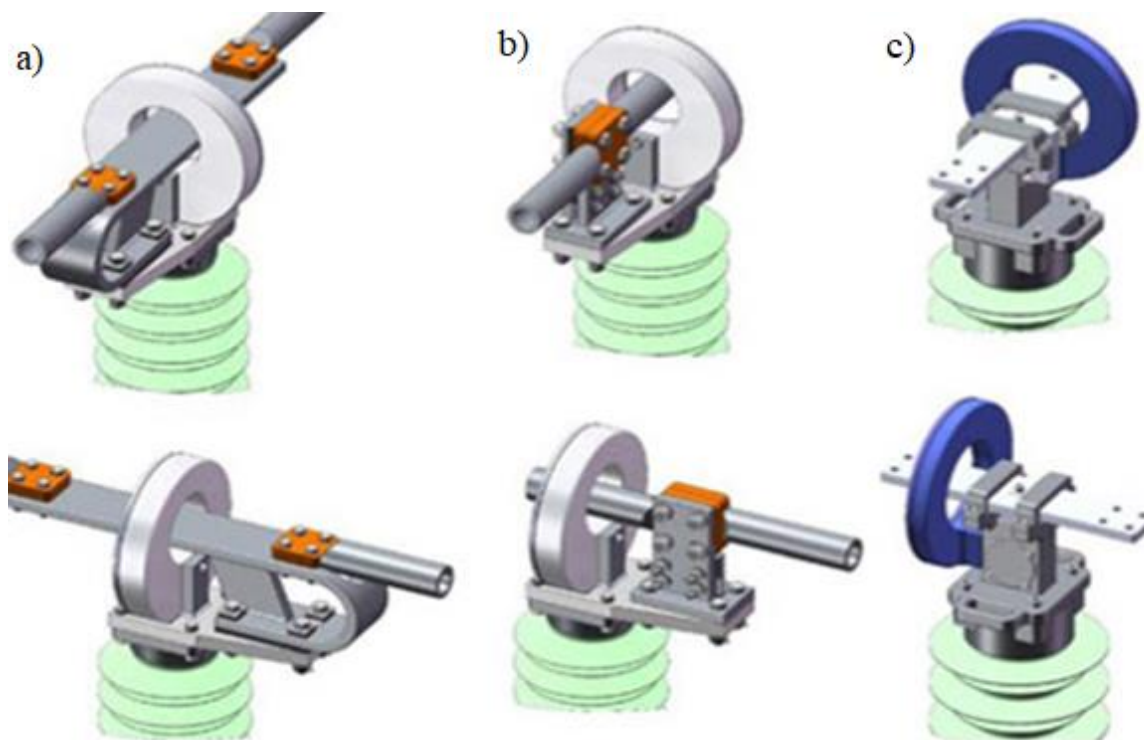


Figure 2.4 – Functional scheme of FOCT

Another advantage of these transformers is that the current measuring element can be made in different modifications, as in [22]. Some examples can be seen in the Figure 2.5.



a – sensor with round to rectangular busbar adapter;

b – round busbar mount sensor;

c – rectangular busbar sensor.

Figure 2.5 – Different types of optical current busbar mounting sensor

There are many analogues of optical current sensors. Abramenkova I. and Korneev I. analyzed the product characteristics of leading manufacturers by sensor's main parameters in their work [22]. The result of their work is represented below in the table 2.1.

Table 2.1 – Comparative characteristics of fiber optic current sensors of various companies

Characteristic	Nxt Phase	Field Metrics	ABB	Airak
Rated current, kA	0,1–100	0,6–20	1–3,5	0,003–30
Rated voltage, kV	69–750	11–36	75–800	3,6–36
Accuracy, %	0,25	0,2	0,2	1
Frequency bandwith, Hz	0,01–6000	5000	10000	5000
Mass, kg	49 –65	5 – 15	50 – 186	0.029– 0.6

2.5 Insulation design

Due to the digitalization, FOCT are becoming more popular today. They are replacing conventional transformers around the world. One of the main requirements for the operation of new generation transformers is reliable operation at voltages reaching many hundreds of kilovolts. Therefore, special attention is paid to external insulation and calculation of dielectric strength [13].

The most commonly used insulators for FOCT are made of polymer, but conventional CT are mostly made of porcelain. Since 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, it is necessary to understand why world-leading companies apply polymer insulation in FOCT design.

Porcelain insulators account for a large proportion of manufactured CT. However, in modern apparatus engineering, polymer insulation is increasingly being used. And this is due to the high level of electrical and mechanical strength (achieved by reinforcing them with fiberglass).

The advantages of polymer insulators include a higher electrical resistance to pollution, compared to similar porcelain insulators with an equal creepage distance, this advantage is even more pronounced due to the use of the hydrophobicity of the material. Another important advantage of polymer insulator is its flexibility, which allows the installation of optical transformers in vertical and inclined positions, and does not affect the accuracy of measurements. The compactness of the transformers allows them to be installed in conditions that are unacceptable for conventional transformers. Insensitivity to external electromagnetic fields does not require analysis of the relative position of the tires; and light weight allows installation without the use of cranes [38].

Giving the polymer insulator a ribbed shape, we are able to reduce the leakage current to the required level over the surface of the shell when it is dirty and moistened. An important component of the polymer insulator is the profile of the ribs, which are important self-cleaning insulator. Depending on the growth of pollution, an insulator with a small protrusion of ribs (the ribs are the same), it is necessary to increase the length (construction height) of the insulator 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 to the problem is the new design of insulators with variable protrusion of ribs.

An insulator with a variable overhang of ribs at the same construction height allows an increased length of the creepage path. In addition, dirt resistance is increased due to the variable protrusion of the ribs.

As a result, FOCT can be represented as an adaptable system for any equipment. Both for old-fashioned analog output for substations with old complementary equipment and digital output for modern digital substations.

3 REVIEW OF EXTERNAL INSULATION CALCULATION METHODS

Continuous 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.

One of the most important objects of the electric networks' equipment is electrical insulators. Their reliability depends on such factors as network uninterrupted operation and supplied electricity quality.

The aim of insulator operation is to prevent flow of electricity from the point with high potential to the earth. So, insulators play a significant role in electrical network system, especially in distribution electrical lines where the conductors are generally supported by the insulators.

Flash over is the main reason of insulator failure. This process happens between the line and earth during the overvoltage in the system. The large amount of heat is produced by arcing, due to the flash over process. All these factors cause cracks in insulator body.

So, the insulation material must have certain specific properties to serve as an effective insulation.

3.1 Insulators overview

The insulation material is the material that is used for insulating purpose and possess some specific properties, which are listed in, the publication "Electrical Insulator. Insulating Material. Porcelain, Glass, Polymer Insulator" [39]:

- material should be mechanically strong to withstand tension and weight of conductors;
- material should possess high dielectric strength to withstand the voltage stresses;
- material should possess high insulation resistance to prevent leakage current to the earth;
- material should be free from unwanted impurities;

- material should not be porous;
- its physical as well as electrical properties should be less effected by changing temperature.

According to the insulation material insulators are divided into porcelain, glass and polymer types. Due to the fact, that glass is unappropriated material for the transformer insulation this material will be ignored. Quick overview of each type of insulator is set out in table 3.1.

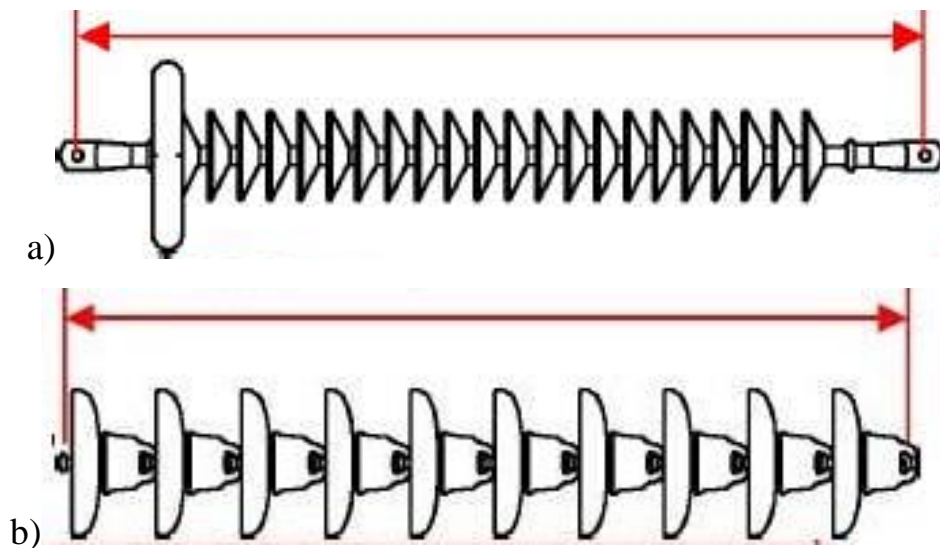
Table 3.1 – Distinctive features of insulators

Insulating material	Porcelain Insulators	Polymer Insulators
Weight	Relatively heavy weight	Low weight
Reliability	Medium reliability	Medium reliability
Mechanical strength	Low impact resistance	High
Resistance to vandalism	Low	High
Hydrophobicity	High with coating material	High

According to the “AC Transmission Line Reference Book – 200 kV and Above” by USA Electric Power Research Institute (ERPI) [35], various parameters have been defined to characterize insulator shape and dimensions. The most often used parameters are:

- section length (also known as connecting length) which refers to the shortest distance between fixing points of the live and grounded (earthed) hard-ware, ignoring the presence of any stress control rings, but including intermediate metal parts along the length of the insulator, as represented in Figure 3.1;

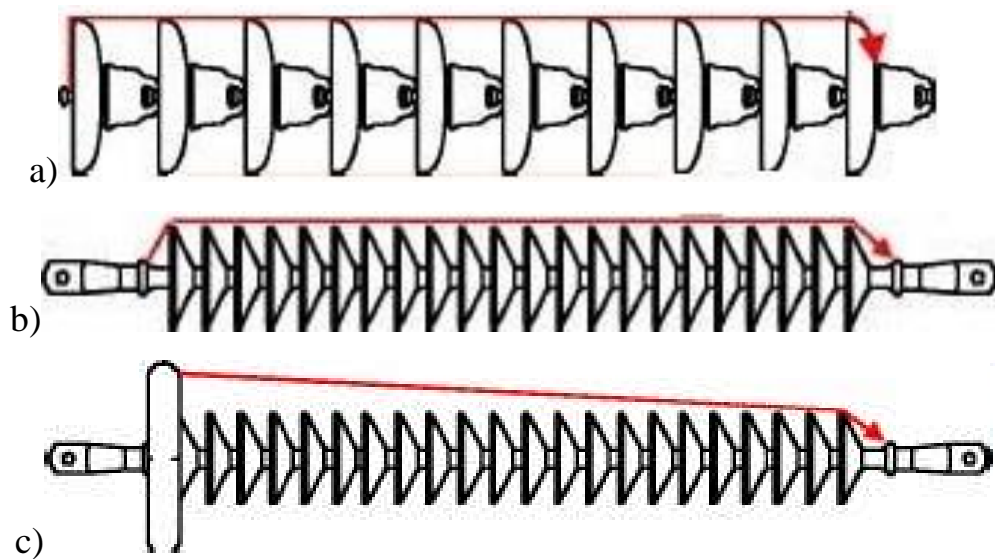
- dry arc distance, – the shortest distance in the air external to the insulator between those parts that normally have the operating voltage between them. The dry arc distance of various types of insulator configurations are illustrated in Figure 3.2;



a – longrod insulator;

b – disc insulator string.

Figure 3.1 – Definition of section length



a – disc insulator string;

b – long rod insulator without corona rings;

c – long rod insulator with corona rings.

Figure 3.2 – Definition of dry arc distance

- strike distance, – the shortest distance from the energized hardware to the grounded hardware or structure. It may correspond to the dry arc distance;
- leakage (or creepage) distance;

– the shortest distance over the insulator surface between the end fittings is the leakage or creepage distance. Since there is a linear relationship between the contamination flashover strength and leakage distance, the concept of specific leakage distance is commonly used. In the first edition of IEC publication 60815 (according to IEC 1986), the specific creepage distance was defined as the leakage distance divided by the phase-to-phase value of the maximum voltage for the equipment. This definition was based on the assumption that the insulation was installed between phase and ground, which is not always the case. To overcome this deficiency, IEC introduced the “unified specific creepage distance” concept, which is the leakage distance divided by the maximum operating voltage across the insulator. For the same pollution class, the unified specific creepage distance is $\sqrt{3}$ times the specific creepage distance. Both are usually expressed in mm/kV;

– protected leakage (or creepage) distance. This parameter is the part of the leakage distance that is not easily accessible to natural cleaning. It is defined as the part of the creepage distance on the illuminated side of the insulator that would lie in shadow if light were projected on to the insulator at 90° (or 45° in special cases) to the longitudinal axis of the insulator;

– form factor. Form gives the relationship between the resistivity of a surface layer and the overall resistance of that same surface. This dimensionless ratio is calculated by the integral of the reciprocal value of the insulator circumference along the length of the leakage path (L), Figure 3.3;

– surface area. It is an area of the insulator over which the measurement is performed. Evaluating the integral of the insulator circumference along the length of the leakage path (L) gives the surface area, as presented in Figure 3.3.

$$L = \int_0^L \frac{dl}{2\pi \cdot r(l)},$$

where l is the leakage length path;

$r(l)$ is the radius of the insulator.

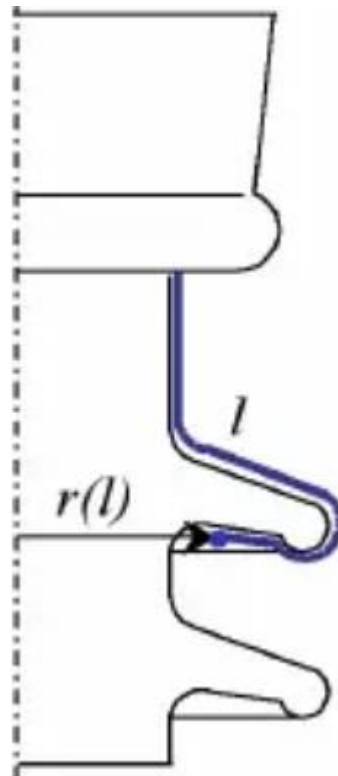


Figure 3.3 – Definition of form factor

3.1.1 Porcelain insulators



Figure 3.4 – Porcelain Insulators

Nowadays, porcelain is the most common material for the insulators. The porcelain is aluminum silicate, which is mixed with plastic kaolin, feldspar and quartz to obtain final hard and glazed porcelain insulator material. Insulator should be glazed, so that

water does not accumulate on the surface of the insulator. Moreover, porcelain has to be free from the porosity, because it is the main reason of its dielectric property's deterioration.

Porcelain insulators have the following advantages, according to the publication "Top 10 advantages of porcelain insulators" [38]:

- porcelain is environment friendly. It may serve as a recycled material for the production of ceramic and similar products, at the end of the service life;

- electrical strength of porcelain is slightly higher than the polymer: 25+ kV/mm versus 20 kV/mm at polymer, which means that the porcelain has better dielectric properties than the polymer;

- the porcelain insulator has much higher durability of the surface, it does not degrade or carbonate during charges;

- porcelain possesses a high thermal resistance. So, the dielectric properties do not depend on the temperature. These insulators are suitable for extremely hot or cold weather conditions;

- porcelain is highly resistant to corrosion in acidic, as well as, caustic environments;

- porcelain has a wide range of application. High plasticity during manufacturing permits a huge variety of shapes to be created and applied;

- porcelain does not suffer in junction with metal. This composition is resistant to transition phenomena during the discharge or brush discharge;

- the ceramic material offers very high mechanical strength under pressure and hardness. The ceramic insulator does not deform unless external force is applied. Long useful life service can be guaranteed up to 40 years. Therefore, many users have provided long-term operational references in a number of applications.

But, along with the advantages of these insulators, there are a number of some important disadvantages:

- dimensional tolerances are difficult to control during processing. It results in higher manufacturing cost because of more accurate technological process;

- they are weak in tension. Hence, the installation, transport and packing processes are risky, expensive and require more labor. Moreover, they are highly fragile and susceptible to shock and vibration. From 10 to 15% breakages are reported during transportation, storage and installation [39];

- they are heavy, approximate weight of 330 kV insulator is about 115 kgs.

- porcelain insulators are susceptible to explosion and breakages, due to high fragile properties, stone throwing, etc.;

- the surface of insulator can be cracked when hit with heavy items, they are more susceptible to vandalism because of poor shock resistance (Table 3.1).

3.1.2 Polymer Insulators

As a possible alternative to the porcelain insulators there is a polymer or so-called composite insulators. After more than 35 years, since the first type of composite insulators was launched, they have undergone many design improvements. They become suitable for high voltage networks, according to the work “Electrical Conductivity in Polymer-Based Composites” by Taherian R. and Kausar A. [4].

There are, at least, two components of composite insulator:

- glass fiber reinforced epoxy resin rod (FRP), providing the mechanical strength, so-called core, which can be observed at Figure 3.5;

- silicone rubber or EPDM (Ethylene Propylene Diene Monomer) made weather ribs, providing the dielectric strength, so-called coating, which can be observed at Figure 3.5.

That is why polymer insulator is called composite, due to composition of two parts – core and ribs. End fittings fix the core from the both sides.

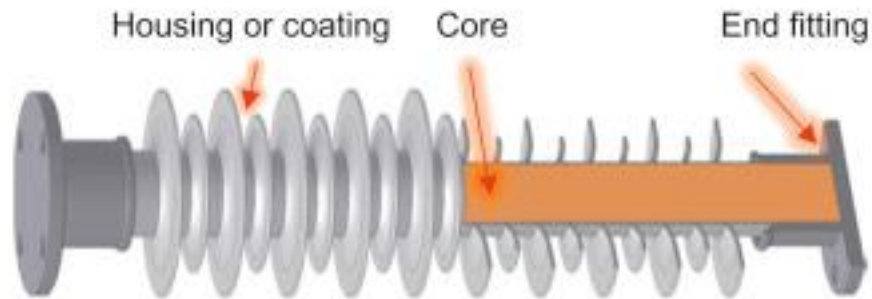


Figure 3.5 – Different components of composite insulators containing of composite core, polymeric housing, and metallic connectors

Overview of polymer insulator major components [39]:

- the shell is the coating material for the rod. The primary function of the shell is to keep water out of the rod and protect it from ultraviolet radiation (UV);
- end fittings have the function of fastening the insulator to the support and transferring mechanical load from the fiberglass rod to the conductor. Fitting is often made of galvanized steel, but sometimes aluminum is used;
- end fitting seal is located at the junction of end fitting at the polymer, due to the necessity of a tight seal to keep water out;
- corona rings are designed to reduce the electrical field stress at the end fittings. Application of that part of construction begins from the 220 kV and above. Corona rings are not interchangeable.

Coating material determines the insulating properties of insulators. Nowadays, silicon rubber is the most commonly used material for polymer insulators. Hydrophobicity, long-term stability against different weather conditions, waterproofing properties, all these factors make the silicon rubber the best material for coating composite insulators. In addition, the hydrophobicity of silicone rubber is always consistent with other polymers [4].

Polymer insulators have the following advantages:

- polymers are much lighter, than porcelain, and possess similar dielectric properties. As a result, – insulator acts on supporting structure with less load, lower cost for installation, transportation and packing;

- due to the polymer materials flexibility the opportunity of its breakage is much less;
- it has pretty high tensile strength, due to crimping technology of insulator manufacture process;
- due to the high plasticity of coating material it is possible to adapt the insulator to specific requirements. As a result, – space saving, lower price and high level of safety are achieved;
- due to hydrophobicity, as shown at Figure 3.6, of coating material insulator possesses self-cleaning property, water doesn't form a continuous film on the surface of insulator, but remains in a form of droplets which leads to a low failure rate in composition with low total maintenance costs;
- much shorter manufacturing time results in higher economical effect;

Polymer insulator disadvantages are the following:

- when water enter in the gap between the core and ribs the insulator electrical failure may occur;
- excessive compression of the end fittings can lead to cracks in the core which leads to mechanical damage to the polymer insulator;
- due to polymer flexibility the mechanical loads require the additional components to be reliable.



Figure 3.6 – High Hydrophobicity of the polymer insulator

3.2 Contamination Flashover Comparison

Flashover is a multi-step process which may be a result of a number of conditions [21]. The basis of this process for porcelain insulators consists of:

- contamination created by the dust of other conductive materials on the insulator surface, including surface wetting;
- ohmic heating. The leakage current flows through the electrolyte, which formed by the water on the insulator surface. So, there is an accumulated energy dissipation heating which forces water evaporation, leading to the increase in drying rate;
- formation of the dry band;
- partial discharges and flashover. When one of the dry band discharges extends across the remaining wet surface of insulator, – flashover occurs.

All these steps should occur sequentially. Then, flashover takes place. But the electrolyte conductive layer is ruined or decreased by rain – flashover probability is reduced.

Karady G., Shah M. and Brown R have analyzed the laboratory data and literature in their work “Flashover Mechanism of Silicone Rubber Insulators Used for Outdoor Insulation” [21] and suggest several additional steps that occur in the flashover process of a hydrophobic polymer insulators:

- the remaining insulator dry surface is slowly wetted by the droplet migration. This process transforms the leakage current from capacitive to resistive, due to high resistance conductive layer formation;
- due to electric field effect, the closely displaced water drops form a so-called filament. Due to formation of these filaments – flashover tends to take a longer time for a hydrophobic surface. Moreover, to form filaments the electrical field has to be higher;
- hydrophobic surface spot discharges. Filaments reduce the distance between the terminals of the case, increasing the electric field between adjacent threads. When the voltage is sufficient, surface discharge activity may occur;

- hydrophobicity reduction. Discharge processes in the water drops areas reduce the hydrophobicity of surface due to the polymer chains breaking. This results in easier formation of continuous water conductive layer;
- formed dry bands increasing the aging rate, due to surface erosion;
- hydrophobicity possible full or partial recovery, if the insulator free from discharges for a certain time. This ability depends on the material, design and service environment;
- UV damage can cause surface crazing which traps and holds contaminants that can promote leakage current flow during wetting.

As for porcelain insulators, the sequence plays a vital role for flashover to occur. This process can be interrupted. Thus, visible activity does not always result in flashover.

As a conclusion, hydrophobic surfaces have higher flashover voltages, than common porcelain insulators. Due to the fact, that such surfaces require higher values of leakage current.

3.3 Factors that influence the electric field distribution along the height of polymer insulator

There are numerous factors that influence the electric field distribution. The most important, according to the publication “Electric field distribution along the surface of high voltage polymer insulators and its changes under service conditions” [20], of these include:

- geometry of insulator, including weather-shed system, fiberglass rod and end fittings. The shape and size of the geometry are different for composite insulators. Depending upon the shape and size, capacitance is different. So, the geometry of insulator makes the electric field nonlinear. And also, electric field is higher at energized end and along the axis of polymeric insulator;
- electrical properties of polymer weather-shed, fiberglass rod material and possibly semi-conductive grading. Electrical properties such as permittivity of the material are different from each other.

- corona rings dimensions and displacement. Electric field would be affected if the corona rings are displaced in a wrong way;
- the geometry of the attachment hardware, conductor bundles, grounded hardware and grounded structure;
- the orientation of the insulator and its physical relationship to the attachment hardware, corona rings, conductor bundle, grounded hardware and line structure;
- line voltage.

Distribution of the electric field on HV insulators in normal conditions is determined by the geometrical factor and the distribution of the capacitance along the insulator surface. There are special methods to equalize the distribution of the electric field along the insulator length, but they only apply on a voltage >220 kV

In terms of design the main point of the FOCT is their low weight and fast installation procedure, etc. Polymer type insulators have the same advantages in comparison with other types. Moreover, some of their drawbacks are overlapping with FOCT design. To improve insulator strength, if it is necessary, fiberglass reinforcement plate can be placed in body of insulator. To reduce hygroscopicity, such insulators are coated externally with waterproof varnishes.

So, all these factors make polymer insulator the best choice for FOCT design.

Internal insulation is not needed, as the fiber cable is dielectric, so the FOCT insulation economical advantage is proved.

3.4 Calculation practice in the US

A typical insulation coordination process is presented in Figure 3.7.

According to the 3rd edition of “EPRI AC Transmission Line Reference Book” [35, 27] two principal methods for coordination are described: deterministic and probabilistic. In the simpler deterministic process, the stress and strength curves of Figure 3.8 would not overlap but would be separated by a safety margin. The more sophisticated probabilistic process provides a more realistic representation of the overlap of the curves in cost-effective designs. This method is used to calculate the risk of line flashover caused

by switching surges. The calculation requires knowledge of the probability of overvoltage amplitudes, the strength of all the insulation elements of the line, and the value of the parameters affecting the strength.

Line insulation coordination includes the selection of phase-to-ground and phase-to-phase clearances, tower strike distances, tower footing resistance, insulator lengths, and the leakage or creepage distance of insulators. Any overvoltage counter measures, such as surge arresters and breaker-closing resistors, must also be selected, if required. The lowest values of the withstand insulation voltages must meet desired line performance criteria when operating in the field.

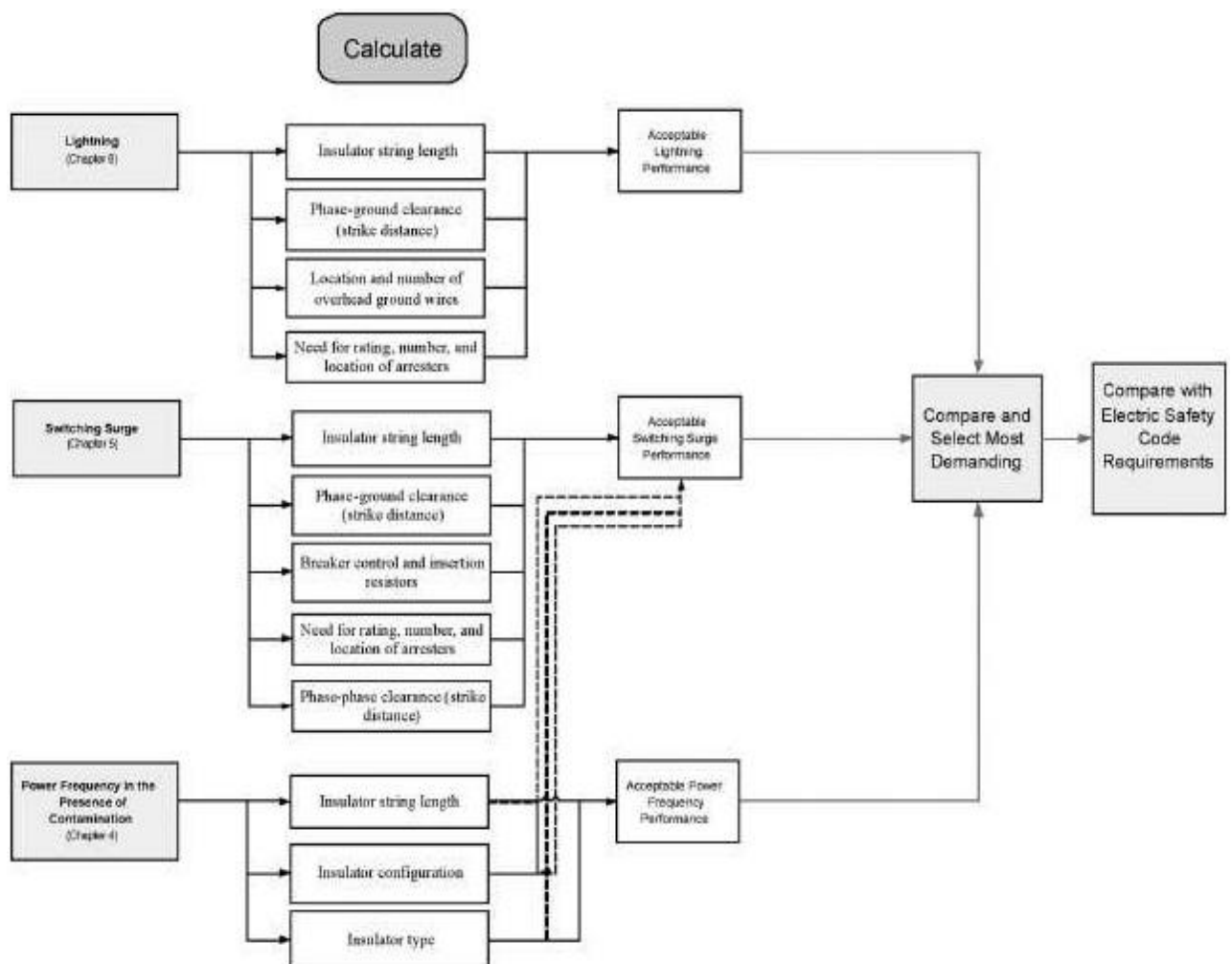


Figure 3.7 – Insulation coordination process

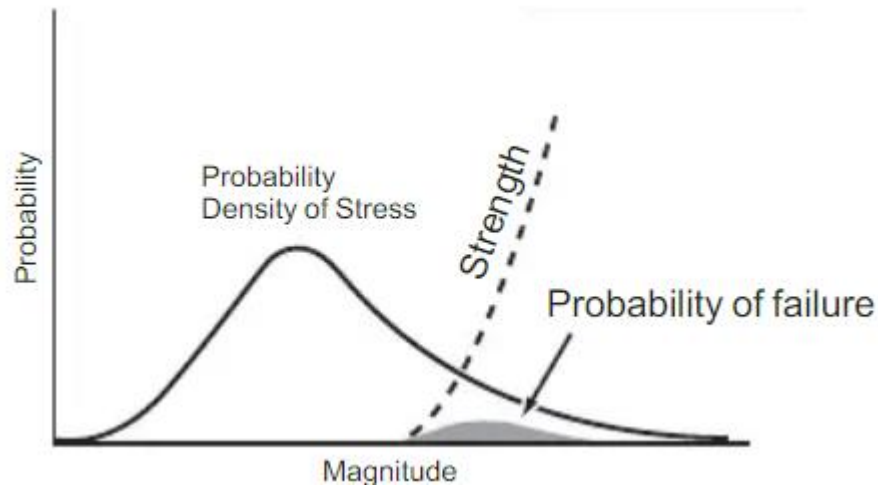


Figure 3.8 – The balance of stress and strength in insulation coordination

Two approaches to insulation coordination for transient overvoltages are in use today in US. There are deterministic method and a probabilistic or statistical method. Many commonly–used procedures, however, are a mixture of both methods. Both are discussed extensively in such literature like IEC 1996 and IEEE 1999a. Obviously, the universal availability of computers and software allows designers to use sophisticated probabilistic techniques as easily as the simpler deterministic methods, providing that appropriate stress and strength data are available. It is also recognized that many utilities simply continue to use old proven designs rather than risk potential savings against problems with new optimized designs, unfamiliarity of workers with new configurations for construction and maintenance, and requirements for new families of spare parts.

The principles are applicable to all three types of voltage stress and insulation strength–namely, lightning, switching surges, and power frequency voltage.

3.4.1 Deterministic Method

The deterministic method assumes that there is a known maximum overvoltage, V_{\max} , which may stress the insulation, a known minimum insulation withstand voltage V_w , and that these occur simultaneously. Insulation is designed so that V_w is larger than V_{\max} by a safety margin, as shown in Figure 3.9, according to EPRI 1982. This safety factor covers only the uncertainties involved in the designer's evaluation of V_{\max} and

V_w . The safety factor should not be confused with the protective ratio, which is used in connection with internal insulation that is protected by an external surge arrester. Transmission lines designed in the past using the deterministic method characteristically have very conservative clearances and strike distances. Designs based on such an approach can be more expensive than those obtained from modern probabilistic methods. Today the deterministic method is usually applied when no statistical information on stress or strength is available, especially for coordination and design of non-self-restoring insulation.

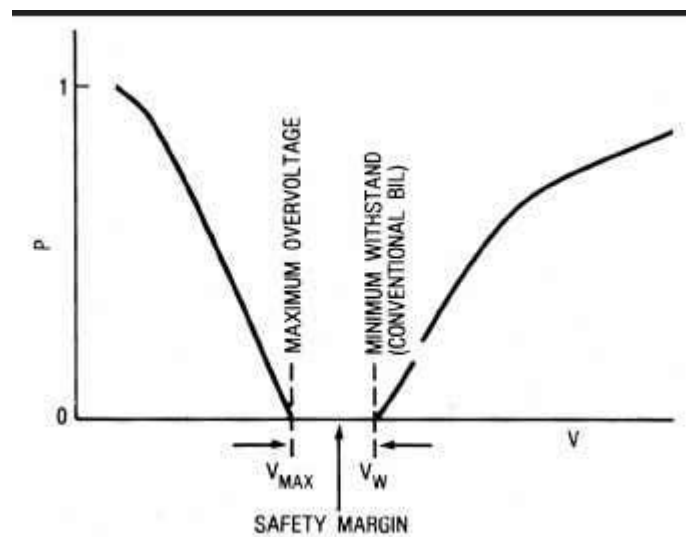


Figure 3.9 – Illustration of deterministic method for insulation design

3.4.2 Probabilistic (Statistical) Method

In actuality, both the stress (overvoltage) and the strength (insulation withstand) exhibit probabilistic behavior. The potential benefit of a probabilistic approach is that the combination of maximum overvoltage and minimum insulation strength rarely occurs. Therefore, considerable economy may be achieved for self-restoring insulation by modeling the probabilistic nature of both the voltage stress and the insulation strength. This approach nearly always results in a substantial decrease in line insulation, tower dimensions, weight, width of right-of-way, and cost. That decreased cost must then be weighed against the increased risk of failure and the costs of such failures. The

probabilistic method is applied by modeling and combining the probability distributions of the overvoltages and the insulation strength.

By repeating the calculations for different types of insulation and for different states of the network, the total outage rate of the system due to the insulation failures can be estimated. The application of probabilistic insulation coordination makes it possible to estimate the failure frequency directly as a function of the selected system design factors. In theory, optimization of the insulation could be possible, if outage costs could be related to the different types of faults. In practice, it is very difficult to evaluate the consequences of insulation faults indifferent operation states of the network and the uncertainty of the cost of the undelivered energy. Hence it is usually better to slightly over-dimension the insulation system rather than optimize it. The design of the insulation system is then based on the comparison of the risks corresponding to the different alternative designs. Virtually, all probabilistic calculation methods embody a nonzero risk of failure. This results from the inability of statistical models to precisely represent insulation strength or insulation stresses. As an example, the typical statistical model for air gap behavior gives a flashover rate that is never zero, even for very small voltages. Designers recognize that in designing for nonzero levels of failure, limitations in modeling techniques result in conservatism in the designs. Even designs with a relatively high 10% failure rate for switching surges have never in practice flashed over.

Yet probabilistic techniques are not used across the board above 200 kV, due to the fact that many utilities continue to use old “proven designs,” which are based on deterministic approaches because sufficient probability distributions are not known or are of dubious accuracy.

3.5 Application of insulation coordination according to IEC 71–2 Insulation coordination

According to IEC 71–2[27], transmission–line insulation coordination follows to a great extent the same procedure used for other equipment, which is described more fully in IEC71–1 (IEC 1993). Line insulation coordination is a simplified version (it stops at

step 3 of 5 steps) of the general procedure (due to the self-restoring characteristics of line insulation). Hence the line insulation coordination follows the following steps:

- determination of the representative overvoltages (U_{rp});
- determination of the coordination withstands voltages (U_{cw});
- determination of the required withstand voltages (U_{rw}).

IEC 71–2 provides the following guidelines for transmission–line insulation coordination:

- the operating voltage and the temporary overvoltages determine the required insulator string length and the shape of the insulator unit for the pollution site severity;
- in directly grounded neutral systems with ground fault factors of 1.3 and below, it is usually sufficient to design the insulators to withstand the highest phase–to–ground system voltage;
- for higher ground–fault factors, and especially in isolated or resonant grounded neutral systems, consideration of the temporary overvoltages may be necessary;
- where consideration must be given to free–swinging insulators, the clearances should be determined under extreme swing conditions;
- an insulation failure due to ground–fault overvoltages causes a double phase–to–ground fault;
- ground–fault overvoltages should be taken into account in systems with high ground–fault factors—i.e. for transmission lines in resonant grounded–neutral systems;
- as a guide, acceptable failure rates between 0.1 and 1.0 flashovers/year are typical;
- special considerations are necessary for lines where energization and re–energization overvoltages are normally controlled to low amplitudes, since in this case the slow–front overvoltage generated by ground faults may be more severe;
- as a guide, suitable acceptable failure rates for energization are on the order of 0.005–0.05 flashovers/year;
- re–energization overvoltages require attention for trans–mission lines when fast three–phase reclosing is applied, because of trapped charges. Acceptable failure rates of 0.005–0.05 flashovers/year may be suitable;

– re-energization overvoltages can be disregarded when single-phase reclosing is used on transmission lines;

– slow-front overvoltages are among the factors determining the air clearances and, for some types of insulators, the insulator fittings. Usually their importance is restricted to transmission lines in the higher system voltage range of 123 kV and above. Where free-swinging insulators are applied, air clearances for slow-front overvoltages are generally determined assuming moderate(mean) swing conditions.

The IEC procedure is outlined in Figure 3.10

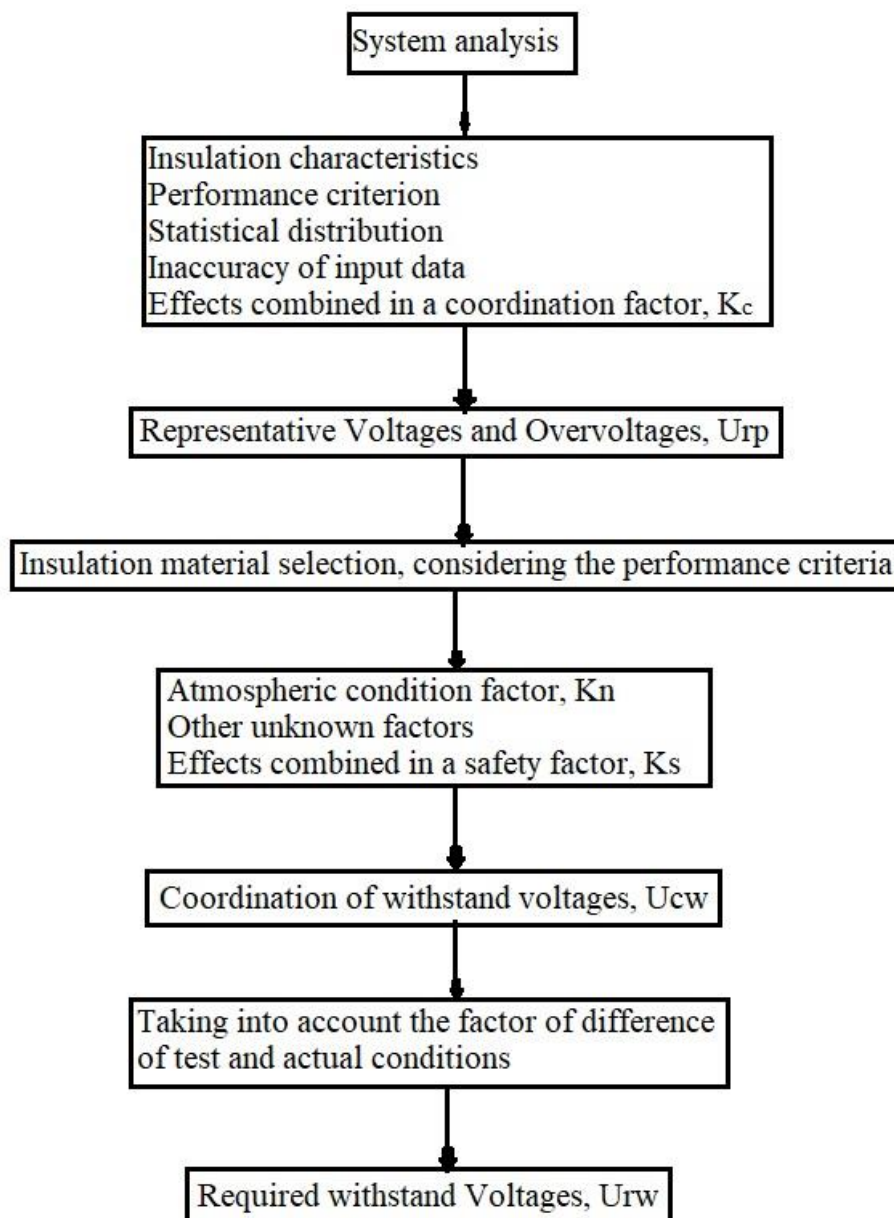


Figure 3.10 – Insulation coordination procedure.

3.5.1 Insulation Coordination for Power–Frequency and Temporary Overvoltages

The coordination withstand voltage for the continuous(power–frequency) voltage is the highest phase–to–phase system voltage, and this voltage divided by the square root of 3 for phase–to–earth insulations. For coordination using the deterministic method, the short–duration withstand voltage is the representative temporary overvoltage. When a statistical procedure is adopted, and the representative temporary overvoltage is given by an amplitude/duration distribution frequency characteristic, the insulation that meets the performance criterion is determined, and the amplitude of the coordination withstand voltage is equal to that corresponding to the duration of 1 min on the amplitude/duration withstand characteristic of the insulation. When contamination is present, the response of external insulation to power–frequency voltages becomes important, and may dictate external insulation design. Flashover of insulation generally occurs when the surface is contaminated and becomes wet.

3.5.2 Insulation Coordination for Slow–Front Overvoltages

There are two methods to determine:

- deterministic method, which involves determining the maximum voltage stressing the equipment and then choosing the minimum dielectric strength of this equipment with a margin that covers the uncertainties inherent in the determination of these values. The coordination withstands volt–age is obtained by multiplying the assumed maximum value of the corresponding representative overvoltage by a safety factor called the deterministic coordination factor;
- statistical method for Slow–Front Overvoltages, which is the same as discussed above. Slow–front overvoltages of interest for overhead lines are phase–ground fault overvoltages and energization and re–energization overvoltages.

3.5.3 Insulation Coordination for Fast-Front Overvoltages

There are two methods to determine:

– deterministic method. For fast-front lightning overvoltages, a deterministic safety factor of 1 is applied to the assumed maximum value of the overvoltages. This is because, for lightning, the representative overvoltage includes probability effects. For fast-front switching overvoltages, the same relationships apply as for slow-front overvoltages;

– statistical method, which is based on the probability distribution of the representative lightning overvoltages. For internal insulation, the assumed withstand voltage has a withstand probability of 100%. The withstand probability at higher voltages is assumed to be zero. This means that the coordination withstand voltage is equal to the representative lightning overvoltage amplitude at a return rate equal to the adopted acceptable failure rate. For external insulation, the conventional deviation of the discharge probability is usually small as compared to the dispersion of overvoltages.

4 OPTIC FIBER 35 kV CURRENT TRANSFORMER MAIN NODES CALCULATION

4.1 Busbar thermal behavior analysis

Thermal aspects are becoming very important due to the fact that they guarantee the correct operation of electric power products. The specified temperature limits should not be exceeded a specific value. Thus, knowledge of temperature behavior is a vital factor in order to predict reliability and performance in its working environment.

Thermal analysis is a very important issue in electrical devices and apparatus design especially for high current ratings. Calculation was made by the method given in the next references [6, 11, 14, 32], with implementation of numerical method.

Heat phenomena in working electrical apparatuses are the condition which defines their current limits. Therefore, using the computational techniques allows engineers to analyze thermal aspect of systems in the early design stage and is a must for modern designers. Such analysis helps in the estimation of the required cooling or alternation of the construction to meet thermal requirements.

In the general case, the task of analyzing the thermal behavior of any element of electrical apparatus is to determine the power of heat sources and calculate its temperature field. Analysis is performed using the similarity theory, which allows to characterize the difficult processes using the dimensionless quantities. The analysis is carried out, in two stages:

- preliminary calculation (scoping calculation), i.e. qualitative analysis of the thermal regime;
- precised thermal design, i.e. refined analysis of thermal conditions

4.1.1 Scoping calculation

On this stage it is necessary to determine the sources of the heat, their heat power, determine the possibility to increase the main component's heat transfer ability, optimize the heat regime.

On the basis of current load, the tubular conductor was chosen, it is presented in the Figure 4.1, with outer diameter 55 mm and inner diameter 49 mm and cross-sectional area 490 mm² according to the ПУЭ.

During the calculation the following assumptions were accepted:

- the busbar 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.

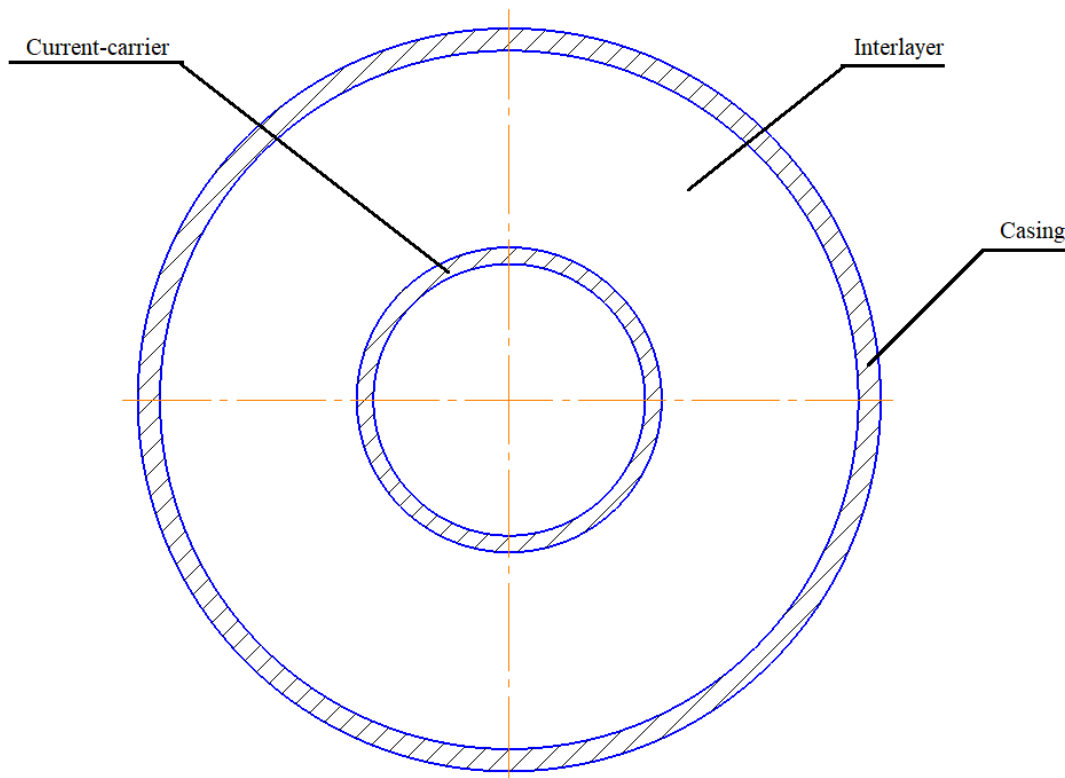


Figure 4.1 – Cross-section of the busbar

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

$$dQ_1 = dQ_2 + dQ_3, \quad (4.1)$$

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.

Heat balance formula in this case is

$$c\gamma q \frac{d\vartheta_{cond}}{dt} + \left(\frac{1}{r_{T\Sigma}} - \frac{I_{rated}^2 \rho_0 K_a \alpha}{q} \right) \vartheta_{cond} = \frac{I^2 \rho_0 K_a}{q} + \frac{\vartheta_{amb}}{R_{Th.\Sigma}}, \quad (4.2)$$

where k_{add} is the coefficient of additional losses;

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

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

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

ρ_0 is the air electrical resistivity at 0 ° C;

α is the thermal diffusivity factor, m^2/s ;

c is the specific heat, $kDj/(kg \cdot K)$;

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

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

From the heat balance formula (formula 4.1), the selected conductor cross-sectional area q was confirmed with calculation by the following way

$$q = \frac{I_{\text{rated}}^2 \cdot \rho_0 \cdot (1 + \alpha \cdot \vartheta_{\text{cond}}) \cdot R_{\text{th},\Sigma}}{\vartheta_{\text{cond}} - \vartheta_{\text{amb}}}, \quad (4.3)$$

First of all, it is necessary to find the total thermal resistance, which is composed from the thermal resistance of air inside the busbar between the conductor and shell and ambient components. Each of them contains convective and radiational parts.

$$R_{\text{th},\Sigma} = R_{\text{th},\text{air}} + R_{\text{th},\text{amb}}, \quad (4.4)$$

where $R_{\text{th},\text{amb}}$ is the thermal resistance of the ambience, K/W;

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

As long as, the air thermal resistance components act parallelly, they should be calculated in the following way

$$R_{\text{th},\text{air}} = \frac{R_{\text{th},\text{air},\text{conv}} \cdot R_{\text{th},\text{air},\text{rad}}}{R_{\text{th},\text{air},\text{conv}} + R_{\text{th},\text{air},\text{rad}}}, \quad (4.5)$$

where $R_{\text{th},\text{air},\text{rad}}$ is the radiational component of air thermal resistance, K/W;

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

$$R_{\text{th},\text{air},\text{rad}} = \frac{\vartheta_{\text{cond}} - \vartheta_{\text{case}}}{P_{\text{rad}}}, \quad (4.6)$$

where ϑ_{cond} is the temperature of the conductor;

ϑ_{case} is the temperature of the case(shell);

P_{rad} is the amount of radiated heat transferred from the conductor to the case, W.

$$P_{\text{rad}} = 5.67 \cdot \frac{\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right]}{\left(\frac{1}{\varepsilon_1}\right) + \left(\frac{F_1}{F_2}\right) \cdot \left(\frac{1}{\varepsilon_2 - 1}\right)}, \quad (4.7)$$

where T_1, T_2 are the absolute temperature of conductor and case, K;

$\varepsilon_1, \varepsilon_2$ are the degree of blackness of conductor and case, accordingly;

F_1, F_2 are the surface coefficient of conductor and case, accordingly, length of round in this case, m.

$$R_{th.air.conv} = \frac{1}{2\pi \cdot \lambda_{eq}} \ln \frac{D}{d}, \quad (4.8)$$

where D, d is the diameter of the case and conductor, m;

λ_{eq} is the equivalent heat transfer factor, $W/(m^2K)$.

$$\lambda_{eq} = \lambda_{air} \cdot \varepsilon_K, \quad (4.9)$$

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

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

In this case the convection factor will be

$$\varepsilon_K = A[GrPr]^{0.3}, \quad (4.10)$$

where A_1 is the coefficient, chosen according to the configuration;

Gr is the Grashof number or criteria of pulling up force;

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

$$Gr = \frac{\beta_{air} \cdot g \cdot L^3 \cdot (\vartheta_{cond} - \vartheta_{case})}{\nu^2}, \quad (4.11)$$

where β_{air} is the air volumetric thermal expansion coefficient, $1/^\circ C$;

ν is the air kinematic viscosity factor, $kg/(m \cdot s)$;

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

Convective ambient thermal resistance is calculated by the nature convective in unlimited space

$$R_{th.amb.conv} = \frac{1}{K_{tk} \cdot \pi \cdot L_{case}}, \quad (4.12)$$

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

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

$$K_{tk} = \lambda_{air} \cdot \frac{Nu}{L_{case}}, \quad (4.13)$$

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

$$Nu = C(Gr_1 \cdot Pr_1)^n, \quad (4.14)$$

where C_{pr} , n are the factors of the dimensionless equation, defined by the result of the multiplying of Gr by Pr.

$$Gr_1 = \frac{\beta_{air} \cdot g \cdot L_{case}^3 \cdot (\vartheta_{case} - \vartheta_{amb})}{\nu_1^2}, \quad (4.15)$$

where ν_1 is the air kinematic viscosity factor under the determining temperature, kg/(m·s).

The radiation thermal resistance component is determined in the following way

$$R_{th.amb.rad} = \frac{\vartheta_{case} - \vartheta_{amb}}{P_{rad.1}}, \quad (4.16)$$

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

$$P_{rad.1} = 5.67 \cdot \left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_0}{100} \right)^4 \right] \cdot \varepsilon_2, \quad (4.17)$$

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

Resulted thermal resistance from the case to the ambient is determined similarly to the previous

$$R_{th.amb} = \frac{R_{th.amb.conv} \cdot R_{th.amb.rad}}{R_{th.amb.conv} + R_{th.amb.rad}}, \quad (4.18)$$

4.1.2 Precised thermal design

When the cross-sectional area is confirmed the preliminary calculation is done and the precised calculation is carried out. The aim of that stage is to determine the temperature of the busbar, with known current load, geometrical dimensions and known ways of cooling.

The losses of the heat in the conductor is calculated according to the formula

$$P = \frac{I_{rated}^2 \cdot \rho_0 \cdot (1 + \alpha \cdot \vartheta_{cond})}{q \cdot 10^{-6}}, \quad (4.19)$$

The easiest, but still very precised way, to determine the temperature of the case is the simple iteration method, carried out by the following way

$$\vartheta_{case} = \vartheta_{amb} + P \cdot r_{th.case.amb}, \quad (4.20)$$

where $r_{th.case.amb}$ is the result thermal resistance to medium through the case.

$$r_{th.case.amb} = \frac{1}{\alpha_t \pi \cdot L_{case}}, \quad (4.21)$$

where α_t is the result factor of heat transfer from the surface of conductor.

$$\alpha_t = \alpha_{conv} + \alpha_{rad}, \quad (4.22)$$

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

$$\alpha_{conv} = \frac{\lambda_{air} \cdot Nu_{conv}}{L_{case}}, \quad (4.23)$$

$$Nu_{conv} = C(Gr_{coef} Pr_{coef})^n, \quad (4.24)$$

$$Gr_{coef} = \frac{\beta_{air} \cdot g \cdot L_{case}^3 \cdot (\vartheta_{case} - \vartheta_{amb})}{\nu_1^2}, \quad (4.25)$$

$$\alpha_{rad} = 5.67 \cdot \frac{\left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_2}{100} \right)^4 \right] \cdot \varepsilon_2}{T_2 - T_0}, \quad (4.26)$$

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

After the obtaining the accurate temperature value of the case it is possible to determine the accurate temperature value of conductor, using the previously defined method by the following way

$$\vartheta_{cond1} = \vartheta_{case} + P \cdot r_{th.case.cond}, \quad (4.27)$$

where $r_{th.case.cond}$ is the result thermal resistance to the case through the interlayer.

$$r_{th.case.cond} = \frac{r_{conv} \cdot r_{rad}}{r_{conv} + r_{rad}}, \quad (4.28)$$

$$r_{conv} = \frac{1}{2\pi \cdot \lambda_{eq}} \cdot \ln \frac{D}{d}, \quad (4.29)$$

$$\lambda_{eq} = \lambda_{air} \cdot \varepsilon_K, \quad (4.30)$$

$$Gr_{coef} = \frac{\beta_{air} \cdot g \cdot L_{cond}^3 \cdot (\vartheta_{cond} - \vartheta_{case})}{\nu^2}, \quad (4.31)$$

$$r_{rad} = \frac{\vartheta_{cond} - \vartheta_{case}}{P_{rad}}, \quad (4.32)$$

$$P_{rad} = 5.67 \cdot \frac{\left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_2}{100} \right)^4 \right]}{\left(\frac{1}{\varepsilon_1} \right) + \left(\frac{F_1}{F_2} \right) \cdot \left(\frac{1}{\varepsilon_2 - 1} \right)}, \quad (4.33)$$

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

4.1.3 Determination of the conductor temperature under the short-circuit mode

Using the adiabatic heating curves of the conducting materials [12] it is possible to determine the temperature under the short-circuit mode.

$$A(\vartheta_{sc}) = A(\vartheta_n) + j_{sc}^2 \cdot t_{sc}, \quad (4.34)$$

where $j_{th.st}$ is the short-circuit current density, $A \cdot m^2$;

$t_{th.st}$ is the short-circuit time, s.

Or we can substitute the current density in this formula and obtain the same

$$A(\theta_{sc}) = A(\theta_H) + \left(\frac{I_{th.st}}{(S_r - S_{r0}) \cdot 10^{-6}} \right) t_{th.st}, \quad (4.35)$$

where $(S_r - S_{r0})$ are the conductor cross-sectional area, m^2 .

4.1.4 Determination of the electrodynamic forces under the short-circuit mode

According to the Ampere's Law

$$F = I_{sc} \cdot l \cdot B_b \cdot \sin \gamma, \quad (4.36)$$

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 ;

$\sin \gamma$ is the angle between the current flow and induction vector.

$$B = \mu_0 \cdot H, \quad (4.37)$$

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

μ_0 is the magnetic permeability, H/m .

$$H = \frac{I_{sc}}{2\pi \cdot l}, \quad (4.38)$$

All calculation results are represented in the appendix A. According to that method, the short-circuit temperature of the conductor will be $175 \text{ }^\circ\text{C}$. The temperature of the conductor of the busbar to the end of the short circuit does not exceed $250 \text{ }^\circ\text{C}$, and the time of reaching this temperature more than 4 seconds.

Electrodynamic forces of the conductors under the short-circuit mode will be 125 N.

On the results of the calculation it can be concluded, that the busbar fully meets the requirements of the ГОСТ434-78.

4.2 Calculation of the external insulator

Aim of the calculation is to define the construction design of the insulator.

The calculation is carried out in the following stages, using the well-known method described by Afanasiev V.V. [7]:

- the calculated withstand stresses of the external insulation in the dry state are assumed to be 10% higher than the corresponding test voltages of 50 Hz;

- the active insulating height of the insulator is determined, equal to its full height minus the axial dimensions of the metal reinforcement. The value of the active insulating height is determined by the accepted values of withstand stresses in the dry state and the characteristics of the air gaps along the surface of the insulator;

- in insulators of an outdoor installation, the number of ribs is performed based on the discharge voltage under the rain. The departure of the ribs is taken equal to half the gap between the ribs;

- for outdoor installation insulators, according to the results of previous calculations, the surface contours of the insulating body are constructed and the length of the overlapping path in the dry state and the length of the creepage path are determined. Comparing the obtained results, the insulator's ability to withstand the test voltage in the rain is established and the specific creepage distance is determined, which is compared with the rated. If necessary, increase the active height or size of the edges;

- according to the conditions of mechanical strength, the outer and inner diameters of the insulating body are determined.

The following initial conditions must be given for the determination of the insulator active height, amount and dimensions of ribs:

- rated voltage;

- rated mechanical stress on the insulator;
- working conditions (type of installation, performance category).

For the outdoor insulators the leakage path should be accepted, according to the ГOCT 9920–89.

4.2.1 Determination of the testing voltages

Based on the rated voltage the following basic parameters were accepted according to the ГOCT 1516.3

$$U_{\text{rated}} = 35,$$

$$U_{\text{short.time.dry}} = 105,$$

$$U_{\text{short.time.rain}} = 85,$$

$$U_{\text{gr.imp}} = 185,$$

where U_{rated} is the rated voltage of current transformer, kV;

$U_{\text{short.time.dry}}$ is the short–time test voltage, kV;

$U_{\text{short.time.rain}}$ is the short–time test voltage under the rain, kV;

$U_{\text{gr.imp}}$ is the voltage of impulse, kV.

The minimal leakage path length was defined from the table 3.10 [7], for the insulation category “B”, the value is $l_{\text{leakage.path}} = 105$ cm.

Calculational breakdown voltage U_{test} related to the insulators, that testing separately. It must more, than U_{test} in 1.1 times.

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

$$U_{\text{test.dry}} = 1.1 \cdot U_{\text{short.time.dry}},$$

$$U_{\text{test.rain}} = 1.1 \cdot U_{\text{short.time.rain}},$$

where $U_{\text{calc.rain}}$, $U_{\text{calc.dry}}$ are the test breakdown voltage under bad, normal weather conditions, and impulse accordingly, kV.

4.2.2 Electrical calculation of the insulator

For the determination of the active height, amount and dimensions of the insulator ribs and the insulator wall thickness the electrical calculation is carried out. Active height of this type of insulator is determined by the testing voltage of external insulation under the rain according to the following formula

$$U_{\text{test.rain}} = k_{\text{save}} \cdot k_v \cdot U_{\text{calc.rain}}$$

where k_{save} is the safety factor;

k_{height} is the installation height factor, which is defined by the following way:

$$k_v = \frac{1}{1.1 - 10^{-4} \cdot H_{\text{inst}}}$$

where h_{inst} is the installation height.

Active height of the insulator of external type is determined by the method, according to the chapter 3.8 of Afanasiev V.V. ‘Справочник по Электрическим Аппаратам Высокого напряжения’, its value is calculated for each case and the largest of the obtained values is selected for the further calculations.

$$\begin{aligned} h_{\text{act.r}} &= 115 - \sqrt{13325 - 50 \cdot U_{\text{calc}}}, \\ U_{\text{calc.r}} &= 264.5 - 0.02 \cdot (115 - h_{\text{act.r}})^2, \\ h_{\text{act2}} &= 338.2 - \sqrt{111663 - 143 \cdot U_{\text{calc}}}, \\ U_{\text{calc2}} &= 788.5 - 0.007 \cdot (338.2 - h_{\text{act2}})^2, \end{aligned}$$

$$h_{\text{act}3} = 1716.4 - \sqrt{312 \cdot 10^4 - 1226 \cdot U_{\text{calc}}},$$

$$U_{\text{calc.}3} = 2544.87 - 0.000815(1716.4 - h_{\text{act}3})^2.$$

So now, the discharge voltage under the rain can be calculated, according to the following formula

$$U_{\text{d.r}} = 2.25 \cdot h_{\text{act}2} + 22,$$

$$h_{\text{act.rain.out}} = 0.444 \cdot U_{\text{d.r}}.$$

4.2.3 Insulator configuration

Configuration and amount of ribs of the insulator is defined after the determination of the insulator active height. Amount of ribs on insulator providing necessary leakage path is

$$n_r = \frac{l_{\text{leakage.path}} - h_{\text{act}}}{l_{\text{ut}} - l_2},$$

where $l_{\text{leakage.path}}$ 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 should be calculated by the following formula

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

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

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

where h_r is the rib out length, mm;

α_p is the shortest distance between the ribs, cm;

t is the distance between the ribs, cm.

According to the ГОСТ 9920–89 the ratio between the pitch and reach of the ribs h_r/α_p must be equal or greater than 0.8. For simple rib profiles, this value can be reduced to 0.65 and relationship between creepage distance of one rib and air gap should not be greater, than 4.5. As shown in Figure 4.2 and Figure 4.3.

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

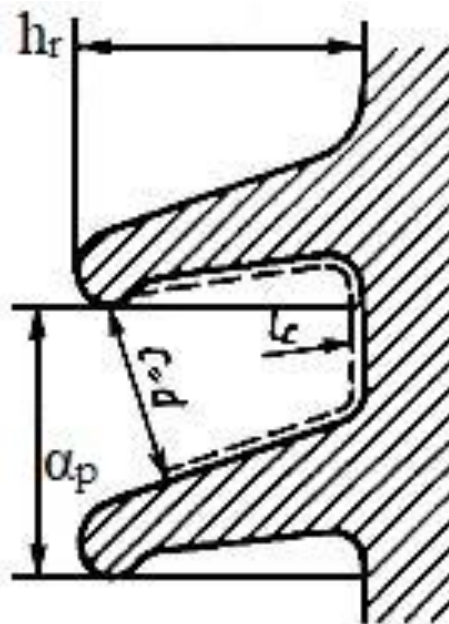


Figure 4.2 – Configuration of the insulator ribs with constant length

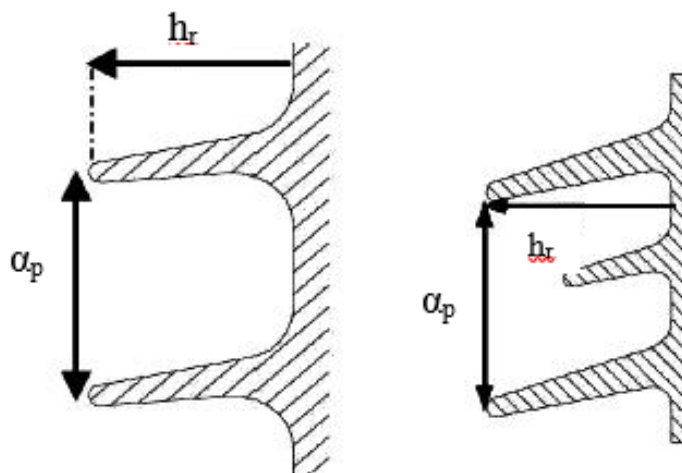


Figure 4.3 – Configuration of the insulator ribs with variable length

The angle of the ribs should be from 5 up to 25 degrees, as represented in Figure 4.4.

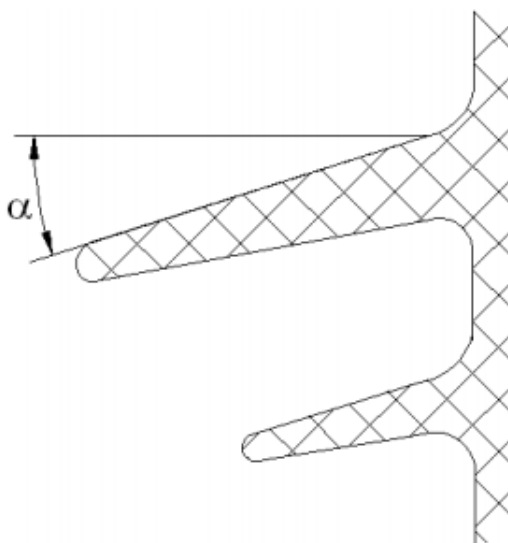


Figure 4.4 – Angle of the insulator rib

All calculation results are represented in the appendix B. According to that method, the withstand voltage value under the rain is 121 kV, active height is 60cm and there are installed 10 ribs under the angle of 10 degrees on the insulator surface.

On the results of the calculation it can be concluded, that calculated insulator fully meets the requirements of the ГOCT 9920–89 and ГOCT 1516.3–96.

5 OCCUPATIONAL SAFETY

Since the topic of the graduation project is "35 kV, 1500 A Fiber Optic current transformer", calculations in a premise equipped with personal computers with visual display terminals are involved. Let's consider the measures of safety, occupational health and fire safety for a premise equipped with visual display terminals, in accordance with the methodical instructions and regulations in the field of occupational safety.

In this Chapter "display screen equipment" means any alphanumeric or graphic display screen, regardless of the display process involved. "Employee" means an employee who habitually uses display screen equipment as a significant part of his or her normal work. "Workstation" means an assembly comprising display screen equipment, which may be provided with a keyboard or input device or software, or a combination of the foregoing, determining the operator and machine interface, and includes:

- a work chair and work desk or work surface;
- any optional accessories and peripherals;
- the immediate work environment of the display screen equipment.

Based on the analysis of the work of existing equipment and technological processes in the premise equipped with personal computer (PC) with visual display terminal (VDT), in accordance with ГОСТ 12.0.003–74 (1999) "Occupational safety standards system. Dangerous and harmful production effects. Classification", the following dangerous and harmful manufacturing factors that could cause injury or damage to the health of employees were identified:

- due to the low mobility of employees, prolonged stay in a static position, which leads to static muscle tension. This can be a reason of Musculoskeletal Disorders (MSD), which are injuries and disorders that affect the human body's movement or musculoskeletal system. When a worker is exposed to MSD risk factors, they start to get tired. When fatigue outruns their body's recovery system, they develop a musculoskeletal imbalance. Over time, as fatigue continues to outrun recovery and the musculoskeletal imbalance persists, a musculoskeletal disorder develops. The most dangerous thing is that the concentration of attention on the monitor screen dulls the timely warning of pain,

which is an alarm for the body. Diseases of the hands are observed in PC workers 7–12 times more often than in others, and quite often misdiagnosed as inflammation of the tendons, instead of Carpal tunnel syndrome;

– special place among the occupational diseases is an ocular disease caused by irrational lighting, lighting of workstations with PCs and non-compliance with the mode of work. The specificity of the lighting is due to the optical diversity of the visual objects of the PC user are the screen, documentation and keyboard located in different areas of observation, which requires repeated movement of the line of sight from one to another. Working documentation is most often placed in a table in a horizontal plane at the distance of the optimum visibility, objects of distinction have a negative contrast – dark objects on a light background. There is a constant re-adaptation from bright objects with positive contrast to dark with negative contrast. The objects on the keyboard are larger in size and located in an inclined plane. Bright signs on a dark background of almost vertically oriented screen are located at a distance of 450–600 mm, which requires an unusual horizontal orientation of the line of vision. In an eight-hour work day, the monitor casts approximately 30,000 views on the screen, the eye works with overload and cannot adapt to this situation sufficiently. Such features lead to the tension of the muscular and light-sensing apparatus of the eyes, which is one of the causes of asthenopic phenomena (cut in the eyes, pain in the eyes, breaks in the brow area, blurry of contours, blurred image). A constant glance at the frosted glass of the monitor screen reduces the frequency of eye flickering, which causes the cornea to dry out and distort, blurred vision (Sikka syndrome);

– monotonous work at a PC is particularly noticeable. Average person makes more than 600 identical actions during the 75% of working time in one hour. In composition with insufficient workplace ergonomic and electromagnetic radiation this can lead to the general neurotic nature diseases in the form of increased general fatigue, headache, feeling of the head heaviness of and poor sleep. Persistent neuropsychiatric disorders in the form of increased irritability, anxiety, agitation (excited type), depressive states, overall stiffness at work, decrease in reaction rate (brake type). As a most dangerous

factor, that can be figured out, is the tumor formation caused by electromagnetic fields of low and ultralow frequencies.

5.1 Occupational safety measures

Requirements for space–planning decisions of production facilities buildings for the operation of VDT computers and PCs in accordance with ДСанПіН 3.3.2.007–98 “Гігієнічні вимоги до організації роботи з візуальними дисплейними терміналами електронно–обчислювальних машин”, are:

- placement of workplaces with VDT computers and PCs in basements, on the basement is prohibited;
- the area per workplace should be at least 6 m², and a volume of not less than 20 m³;
- VDT facilities should have natural and artificial lighting in accordance with ДБН В.2.5–28:2018 “Природне і штучне освітлення”;
- natural lighting should be through apertures predominantly north or northeast oriented and provide a natural lighting ratio of not less than 1.5%;
- premises for work with VDT should not be adjacent to premises in which noise and vibration levels exceed the permissible values, according to СН 3223–85 “Санітарні норми допустимих рівнів шуму на робочих місцях”, СН 3044–84 “Санітарні норми вібрації робочих місць”, ГОСТ 12.1.003–83 “Occupational safety standards system. Noise. General safety requirements”;
- VDT facilities should be equipped with heating, air conditioning, or inlet and exhaust ventilation, in accordance with ДБН В.2.5–67:2013 “Опалення, вентиляція та кондиціонування”. The normalized parameters of the microclimate, the ionic composition of the air, the content of harmful substances should meet the requirements of ГОСТ 12.1.005–88 “Occupational safety standards system. General sanitary requirements for working zone air”;

- it is forbidden to use polymeric materials (wood–chip boards, washable wallpaper, synthetic rolls, layered paper plastic, etc.) that release harmful chemicals into the air for interior decoration of VDT premises;

In a laboratory equipped with PCs and VDTs the main purpose of exploitation will be carrying out the calculations, perform analysis, modelling and researches using the PC. The major attention should be devoted to the VDTs. Because this is the main interface, that employee use when work with PC. Modern VDT is a flat screen with resolution:

- for 15–inch monitors – 800 x 600 (SVGA), a higher resolution is impractical, as the fonts and icons will look too small;

- for 17–inch monitors, the optimal resolution is 1024 x 768 (XGA);

- large monitors (with a diagonal size > 17 ") should provide a resolution of 1280 x 1024 (EVGA) or higher. The maximum is 1920 x 1080(FHD);

Directive EC 90/270 EEC, chapter «Minimum safety requirements», establishes the ergonomic characteristics of the VDTs:

- symbols on the screen should be clear and well distinguished;

- brightness and / or contrast should be easily adjustable;

- the image should be flicker–free;

- emissions should be reduced to extremely small levels.

- screens should be free from glare and reflection;

When organizing the workplace of the user of the VDT and the personal computer, it is necessary to ensure that the design of all the elements of the workplace and their relative position are ergonomic and corresponds to the ДСанПіН 3.3.2.007–98 “Гігієнічні вимоги до організації роботи з візуальними дисплейними терміналами електронно–обчислювальних машин”. Amongst the requirements there are:

- the design of the desktop should provide optimal placement on the working surface of the equipment used, taking into account its number and design features (the size of the VDT and PC, keyboard, music stand, etc.) of the nature of the work. It is allowed to use desktops of various designs that meet modern ergonomic requirements. In this case, it is necessary to take into account the anthropometric characteristics of the

worker and arrange the equipment taking into account the observation zone and the reach of the hands;

- the height of the working surface of the table for adult users should be adjustable within 680–800 mm, in the absence of such a possibility, the height of the working surface of the table should be 725 mm. The working table should have a place for legs with a height of at least 600 mm, a width of at least 500 mm, a depth at the knees of at least 450 mm and at the level of elongated legs at least 650 mm;

- the type of working chair (chair) should be selected depending on the nature and duration of work with VDT and PC, taking into account the height of the user. Optimal design and dimensions of the workplace are shown in Figure 6.1

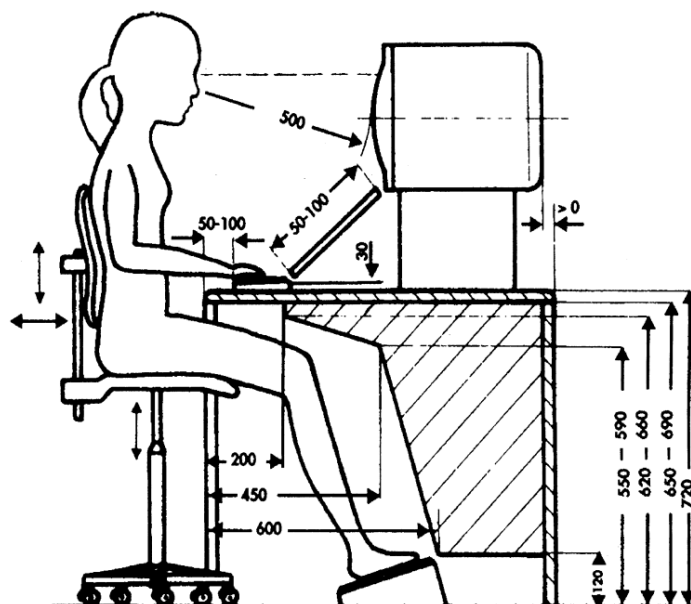


Figure 5.1 – The design and dimensions of the workplace

- In laboratories at permanent workplaces with PC, the optimum microclimate parameters should be provided. Optimal temperature, relative humidity and air velocity in accordance with the requirements of ДСН 3.3.6.042–99 “Санітарні норми мікроклімату виробничих приміщень” and ГОСТ 12.1.005–88 “Occupational safety standards system. General sanitary requirements for working zone air”, are given in table 5.1

Table 5.1 – Climate standards for premises with computer equipment

Season	Type of work	Temperature, °C, not more	Relative air humidity, %	Air velocity, m/c
Cold	easy –1a	22–24	40–60	0,1
	easy –1b	21–23	40–60	0.1
Warm	easy –1a	23–25	40–60	0.1
	easy –1b	22–24	40–60	0.2

The power supply of the electrical equipment of the laboratory with a PC is carried out from an AC network with a voltage of 220 V and a frequency of 50 Hz. In accordance with the requirements of the "Правила улаштування електроустановок" (ПУЕ), electrical equipment in a premise with a PC, it is characterized as electrical installations up to 1000 V, therefore, in accordance with the requirements of Chapter 1.7 of the "ПУЕ" and ГОСТ 12.1.030–81 (2001) "Occupational safety standards system. Electric safety. Protective conductive earth, neutralling", the value of the resistance of the protective grounding circuit of the electrical equipment of the premise with a PC at any time of the year does not exceed – 4 Ohms.

To provide the protection for PC users from noise it is necessary to understand the permissible sound pressure levels in octave bands equivalent to workplace sound levels (table 5.2). According to the ДСН 3.3.6.037–99 "Санітарні норми виробничого шуму, ультразвуку та інфразвуку", the laboratory is the first case: creative activity, high-demand management work, scientific activity, design, programming, teaching and training, computer programmers in laboratories for theoretical work and data processing, reception of patients in medical centers.

Table 5.2 – Permissible sound pressure levels in octave bands equivalent to workplace sound levels

	Sound pressure levels in dB in octave bands with geometric mean frequencies, Hz									Equivalent noise level,dBA
	31.5	63	125	250	500	1000	2000	4000	8000	
Rated value	86	71	61	54	49	45	42	40	38	50

According to the ДСанПіН 3.3.2.007–98 “Гігієнічні вимоги до організації роботи з візуальними дисплейними терміналами електронно–обчислювальних машин” and ДСН 3.3.6.037–99 “Санітарні норми виробничого шуму, ультразвуку та інфразвуку” the following noise reduction measures in the laboratory can be performed:

- use of PC power supplies with fans on rubber suspensions;
- the use of PCs in which thermocouples are installed in the power supply and at critical points of the motherboard (processor, chipset), which allows to software regulate both the moments of switching on of fans and their speed of rotation;
- implementing a modern noise–free peripheral (mousses and keyboards);
- putting the hard disk into Standby mode if the computer does not work for a specified time or use of modern, silent SSDs;
- use of PCs with a manufacturer–installed fan (BOX processor) or modern noise–free passive coolers;
- the location of printers at a considerable distance from most workstations of PC users.

5.2 Fire safety measures

In accordance with the requirements of ДСТУ Б В.1.1–36:2016 “Визначення категорій приміщень, будинків, установок за вибухопожежною та пожежною

небезпекою”, the laboratory equipped with PCs belongs to production facilities of category "Д" of fire danger.

According to the requirements of ДБН В.1.1–7:2016 “Пожежна безпека об’єктів будівництва” the premise has II degree of fire resistance.

For technical and organizational measures to prevent fires in the laboratory equipped with PC and VDT it should be provided the following fire prevention measures. The power equipment, power and lighting circuits, in accordance with the requirements of 3.1 "ПУЕ", have protective devices that disconnect the power supply from the area of the electrical circuit in which the short circuit occurred.

According to the requirements of ДБН В.2.5–56:2014 “Системи протипожежного захисту”, in the laboratories equipped with PC, a system of fire and security alarm should be installed. It should provide detection of thermal and smoke signs of fire and location of fire with accuracy to the location of the sensor.

In production facilities where workplaces with VDT and PC are located, in accordance with the requirements of ДСТУ 4297:2004 “Пожежна техніка. Технічне обслуговування вогнегасників. Загальні технічні вимоги”, carbon dioxide fire extinguishers (ОУ–5 or ВБК 3–5) are mainly used, the advantages of which are high fire extinguishing efficiency, the safety of electronic equipment, and the dielectric properties of carbon dioxide, which makes it possible to use these fire extinguishers even when it fails to de-energize the electrical installation immediately. Manual carbon dioxide fire extinguishers are installed in laboratories with computing equipment at the rate of one fire extinguisher per 40–50 m² area, but not less than two in the laboratory. The distance between the fire extinguishers and the places of possible fires existing shall not exceed 10 m. The PC user must have the skills to use fire extinguishing means.

Computer use at work becomes more prevalent every year. A growing body of evidence suggests a link between computer use and physical discomfort, pain or injury, visual discomfort, stress, fatigue as well as occupational injuries, traumas and professional diseases. Developed measures for safety, sanitation, occupational hygiene and fire safety provided for the laboratories equipped with personal computers with visual display terminals ensure safe and comfortable working conditions.

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. New generation transformers working principle is based on Faraday's effect. Thus, fiber optic current transformers are improved version of 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.

Important advantages of these equipment's are the safe operation, easy control and convenient installation. These devices are manufactured by leading companies around the world (USA, Germany, Canada, China, Japan, Russia). They are complying 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
Maximum thermal stability current, kA	63	40

Continuation of the Table 6.1

Maximum electrodynamic stability current, kA	20 – 170	10 – 212
Power consumption, W	< 60	10-200
Height, m	0.8 – 6.3	0.6 – 7.9
Weight, kg	Power Amplifier and Power Supply – 10; Electron-optical unit – 7; Insulator– from 28 to 80	30 – 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	> 30	> 30

Due to long-term operation of the transformer in HV equipped parks, and consider all parameters of analog transformers and fiber optic ones it can be concluded that the old equipment, require an urgent repair. But as it shows 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.

6.2 Cost and product price

The cost of production is an economic and financial indicator of the enterprise, characterizes the efficiency of management and is the basis for calculating the price. The price of an electrical product is determined by the formula (6.1).

$$Pr = C_{total} + P, \quad (6.1)$$

where Pr is the price of the product, UAH;

C_{total} is the the total cost of the product, UAH;

P is the profit of the product, UAH.

The cost of production is a cost estimate of natural resources such as raw materials, basic materials, fuel, energy, fixed assets, manpower, as well as other costs of production and sale of products. Cost reflects the quantity of actual costs that are productive, non-capital, and provide a simple reproduction process. Cost is an economical form of reproduction of consumed factors of production. The total cost of the product is calculated by the formula (6.2).

$$C_{total} = M + K + W + AW + SA + WE + AE + DC, \text{ UAH} \quad (6.2)$$

where M is the cost of base and raw materials, UAH;

K is the the cost of product's components, UAH;

W is the the basic wages, UAH;

AW is the additional wage, UAH;

SA is the social assignments, UAH;

WE is the general production expenses, UAH;

AE is the administrative expenses, UAH;

DC is the distribution costs, UAH.

The production cost of the product (C_p) is determined by the formula 6.3.

$$C_p = M + K + W + AW + SA + WE, \quad (6.3)$$

The cost of raw materials and basic materials is calculated according to consumption rates and prices. 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.

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

The cost of raw materials and basic materials is given in Table 6.2.

Table 6.2 – The cost of raw materials and basic ones

Name of raw materials and basic materials	Norms of usage	Price, UAH	Sum, UAH
Electrotechnical steel , ton	0.07	12792	895.44
Polymer, kg	30	125	3750
Fiber Optic Cables: Zip Cord	4	42.75	170.5
Paint and varnish production, kg	7	500	3500
Non-ferrous metal hire, kg	20	200	4000
Cable products, kg	6	108	648
Transportation and procurement costs			4270
Total			17233.94

The cost of purchasing components is calculated on the basis of usage rates and prices, taking into account transport and procurement costs. The cost of purchasing components is given in Table 6.3.

Table 6.3 – The cost of purchasing components

Name of purchasing components	Quantity	Price, UAH	Sum, UAH
Insulator	1	5000	5000
Optical sensor	1	13547	13547
Optoelectronic unit	1	12300	12300
Current amplifier	1	13660	13660
Power supply unit	1	4350	4350
Fiber Optic Cables	4	42.75	170.5
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
Total			52782.1

The basic salary of the main virological workers per unit of the product is based on the basis of labor rate and hourly tariff rates. The calculation of basic salary pay per unit of product is given in the table 6.4.

Table 6.4 Basic salary per unit of product

Type of work	Time allowance, hour	Cost of one allow hour, UAH	Wage, UAH
Manufacturing, 3-rd category	500	27	13500
Assembling, 5-th category	410	31	12710
Testing, 6-th category	60	33	1980
Total			28190

Additional wages of workers are paid for the quantity and quality of work performed. It includes allowances and surcharges, performance bonuses, regular and additional vacation pay, etc. Additional wages is 40% of the primary, and is calculated by the formula 6.4.

$$AW = W \cdot \frac{K_a}{100}, \text{ UAH} \quad (6.4)$$

where K_a is the the percentage pf additional wages.

Recoupment for social assignments is a form of redistribution of income to finance public needs, are calculated according to the current legislation and make up 22% of basic and additional wages. Recoupment for social events are calculated by the formula 6.5.

$$SA = (W + AW) \cdot \frac{K_{r,s}}{100}, \text{ UAH} \quad (6.5)$$

where $K_{r,s}$ is the percentage recoupment for social assignments, %.

The general production expenses include the costs of maintaining and operating the equipment, department costs, and production services. The overhead costs are on average 400% of the basic wage and are calculated according to the formula 6.6.

$$WE = W \cdot \frac{\alpha}{100}, \text{ UAH} \quad (6.6)$$

where α is the percentage of working expenses, %.

Administrative expenses include expenses associated with maintenances of administrative and managerial personnel of the enterprise, as well as the maintenances and operation of fixed assets of general industrial purpose, occupational safety of personnel, and others. The administrative costs are on average 500% of the basic wages of the basic production workers and are calculated according to the formula 6.7.

$$AE = W \cdot \frac{\beta}{100}, \text{ UAH} \quad (6.7)$$

where β is the percentage of administrative expenses, %.

Distribution costs consist of the costs associated with the sale of products and include the cost of packaging and packaging materials, transportation of finished goods, advertising, marketing research costs etc. Distribution costs are 2% of production cost and are calculated by the formula 6.8.

$$DC = C_p \cdot \frac{\gamma}{100}, \text{ UAH} \quad (6.8)$$

where C_p is the production cost, UAH;

γ is the percentage of distribution costs, %.

Profit is 30% of total cost and is calculated by the formula 6.9.

$$P = C_{\text{total}} \cdot \frac{\rho}{100}, \text{ UAH} \quad (6.9)$$

where ρ is the profitability of the product, %.

According to the legislation, value added tax is 20% of the wholesale price and is calculated according to the formula 6.10.

$$\text{VAT} = (\text{Pr} - \text{M} - \text{K}) \cdot \frac{\text{R}_{\text{VAT}}}{100}, \text{UAH} \quad (6.10)$$

where R_{VAT} is the value added tax rate, %.

The selling price of the product is calculated by the formula 6.11.

$$\text{Pr}_s = \text{Pr} + \text{VAT}, \text{UAH} \quad (6.11)$$

The wholesale price of the product is calculated by the formula 6.12.

$$\text{Pr}_{ws} = \text{C}_{total} + P, \quad (6.12)$$

Costing and calculation of FOCT is shown in Table 6.5.

Table 6.5 – Calculation of cost and price of FOCT.

Cost Articles	Sum, UAH
Raw materials and basic materials	17233.94
Purchasing accessories	52782.1
Basic wages of main workers	28190
Additional wages of main workers	11276
Recoupment for social events from wages payments of main workers	8682.52
General production expenses	112760
Production cost	230924.56
Administrative expenses	112760
Distribution costs	1332.93

Continuation of the Table 6.5

The total cost of the product	373207.5
Profit	111962.25
Wholesale price	485169.74
VAT	83030.74
Selling price	568200.48
Variable expenses	118164.56
Constant expenses	255042.93

6.3 Operational expenses

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

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

- on 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 (C_{el}) costs are determined by the formula 6.13.

$$C_{el} = P \cdot T \cdot Pr_{el} \cdot K_{los.el}, \text{ UAH} \quad (6.13)$$

where P is the the used power, kW;

T is the annual fund of working time of electrical equipment, hours;

Pr_{el} is the the price of 1 kW*h of electricity, UAH, $Pr_{el} = 2,69 \text{ UAH}$;

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

Recoupment for actual repairs are calculated by the formula 6.14.

$$C_{rep} = S_{rep} \cdot n_{rep}, \text{UAH} \quad (6.14)$$

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

n_{rep} is the number of actual repairs per year.

The cost of maintaining the production area (C_{area}) is calculated by the formula 6.15.

$$C_{area} = C_m \cdot S \cdot K_{area}, \text{UAH} \quad (6.15)$$

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

S is the area occupied by the transformer, m^2 ;

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

Absolute depreciation recoupment is calculated by the formula 6.16.

$$A_{abs} = \frac{C_{area}}{Y}, \text{UAH} \quad (6.16)$$

where Y is the service life, year.

The calculation results of operational expenses, are shown in Table 6.6.

Table 6.6 Operating expenses when using a unit of new and basic product

The composition of actual expenses	Product		Economy, UAH
	Base	New	
The cost of electricity, UAH	359911.24	332225.76	27686

Continuation of the Table 6.6

Costs for actual and average repairs, UAH	1500	1140	360
Costs for product maintenance, UAH	2401	2354	47
Costs for the maintenance of the production area, UAH	8000	7820	180
Other expenses on additional capital, UAH	266.67	260.67	6
Total			28279

6.4 Economic efficiency of innovation project

The economic efficiency of the innovation project is calculated according to the following indicators:

- break-even production;
- cost savings in production;
- saving operating costs.

Break-even production contains the calculation of the critical production volume, break-even point is given at graphics. Break-even production is characterized by critical amount at which the enterprise earns zero profit, i.e. revenues are equal to expenses. Break-even point is determined, after which the profit will start to come.

Critical volume of production is calculated by the formula 6.17.

$$N_{cr} = \frac{C_c * N}{(Pr_{ws} - C_v)}, \text{ units} \quad (6.17)$$

where N is the production volume of new product, units per year, N = 5 units.

Constant costs for the entire volume of annual production:

$$C_C = WE + AC + DC, \text{ UAH} \quad (6.18)$$

Variable costs calculate according to the unit of product:

$$C_V = M + K + W + AW + SA, \text{ UAH} \quad (6.19)$$

The following data are required to build a break-even graph, as well

$$Q_{pr} = Pr_{ws} \cdot N, \text{ thousand UAH} \quad (6.20)$$

The volume of products where there is no profit:

$$Q_{n.p} = \frac{b \cdot C_{total} \cdot X}{Pr_s - a \cdot C_{total}}, \text{ units} \quad (6.21)$$

where a is the variable costs, a=0.65;

b is the conventional costs, b= 0.35;

X is the production capacity of production, X = 50 un/h.

Break-even point is shown in Figure 6.1.

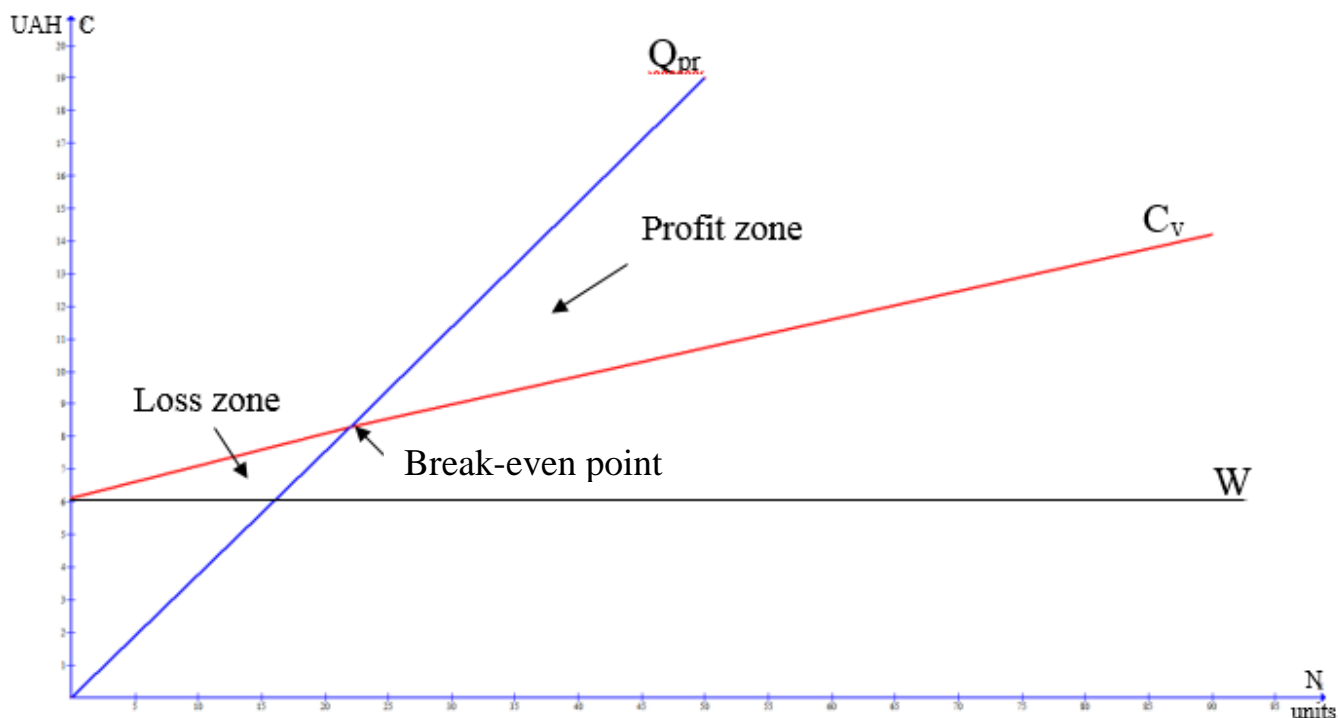


Figure 6.1 - Break-even point

Cost savings in production are calculated on the basis of saving specific types of material, labor and other resources. The cost savings calculation is presented in Table 6.7.

Table 6.7 - Cost savings in manufacturing and operating the product

Name of the indicator	Norms of usage		Price, UAH	Sum, UAH		Economy, UAH
	Base	New		Base	New	
Electrotechnical steel, kg	0.140	0.07	12792	1790.88	895.44	895.44
Polymer, kg	70	30	125	8750	3750	5000
Paint and varnish production, kg	9.5	7	500	4785	3500	1285

Continuation of the Table 6.7

Non-ferrous metal hire, kg	30	20	200	6000	4000	2000
Optical fiber, piece	0	2	42.75	0	85.5	0
Exploitation costs				372078.91	332225.76	28279
In all				393404.79	344456.7	48947.3

At this section, the competitive analysis of the Fiber optic current transformer, the cost of production, the expediency of production, determination of the price of the product and its profit have been carried out. The main indicators of the effectiveness of the innovation project have been identified.

CONCLUSION

Nowadays the development of Fiber Optic Current Transformer is promising in electric power industry. Their further development is not hindered by anything and in a number of countries the work on creating new current transformers is being carried out.

According to the result of all calculations it can be concluded, that the copper busbar conductor temperature to the end of the short circuit does not exceed 250°C, and the time of reaching this temperature is more than 4 seconds, according to ГOCT 434-78.

Electrodynamic forces of the conductors under the short-circuit mode will be 125 N.

Based on the analysis of different materials of insulators and on calculation results of external insulation, it can be inferred that it is rational and profitable to produce FOCT with polymer insulators. They are economically viable and easy to install, due to the high vandal resistance and low weight compared to porcelain one. For the further design the insulation category «Б» was chosen, according to the ГOCT 1516.3-96 and ГOCT 9920-89.

At 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 conventional analog transformers. FOCT has better characteristics and quite acceptable price.

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APPENDIX A

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

Conductor – Case		Case – Ambience		Result	
Designation	Result	Designation	Result	Designation	Result
L_{cond}	0.055	L_{case}	0.299	$R_{th,\Sigma}$	0.549
Gr	581416	Gr1	59232761	q	450
ε_k	5.033	Nu	43.27		
λ_{eq}	0.142	K_{tk}	4.095		
$P_{th,air,conv}$	1.892	$R_{th,amb,conv}$	0.26		
F_1	173	$P_{rad,1}$	7.65		
F_2	939	$R_{th,amb,rad}$	2.614		
P_{rad}	120.861	$R_{th,amb}$	0.236		
$R_{th,air,rad}$	0.375				
$R_{th,air}$	0.313				

Table A.2 – Results of the precised calculations for copper busbar

Conductor – Case		Case – Ambience	
Iteration	Result, $\theta_{case}, ^\circ\text{C}$	Iteration	Result, $\theta_{cond}, ^\circ\text{C}$
1	67.8	1	98.9
2	65.9	2	92.5
3	66.31	3	89.2
4	66.3	4	86.6
		5	84.5
		6	82.1
		7	81.2
		8	80.4
		9	80.2
		10	80.1

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

Thermal calculation		Electrodynamic forces	
Designation	Result	Designation	Result
$A(\theta_H)$	$1.5 \cdot 10^{16}$	H, A/m	3978
Sr_0, mm^2	$2.376 \cdot 10^3$	B, T	$5 \cdot 10^{-3}$
Sr, mm^2	$1.886 \cdot 10^3$	F, N	125
$A(\theta_{sc})$	$2.8 \cdot 10^{16}$		
$\theta_{sc}, ^\circ\text{C}$	175		

APPENDIX B

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

Designation	Value	Unit of measure
U_{rated}	35	kV
$U_{\text{test.dry}}$	115.5	
$U_{\text{test.rain}}$	93.5	
U_{calc}	203.5	
$h_{\text{act.r}}$	58.8	cm
$U_{\text{calc.r}}$	201	kV
$h_{\text{act.r2}}$	51	cm
$U_{\text{calc.r2}}$	210	kV
$h_{\text{act.r3}}$	22	cm
$U_{\text{calc.r3}}$	205	kV
$U_{\text{d.r}}$	136	kV
$h_{\text{act.rain.out}}$	52	cm
n_r	10	
l_r	5,2	cm
U_d	113.27	kV

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

Designation	Value	Unit of measure
U_{rated}	35	kV
$U_{\text{test.dry}}$	115.5	
$U_{\text{test.rain}}$	93.5	
U_{calc}	203.5	
k_{height}	1	
$h_{\text{act.r}}$	58.8	cm
$U_{\text{calc.r}}$	201	kV
$h_{\text{act.r2}}$	51	cm
$U_{\text{calc.r2}}$	210	kV
$h_{\text{act.r3}}$	22	cm
$U_{\text{calc.r3}}$	205	kV
$U_{\text{d.r}}$	136	kV
$h_{\text{act.rain.out}}$	61	cm
n_r	10	
l_r	6	cm
U_d	126.5	kV

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

Designation	Value	Unit of measure
U_{rated}	35	kV
$U_{\text{test.dry}}$	115.5	
$U_{\text{test.rain}}$	93.5	
U_{calc}	203.5	
k_{height}	1	
$h_{\text{act.r}}$	58.8	cm
$U_{\text{calc.r}}$	201	kV
$h_{\text{act.r2}}$	51	cm
$U_{\text{calc.r2}}$	210	kV
$h_{\text{act.r3}}$	22	cm
$U_{\text{calc.r3}}$	205	kV
$U_{\text{d.r}}$	136	kV
$h_{\text{act.rain.out}}$	75	cm
n_r	18	
l_r	5	cm
U_d	130	kV