Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Economics, Management and Humanities

CALCULATION OF INTEGRATED PROTECTION OF ELECTRICAL EQUIPMENT

Master’s Thesis

Study Program: Electrical Engineering, Power Engineering and Management

Branch of study: Management of Power Engineering and Electrotechnics

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MASTER‘S THESIS ASSIGNMENT

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2. Design of protection against dangerous contact in high voltage operation
3. Calculation of protection of HV appliances in case of short-circuit
4. Importance of protections in HV circuit from economic point of view
5. Economic assessment of protection variants in HV network

Bibliography / sources:

KRYUCHKOV, I., NEKLEPAEV, B. Elektricheskaya chast' elektricheskikh stantsiy i podstantsiy. Saint Petersburg, 2014.
BALAKRISHNAN, A. Calculation of important design parameters for grounding systems in substations, 1990.

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III. Assignment receipt

The student acknowledges that the master’s thesis is an individual work. The student must produce her thesis without the assistance of others, with the exception of provided consultations. Within the master’s thesis, the author must state the names of consultants and include a list of references.

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Declaration

I hereby declare that this master's thesis is the product of my own independent work and that I have clearly stated all information sources used in the thesis according to Methodological Instruction No. 1/2009 – "On maintaining ethical principles when working on a university final project, CTU in Prague".

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Abstract

The goal of this work is to develop a methodology for the integrated calculation of the protection of electrical equipment. A comprehensive calculation is a joint calculation of the earthing and protection system.

Short circuits can provide a serious threat to human and animal life and health without a properly calculated and configured protection and grounding system. In addition to the physical damage, there may be economic losses to the company due to the need to repair equipment during short circuits.

The solution of this problem is based on solving the following tasks:

- Analytical calculation of protection;
- Numerical calculation of protection;
- Proposal of integrated methodology of protection calculation of electrical equipment;
- Economic evaluation, allowing to estimate the profitability of protection.

At the end of the paper, conclusions are made about the effectiveness of the developed methodology of complex calculation of the protection system and the economic and technical comparison of the two types of protections. The result of this work can be used for the solution of similar tasks.

Keywords

Grounding system, high-voltage equipment protection, differential protection, analog protection, digital protection.

Contents

List of Appendices

List of Abbreviations

CAPEX	Capital Expenditures
EES	Electrical Energy System
EE	Electrical Energy
HV	High Voltage
IRR	Internal Rate of Return
LV	Low Voltage
NPV	Net Present Value
PP	Payback Period

List of Tables

List of Figures

Introduction

When designing or installing electrical equipment or utilities, mistakes can also be made that can affect electrical safety. For these reasons, parts of the electrical network may become damaged. The nature of accidents is different: there may be short circuits that are disconnected by circuit breakers, or there may be a breakdown in the housing. The difficulty is that the breakdown problem is hidden. With the wrong grounding measures, the damage will not show up until the person touches the equipment and gets an electric shock. The electric shock will happen because the current is looking for a way into the ground and the only suitable conductor is the human body. This should not be allowed to happen.

Such injuries pose the greatest threat to human safety. To protect against them, it is necessary to have a grounding. This paper considers the need for a joint calculation of both the grounding system and the protection system.

Accurate calculation of the protection system helps to prevent the breakdown of electrical equipment and save lives. These measures allow you to save on repairs of electrical equipment, therefore allowing to reduce production costs.

The correct calculation of the protection and earthing system is an important task, because human life depends on it. There are a large number of techniques that allow you to calculate grounding systems [32]. In this paper, I have tested two methods of calculations.

Calculation of such problems can be done in software packages such as MATLAB, ETAP, etc., which allow you to make more accurate calculations of the energy system and its transients, as transients are not constant and asymmetrical. Previously, all this was neglected or made do with corrective empirical coefficients when using analytical methods of calculation. With ETAP it is possible to take into account the dynamics and nature of load changes in the EES according to a certain algorithm.

To solve this problem, I will provide the following solutions: In the first paragraph I will simulate the power system based on the selected equipment.

In the second paragraph I will make a choice of the necessary type of protection of electrical equipment. And also study the available types of grounding systems.

In the third paragraph, I will calculate the analytical calculation of protection. I will also make analytical calculations of the grounding system and find the limits of allowable values, when a person is in the project area, during a possible danger.

In the fourth paragraph, I will make a numerical calculation of protection using the ETAP program. After that, in the fifth paragraph, I will compare the obtained values of analytical and numerical methods. Based on the comparison of the obtained values, I will propose a new methodology for the integrated calculation of protection.

The integrated calculation is a combined calculation of earthing and protection. Previously, calculations were performed separately, when these values were calculated separately from each other. Their connection was through the recommended parameters and correction factors [26].

In the sixth paragraph I will make the economic calculation between digital and analog protections. After that, the two protections are compared from the economic and technical point of view.

There are many types of electrical equipment protections on the market, and it is necessary to consider not only their technical parameters, but also the economic benefits from the installation of protection with a further comparison.

The aim of the work is to develop a methodology for the integrated calculation of protection of electrical equipment with subsequent comparison from the economic point of view of analog and digital protections.

To achieve this aim in the work the following tasks are set and solved:

- Analytical calculation of the model of the grounding system and protection system;
- Numerical calculation of the model of the earthing system and protection system;
- Development of an integrated methodology for calculating the protection system;
- Economic calculation of digital protection;
- Economic calculation of the analog protection.

1. Protection of Working Staff, Animals and Objects from Dangers from High Voltage Equipment

The live parts of the electrical installation should not be accessible for accidental contact, and the open conductive parts accessible to touch should not be energized, posing a risk of electric shock both in normal operation of the electrical installation and in case of damage to the insulation.

The switches belong to the list of power system equipment, the reliability of which has a significant impact on the reliability of electrical installations. In particular, the switches determine the structural reliability of switchgear schemes of power stations and electrical substations.

Grounding system is a device that protects humans and animals from electric shock. By using an earthing device, it is possible to avoid casualties both in the workplace and at home.

1.1. Initial Data

In this work, I will be modeled and calculated a part of Electrical Energy System (EES), which will include two step-down transformers and one Electrical Energy (EE) consumer.

Two step-down transformers were selected to clearly show the selectivity of the different protection devises. And the work of protections at different voltage classes. The parameters of the transformers are shown in Table 1.

Table 1. Transformers data [1]

Type of power transformer	S_{nom}, kV · A	U_{nom}, kV		Losses, kW		Winding circuit
		HV	LV	P_{NL}	P_{SC}	Y/Δ-11
TMN – 10000/110	10000	121	10,5	-	-	
TM – 630/10/6	630	10,5	6	1100	8100	Y/Y-0

Explanation of name of the transformer: T – transformer, M – cooling with natural air and oil circulation, N – with load tap changer.

I have chosen a high voltage electric motor – medium voltage squirrel cage as the load to drive mechanisms that do not require speed control. The parameters of the electric motor are given in Table 2.

Table 2. Electric motor data [2]

Model	U_{nom}, V	P_{nom}, kW	Speed, rpm	Efficiency, %	Frequency, Hz
H17R 400-6	6000	400	1500	94,2	50

2. Choice of the Protection

All existing operated or newly constructed electrical networks shall be provided with necessary and sufficient protection means, first of all against electric shock to people working with these networks, sections of circuits and electrical equipment against overload currents, short-circuit currents, peak currents. These currents can lead to damage both to the networks themselves and to electrical equipment.

The interruption of the transformer can lead to very serious consequences, such as the interruption of power supply to consumers.

In order to protect electrical equipment from any damage and accidents, protection against internal damage. For these purposes are using the current cut off protection, longitudinal differential protection and etc.

2.1. Protection of Electrical Equipment

A variety of phenomena that occur in emergency modes, affect the service life of an electrical equipment. It is necessary to guarantee the safety of electrical equipment and therefore its protection must be universal. When an accident threatens, the protection must act on a signal and the motor must be switched off. The desire to obtain universal protection has given rise to a variety of devices designed to protect electrical equipment, with a different set of advantages and disadvantages.

2.1.1. Longitudinal Differential Protection

Nowadays, differential protection of transformers is usually performed by circuits with current circulation.

Requirements for longitudinal differential protection this protection:

- Single transformers and autotransformers from 6300 kVA;
- On parallel transformers operating with a power of 4000 kVA and more [3].

Differential protection scheme is presented in Figure 1.

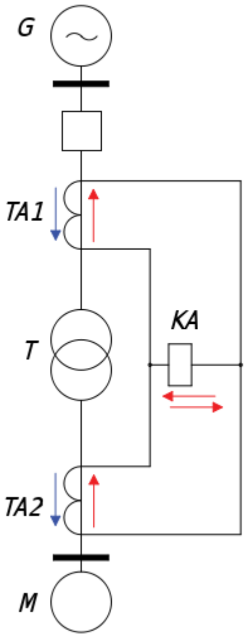

Figure 1. Scheme of the differential protection of the transformer [4]

Differential protection is used as the main protection for transformers in case of damage to their windings, at the inputs and busbars. Differential protection is used as the main protection for transformers in case of damage to their windings and at the transformer lead terminals. As far as in the modeling program is using the transformer which power is 10 MVA, then this protection will be used for this transformer.

The basic principle of transformer protection with differential protection is the comparison of currents on the inputs of the protected transformer. On each side of the transformer are installed current transformers TA1 and TA2, whose secondary windings are connected to each other in parallel, and connecting to relay. The conversion factor of measuring transformers is selected so that in case of occurrence of short-circuit outside the protected area, the resulting current passing through the relay was equal to zero [3].

2.1.2. Surge Arrester

The surge arrester protection is used to protect the transformer winding from damage if the voltage exceeds the permissible values in case of supply system failures.

To protect the transformer from overvoltages surge arrester is installed on each side of the transformer [4]. Surge arrester is presented in Figure 2.

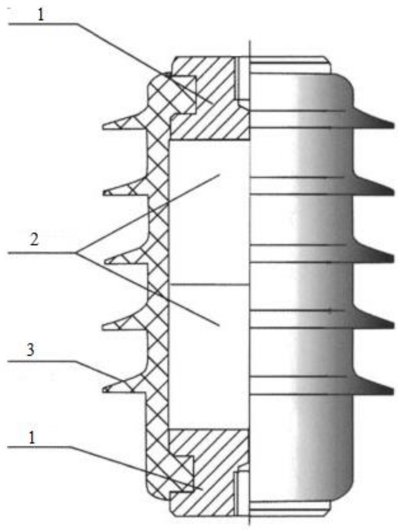

Figure 2. The scheme of the surge arrester [13]

1 – Electrodes, 2 – Resistance, 3 – Housing.

2.1.3. Overcurrent Protection

The current cutoff has two stages and is designed for fast liquidation of interphase short circuits. In order to increase the sensitivity and preserve the speed of current protection on the motor modes, when the motor self-start current exceeds the short-circuit current, it is possible to work with the control from the power direction relay.

Requirements for longitudinal differential protection this protection:

- Protection is used for low power transformers;
- For electric motors.

The overcurrent protection is designed for overload protection of the protected motor. The first stage has independent or dependent time characteristics. The second stage has an independent time-current characteristic [4]. The scheme of connecting overcurrent protection is presented in Figure 3.

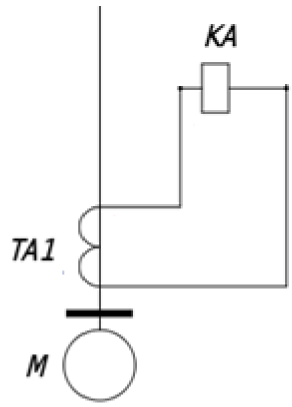

Figure 3. The connection of overcurrent protection [4]

This type of protection I have used for protection of the electric motor in modeling system.

2.1.4. Protection of Phase Interruption and Load Unbalance

The protection is performed with a control current of reverse sequence. It is possible to work with the control of the inverse sequence current-to-current ratio of the forward sequence. The protection works according to the effective value of the current. It can have a dependent or independent time delay [3].

2.1.5. Protection Against Temperature Rise

Temperature control relay signals temperature increase of upper oil layers above the set (permissible) values. This protection automatically triggers additional transformer cooling systems. For example, blowing fans, forced oil circulation pumps in the coolers are activated. If the oil temperature rises even higher, the relay acts to disconnect the transformer from the system [5].

2.1.6. Undervoltage Protection

The undervoltage protection eliminates the possibility of self-starting the motor or its operation at a sharply reduced mains voltage.

Undervoltage protection is used in the operation of protection devices, which control the voltage value in the network and turn off the power switch when the voltage drops to the minimum possible value – setting.

The undervoltage protection works self-contained and can be configured for co-utilization, integrated use with other devices such as current protection or power control [6].

2.1.7. High Rupturing Capacity Fuse

High voltage fuses are used to protect electrical equipment in electrical networks with voltages above 1000 V against short-circuit currents and unacceptable overload currents.

The main technical characteristics of fuses are rated voltage, rated permanent current, the dependence of the prearcing time of the fuse by the current. The breaking capacity of the fuses is characterized by their rated breaking capacity. The protective element of the fuse is a fusible link included in series into the electrical circuit of the protected network.

Fuses that have the ability to sharply reduce the current in a circuit at the short circuit are called current limiting fuses. When short-circuit currents or long overload currents pass through a fusible link, they become excessively hot and melt, passing first into a liquid and then gaseous state. In the process of melting the metal of the insert, an arc is formed between the fuse contacts. The duration of burning and the quenching speed of the electric arc inside the fuse depends on the fuse design and the correct choice of fusible link. After the arc is extinguished, the electrical circuit is completely broken [7].

This type of protection I have used for the protection the second transformer in my program modeling.

Appendix A in Figure A1 shows a 10 kV high voltage fuse.

2.2. Grounding System

Electric current can pose a serious threat to human life and health. An electric shock occurs when a closed loop system is created to which a voltage source is connected. In this connection, if a person is in contact with this closed loop without the equipment protecting it, a person also becomes a conductor. Short-circuits, in addition to the threat of damage to electrical equipment, create a dangerous environment for human life and health. To prevent this threat at an indirect touch and to provide conditions for adjustment of protection of electrical equipment, it is necessary to connect conductive parts of electrical equipment, which in the normal mode should not be under voltage, by a conductor which has a low resistance with the zero-protective conductor [8].

The first letter indicates the connection between earth and the power-supply equipment (generator or transformer):

- "T" — Direct connection of a point with earth;
- "I" — No point is connected with earth, except perhaps via a high impedance.

The second letter indicates the connection between earth or network and the electrical device being supplied:

- "T" — Earth connection is by a local direct connection to earth, usually via a ground rod;
- "N" — the earth connection is supplied by the electricity supply network, either separately to the neutral conductor (TN-S), combined with the neutral conductor (TN-C), or both (TN-C-S). These are discussed below [9].

The symmetry of the electrical system is disturbed by a single-phase earth-fault: the phase voltage changes relative to the earth, resulting in earth-fault currents and overvoltage in networks. This degree of change in symmetry depends on the regime of neutral.

The neutral mode has a significant impact on the operation regimes of electrical receivers, circuit solutions of the power supply system, the parameters of the selected equipment, it should also be noted that the method of neutral grounding determines:

- Safety conditions of work in electrical networks, protection from the threat of electric shock;
- Overvoltage limiting method;
- Electromagnetic compatibility in normal and emergency modes;
- Fire safety;
- Single-phase currents, fault tolerance, electrical equipment selection;

- Electricity supply security;
- Design of the network and its operation.

2.2.1. TN-S System Earthing

TN-S system is the most reliable and safe grounding system which maximizes the protection of electrical equipment. TN-S system is presented in Figure 4.

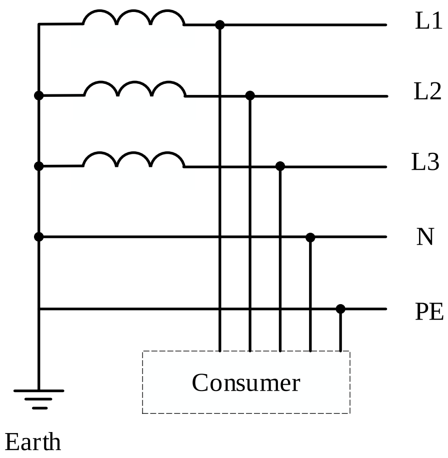

Figure 4. TN-S system diagram [10]

A distinctive feature of power supply lines with grounding on the principle of TN-S is that from the power supply comes five conductors, three of which perform the function of the power phases, as well as two neutral, connected to the zero point:

PN - zero protective conductor, is involved in the electrical equipment circuit;

PE - solidly grounded, performs protective functions [8].

2.2.2. TN-C System Earthing

This system differs from others in the TN system in that the protective earth conductor (PEN) is a working zero-phase conductor along its entire length. The division of the neutral conductor into working and protective earth conductors only occurs at the point of connection of the consumer to the electrical network [9]. TN-C system is presented in Figure 5.

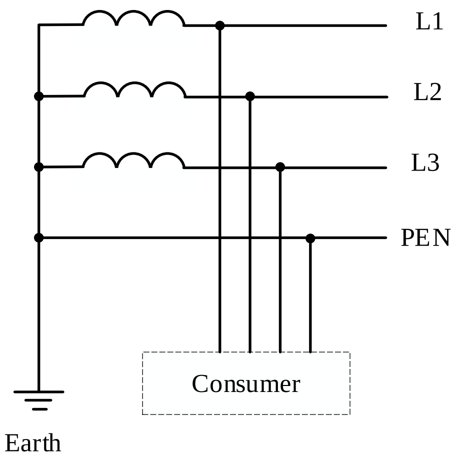

Figure 5. TN-C system diagram [10]

The TN-C grounding system, with its design features, has advantages and disadvantages. The advantage of the system, however, is not related to electrical safety issues:

Savings due to the fact that the power supply to the three-phase consumer is provided by four conductors instead of five, as there is no separate protective earthing conductor.

The possibility of its application without the implementation of modernization built earlier cable and overhead power lines, having four conductors [8].

2.2.3. TN-C-S System Earthing

According to the scheme provided below, when earthing type TN-C-S to the terminals of consumers three-phase load is fed 4 conductors, 3 of which are phase conductors A, B, C, and the fourth - the neutral wire PN. TN-C-S system is presented in Figure 6.

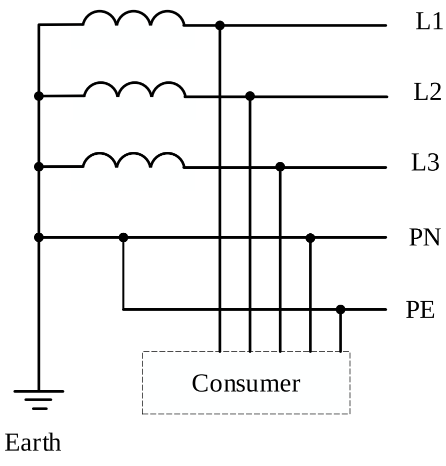

Figure 6. TN-C-S system diagram [10]

The protective wire PE is made in the form of a jumper strap between the metal case of the electric device and the grounding circuit. Connection of the consumer to a single-phase network is carried out by one phase wire and neutral PN with subsequent grounding of the housing made of metal.

2.2.4. TT System Earthing

The application of the TT system extends to electrical networks whose neutrality is solidly earthed. The essence of this method is that the conductive parts of electrical equipment are connected to the grounding device, which is on the consumer's side. Electrical connection between this device and the earthing switch, which is connected to the neutral transformer in the substation, there is no electrical connection [8]. TT system is presented in Figure 7.

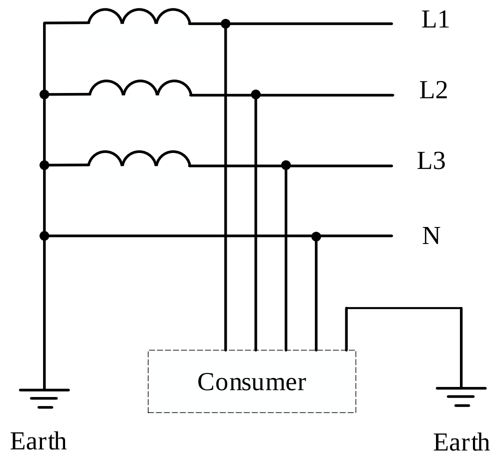

Figure 7. TT system diagram [10]

2.2.5. IT System Earthing

Classic system, the main feature of which is an isolated neutral source - "I", as well as the presence on the consumer side of the protective earth circuit - "T". Voltage from the source to the consumer is transmitted through the minimum possible number of wires, and all current-conducting parts of the consumer equipment must be reliably connected to the earth electrode [8]. IT system is presented in Figure 8.

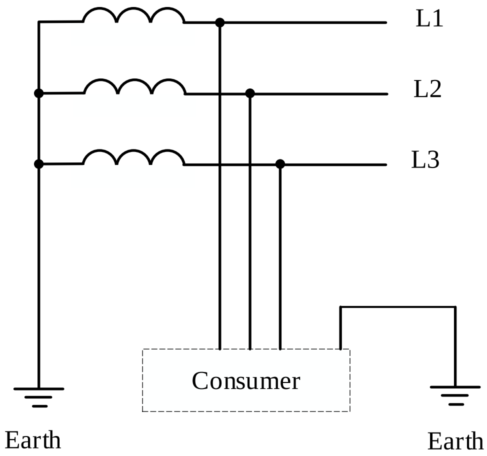

Figure 8. IT system diagram [10]

3. Analytical Calculation of Protection

As it was written in chapter 1, the research object is an EES. For a visual representation, the simulation network is shown below in Figure 9.

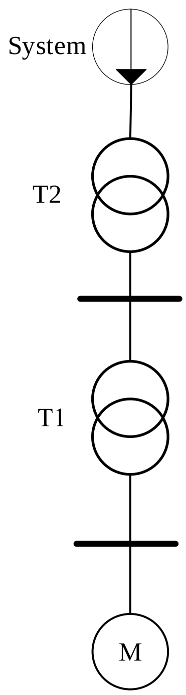

Figure 9. Energy system

3.1. Calculation of the Grounding System

For integrated calculation of the protection system, it is necessary to make a calculation and simulate the grounding system.

A good grounding device should have the following characteristics [11]:

- Low ground resistance. The lower the ground resistance, the more likely it is that lightning current will flow along this road, allowing the current to safely pass to the ground and then dissipate. For each protection system, there is no specific ground resistance value, but in general, the resistance measured at low frequency should be no more than 10 Ohms.
- Good corrosion resistance. The choice of material for the electrodes and their connections is very important. It will be buried in the ground for many years, so the system must be reliable.

Touch voltage occurs between two points in the current flow circuit, which is closed by simultaneous human touch. One of these points is usually a lightning strike or a live electrical installation housing due to a phase conductor short circuit on it. The second point is a conductive surface with zero potential. The step voltage is the result of current flowing through the ground and means the potential difference between two points of the ground, located at a distance of one step, which is considered equal to one meter. Step and Touch Voltage depend on the earth potential gradient, as shown in Figure 10. The greater the distance from the point with the maximum potential, the lower the risk of electric shock [12].

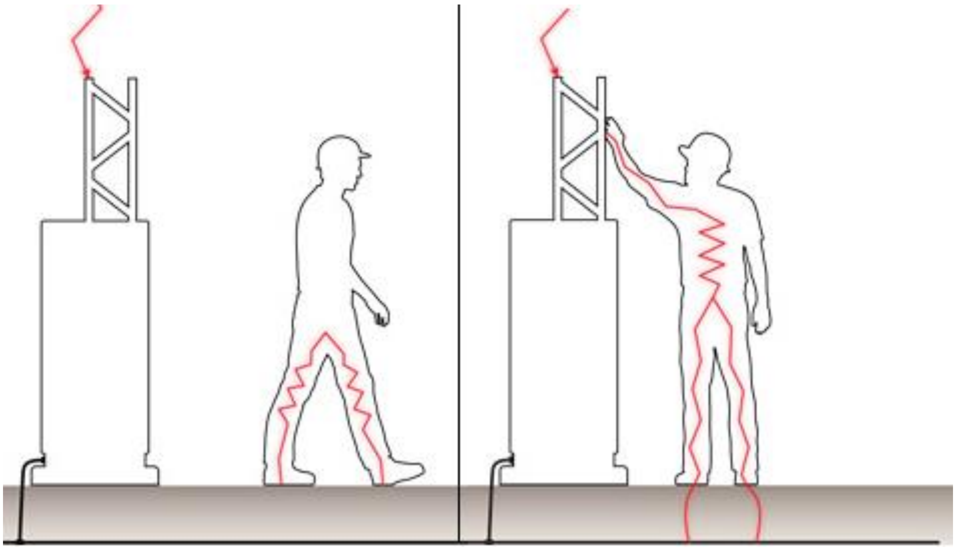

Figure 10. Demonstrative designator of step voltage and touch voltage [16]

It should be noted that when calculating ground protection, it is necessary to take into account the different layers of the ground.

Let's make an analytical calculation of the protective earthing:

The total length of horizontal earthing devices can be found using the following formula:

$$l_h = (24+2)\cdot 8 + (60+2)\cdot 3 = 394 \text{ m} \tag{1}$$

where 24 and 60 are substation dimensions, m,

8 and 3 are number of horizontal conductors in each direction.

Figure 11 shows the grounding system arrangement.

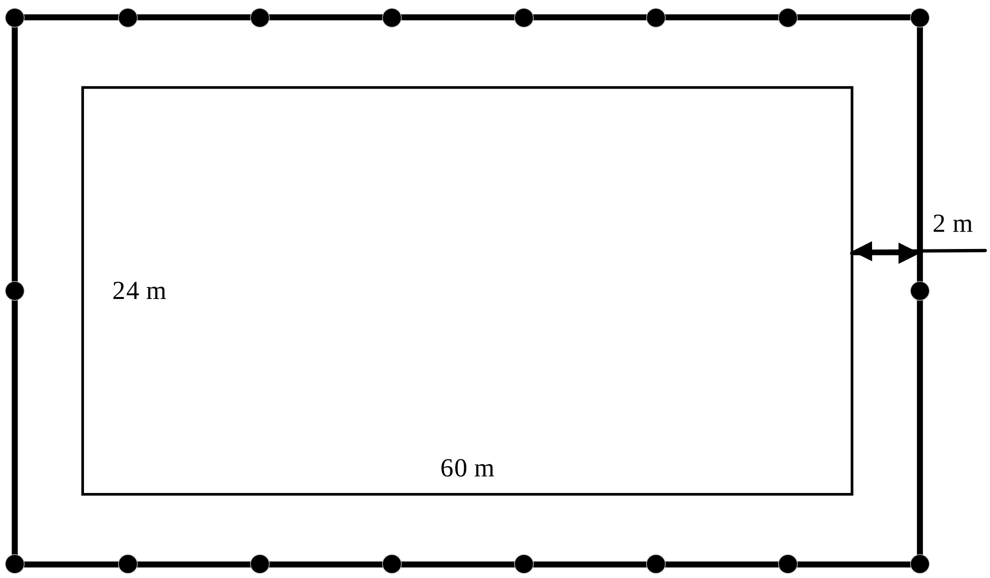

Figure 11. Grounding system area

The soil on which the EES will be designed is multi-layered, which should be taken into account in the calculations. The soil resistivity of the first layer is chosen $\rho_1 = 1000$ Ohm-m [17]. The soil resistivity of the second layer is chosen $\rho_2 = 100$ Ohm-m [17]. The soil resistivity is calculated by the formula (2) [18]:

$$\rho_{soil} = \frac{\rho_1 \cdot \rho_2 \cdot L}{[\rho_1 \cdot (L - H + f) + \rho_2 \cdot (H - f)]} = \frac{1000 \cdot 100 \cdot 8}{[1000 \cdot (8 - 5 + 0.7) + 100 \cdot (5 - 0.7)]} = 193.7 \text{ Ohm,} \tag{2}$$

where L is length of vertical rods, m,

H is topsoil depth, m,

f is the laying depth of the vertical ground conductor, m (Appendix A, Figure A. 2).

It is supposed to create the grounding device in the form of vertical rods with L = 8 m length and 12 mm cross section. The primary number of rods is nine.

The seasonality fluctuation coefficient is selected from the climatic conditions at the proposed construction site [17]. I have selected the third climatic zone (Appendix A, Table A. 1).

$$\rho_{soil\ v} = k_v \cdot \rho_{soil} = 1.5 \cdot 193.7 = 290.56 \text{ Ohm·m} \tag{3}$$

$$\rho_{soil\ h} = k_h \cdot \rho_{soil} = 2.3 \cdot 193.7 = 445.52 \text{ Ohm·m} \tag{4}$$

where ρ_{soil} is soil resistivity, Ohm·m,

k_v is seasonal coefficient for vertical earth electrodes,

k_h is seasonal coefficient for horizontal earth electrodes.

The resistance of the vertical grounding conductor is determined by the following formula [20]:

$$r_v = \frac{\rho_{soil\ v}}{2\pi L}\left(\ln\frac{2L}{d} + \frac{1}{2}\ln\frac{2t + \frac{L}{2}}{2t - \frac{L}{2}}\right) = \frac{290.56}{2 \cdot \pi \cdot 8}\left(\ln\frac{2 \cdot 8}{20 \cdot 10^{-3}} + \frac{1}{2}\ln\frac{2 \cdot 4.2 + \frac{8}{2}}{2 \cdot 4.2 - \frac{8}{2}}\right) = 41.27 \text{ Ohm·m} \tag{5}$$

where $\rho_{soil\ v}$ is soil resistivity of vertical conductor with seasonality fluctuation coefficient, Ohm·m,

L is length of vertical rods, m,

d is the diameter of vertical conductors, mm,

t is the depth from the beginning of the earth electrode to the middle of the vertical earth electrode:

$$t = f + \frac{L}{2} = 0,7 + \frac{7}{2} = 4.2 \text{ m} \tag{6}$$

The vertical conductor resistance in the grounding device loop taking into account the utilization rate:

$$R_v = \frac{r_v}{\eta_v} = \frac{41.27}{0.53} = 77.86 \text{ Ohm} \tag{7}$$

where r_v is resistance of the vertical grounding conductor, Ohm·m,

η_v is utilization rate for the vertical ground conductors.

The resistance of horizontal steel tape in grounding devise loop is determined by the formula [21]:

$$r_h = \frac{\rho_{soil\ h}}{\pi l_h} \ln \frac{1.5 \cdot l_h}{\sqrt{b \cdot f}} = \frac{445.7}{\pi \cdot 394} \ln \frac{1.5 \cdot 394}{\sqrt{20 \cdot 10^{-3} \cdot 0.7}} = 3.07 \text{ Ohm} \tag{8}$$

where $\rho_{soil\ h}$ is soil resistivity of horizontal conductor with seasonality fluctuation coefficient, Ohm·m,

l_h is total length of horizontal conductors, m,

b is the diameter of wires in vertical conductors, mm^2,

f is the laying depth of the vertical ground conductor, m.

The horizontal conductor resistance in the grounding device loop taking into account the utilization rate:

$$R_h = \frac{r_h}{\eta_h} = \frac{3.07}{0.45} = 6.81 \text{ Ohm} \tag{9}$$

where η_h is utilization rate for the horizontal ground conductors,

r_h is the resistance of horizontal steel tape, Ohm·m.

The required resistance of the grounding device used for both electrical installations with voltages of 1 kV or higher must not exceed $R_{GS} = 4$ Ohm [22].

The required resistance of the vertical rods is:

$$R_v^{'} = \frac{R_h \cdot R_{GS}}{R_h - R_{GS}} = \frac{6.81 \cdot 4}{6.81 - 4} = 9.7 \text{ Ohm} \tag{10}$$

where R_h is the horizontal conductor resistance, Ohm,

R_{GS} is maximum allowable ground resistance, Ohm.

The refined number of vertical conductors:

$$N_v^{'} = \frac{R_v}{R_v^{'}} = \frac{77.17}{9.7} = 8.6 \text{ Ohm} \tag{11}$$

where R_v is vertical conductor resistance in the grounding, Ohm,

$R_v^{'}$ is required resistance of the vertical rods, Ohm.

Thus, the clarified number of vertical ground conductors is 9. The vertical conductors resistance in this case:

$$R_v^{''} = \frac{r_v}{N_v^{'} \cdot \eta_v^{'}} = \frac{41.21}{9 \cdot 0.53} = 8.65 \text{ Ohm} \tag{12}$$

where r_v is resistance of the vertical grounding conductor, Ohm·m,

$N_v^{'}$ is the clarified number of vertical ground conductors,

The grounding system resistance will be determined as [23]:

$$R_{GS} = \frac{R_h \cdot R_v^{"}}{R_h + R_v^{"}} = \frac{6.81 \cdot 8.65}{6.81 + 8.65} = 3.81 \text{Ohm} \tag{13}$$

where R_h is the horizontal conductor resistance, Ohm,

$R_v^{"}$ is the vertical conductors resistance, Ohm.

3.2. Step and Touch Voltages Calculation

Human safety depends on preventing the absorption of a critical amount of shock energy before the fault is corrected and the system is de-energized. The maximum control voltage of any fault circuit must not exceed the limits found below [24].

The surface layer coefficient is calculated using the following formula [25]:

$$C_s = 1 - \frac{0.09 \cdot (1 - \frac{\rho_{soil}}{\rho_{layer}})}{2 \cdot h_{layer} + 0.09} = 1 - \frac{0.09 \cdot (1 - \frac{193.7}{5000})}{2 \cdot 0.2 + 0.09} = 0.82 \tag{14}$$

where h_{layer} is thickness of the surface layer, m,

ρ_{soil} is the soil resistivity, Ohm·m,

ρ_{layer} is resistivity of the surface layer, Ohm·m.

According to the substation design, the surface layer consists of gravel with a thickness of 0.2 m, its resistivity is 5000 Ohm·m [25].

Allowable step voltage values for a worker with an average weight of 50 (15) and 70 (16) kg [26]:

$$E_{step50} = (1000 + 6 \cdot C_s \cdot \rho_{layer}) \cdot \frac{0.166}{\sqrt{t_s}} = (1000 + 6 \cdot 0.82 \cdot 5000) \cdot \frac{0.166}{\sqrt{0.1}} = 13490 \text{ V} \tag{15}$$

$$E_{step70} = (1000 + 6 \cdot C_s \cdot \rho_{layer}) \cdot \frac{0,157}{\sqrt{t_s}} = (1000 + 6 \cdot 0.82 \cdot 5000) \cdot \frac{0.157}{\sqrt{0.1}} = 12760 \text{ V} \tag{16}$$

where t_s – the duration of the fault in seconds, by the condition of setting the protection this time must be equal to 0.1 second,

C_s is surface layer coefficient,

ρ_{layer} is resistivity of the surface layer, Ohm·m.

Limits of allowable touch voltage calculated for a body weight of 50 (17) and 70 (18) kg [27]:

$$E_{touch50} = (1000 + 1.5 \cdot C_s \cdot \rho_{layer}) \cdot \frac{0,166}{\sqrt{t_s}} = (1000 + 1.5 \cdot 0.82 \cdot 5000) \cdot \frac{0.166}{\sqrt{0.1}} = 3767 \text{ V} \quad (17)$$

$$E_{touch70} = (1000 + 1.5 \cdot C_s \cdot \rho_{layer}) \cdot \frac{0.157}{\sqrt{t_s}} = (1000 + 1.5 \cdot 0.82 \cdot 5000) \cdot \frac{0.157}{\sqrt{0.1}} = 3563 \text{ V} \quad (18)$$

where t_s – the duration of the fault in seconds, by the condition of setting the protection this time must be equal to 0.1 second,

C_s is surface layer coefficient,

ρ_{layer} is resistivity of the surface layer, Ohm·m.

3.3. Calculation of Short Circuit

The parameters of the substitution circuit will be calculated in named units. In this case all magnetically coupled circuits are represented as an equivalent electrically coupled circuit. The manual calculation of the circuit parameters is done with approximate consideration of the transformation coefficients.

Will be introduced power supplies and connections between them and the fault location which will be surrounded by short-circuit currents. The fault location will be marked on the structural diagram in the Figure 12. As a result of the analysis, the short-circuit current will be calculated.

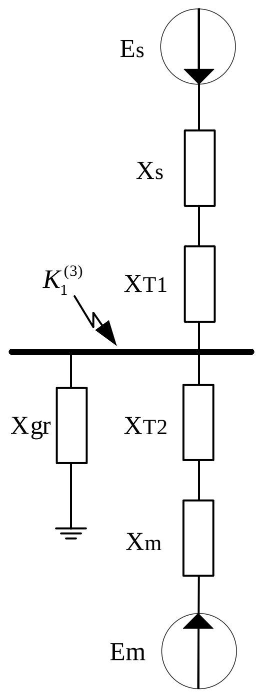

Figure 12. Equivalent circuit of a simplified power system

Calculation of the parameters of the equivalent circuit.

Calculations of the System:

$$x_1 = x_s = \frac{{U_{HV1}}^2 \cdot {U_{LV1}}^2}{S_S \cdot {U_{HV1}}^2} = \frac{121^2 \cdot 10.5^2}{2500 \cdot 121^2} = 0.044 \text{ kA} \quad (19)$$

where U_{HV1} is a voltage on the primary winding of the transformer T1,

U_{LV1} is a voltage on the secondary winding of the transformer T1,

S_S is an apparent power of the System, MVA.

Parameters of the asynchronous motor:

$$x_4 = x_m = x_{oe} \cdot \frac{{U_m}^2 \cdot {U_{HV2}}^2}{S_m \cdot {U_m}^2} = 0.151 \cdot \frac{6^2 \cdot 10.5^2}{0.46 \cdot 6^2} = 36.25 \text{ Ohm} \quad (20)$$

$$I_0 = \frac{P_н \cdot U_0}{\sqrt{3} \cdot U_н \cdot \cos\varphi \cdot \eta} = \frac{0.4 \cdot 0.57}{\sqrt{3} \cdot 6 \cdot 0.87 \cdot 0.94} = 0.027 \text{ kA}, \quad (21)$$

where $U_0 = \frac{U_н}{U_{HH1}} = \frac{6}{10.5} = 0.57$ kV,

U_m is a voltage of the asynchronous motor, kV,

U_{HV2} is a high voltage of the transformer T2, kV,

$x_{oe} = 15.118\%$.

$$\sin\varphi = \sqrt{1 - \cos^2\varphi} = \sqrt{1 - (0.87)^2} = 0.49 \quad (22)$$

$$E_2 = E_M = \sqrt{\left(\frac{U_{LV1}}{\sqrt{3}} \cdot \cos\varphi\right)^2 + \left(\frac{U_{LV1}}{\sqrt{3}} \cdot \sin\varphi - I_0 \cdot x_4\right)^2} = \sqrt{5.27^2 + 2.02^2} = 5.64 \text{ kV} \quad (23)$$

where $\cos\varphi$ is a power factor,

I_0 is a current of the asynchronous motor, kA.

Transformer T-1:

$$x_2 = x_{T1} = \frac{U_{K\%}}{100} \cdot \frac{{U_{HV1}}^2}{S_{T1}} \cdot \frac{{U_{LV1}}^2}{{U_{HV1}}^2} = 0.105 \cdot \frac{121^2}{10} \cdot \frac{10.5^2}{110^2} = 1.16 \text{ Ohm} \quad (24)$$

where $U_{K\%}$ is a short circuit voltage of the transformer T1,

S_{T1} is an apparent power of the transformer T1, MVA,

U_{HV1} is a high voltage of the transformer T1, kV,

U_{LV1} is a low voltage of the transformer T1, kV.

Transformer T-2:

$$x_3 = x_{T1} = \frac{U_{K\%}}{100} \cdot \frac{{U_{HV2}}^2}{S_{T2}} = 0.055 \cdot \frac{10.5^2}{0.63} = 9.62 \text{ Ohm} \quad (25)$$

where $U_{K\%}$ is a short circuit voltage of the transformer T2,

S_{T2} is an apparent power of the transformer T2, MVA,

U_{HV2} is a high voltage of the transformer T2, kV.

Then I have carried out the first transformation of the substitution scheme with respect to the short-circuit point. Serial addition of the circuit branches is used. The transformation of the substitution scheme relative to the point is shown in Figure 13.

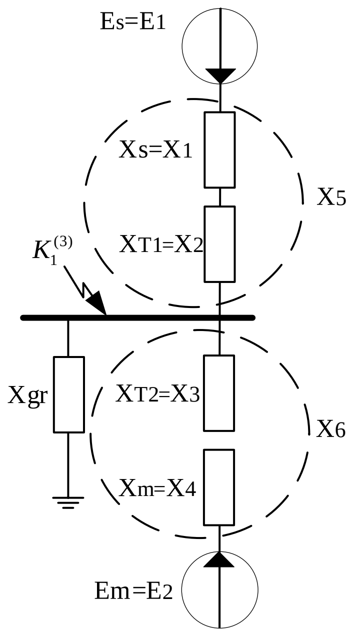

Figure 13. Converted substitution scheme

$$x_5 = x_1 + x_2 = 0.04 + 1.16 = 1.20 \text{ Ohm} \quad (26)$$

Then a parallel transformation is performed and a star-incomplete triangle through the distribution coefficients. The scheme is shown in Figure 14.

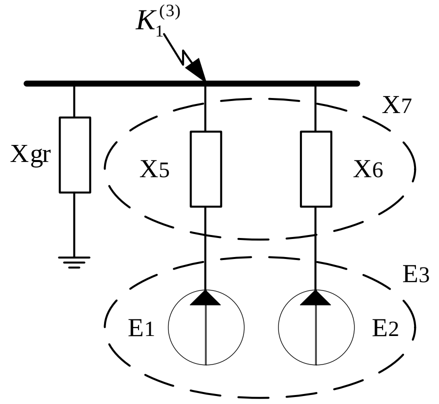

Figure 14. Converted substitution scheme

$$x_7 = \frac{x_5 \cdot x_6}{x_5 + x_6} = \frac{1.2 \cdot 45.87}{1.2 + 45.87} = 1.71 \text{ Ohm} \tag{27}$$

$$x_{eqv} = \frac{x_7 \cdot x_{gr}}{x_7 + x_{gr}} = \frac{1.71 \cdot 3.81}{1.71 + 3.81} = 1.18 \text{ Ohm} \tag{28}$$

$$E_3 = E_{eqv} = \frac{E_1 \cdot x_6 + E_2 \cdot x_5}{x_5 + x_6} = \frac{284.9}{47.08} = 6.05 \text{ Ohm} \tag{29}$$

Find the short-circuit current:

$$I_{SC} = \frac{E_{eqv}}{x_{eqv}} = \frac{6.05}{1.18} = 5.127 \text{ kA} \tag{30}$$

Calculation of the maximum grid current [28]:

$$I_G = D_f \cdot S_f \cdot I_{fg} = 1 \cdot 0.27 \cdot 5127 = 1384.3 \text{ A} \tag{31}$$

where $S_f = 0.27$ A, $2D_f = 1$.

Calculation of the ground potential rise [29]:

$$GPR = I_G \cdot R_G = 1384.3 \cdot 3.81 = 5274 \text{ V} \tag{32}$$

4. Numerical Calculation with the Program

Numerical calculation is the method of boundary elements. Such as the method for solving a system of partial differential equations, such as the modified Newton method for finding the electromagnetic field pattern and the method of nodal potentials, to calculations of short-circuit currents.

As was mentioned in the chapter 1, the researched object is an electrical energy system. For a visual representation, the modeling network is shown below in the Figure 15.

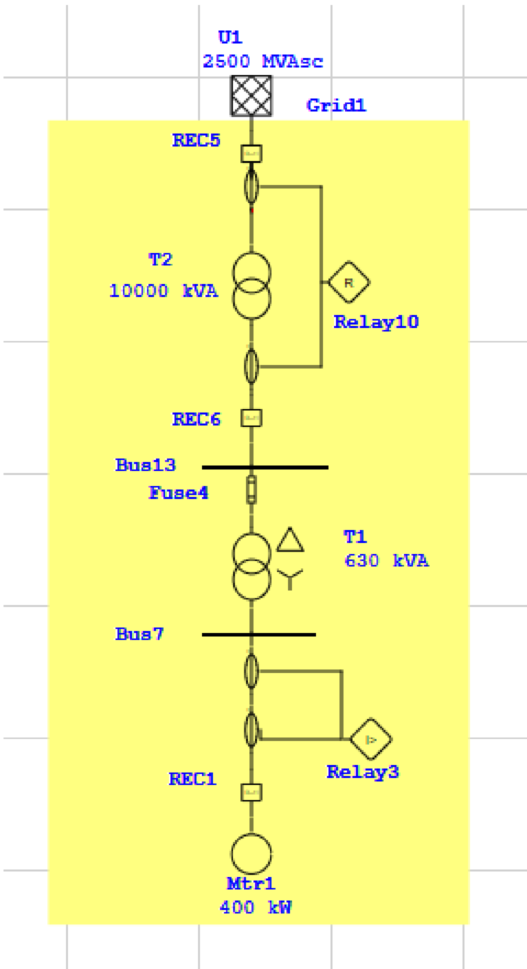

Figure 15. The modeling system

On the given scheme the basic elements are protected devices and protection devices.

Considered system consists of following main components:

- Grid1 (yellow area) – Grounding system;
- U1 – System
- Fuse4 – High rupturing capacity fuse;
- T2 and T1 – Two winding transformers;
- Mtr1 – Asynchronous motor;
- Relay10 and Relay3 – Differential relay and overcurrent relay.

The system is structurally divided into three compartments: section with the protection of the transformer with 10 000 kVA which protected by differential relay, the second section is a section with the transformer with 630 kVA which protected by fuse and the last section with the motor, where protection is overcurrent relay.

In the circuit high voltage circuit breakers REC5 and REC6 perform differential shutdown of the transformer T2. The signal, which comes from the relay Relay10. Transformer T1 is protected by a high-voltage fuse Fuse4. The Mtr4 high voltage motor is switched off by the REC1 high-voltage circuit breaker, whose signal is received from the Relay3 relay.

4.1. Configuring of Equipment Parameters

To set the equipment to be protected, we enter the already known transformer values. Figure 16 shows catalog data of the equipment, where the values of its primary and secondary voltages and power are adjusted. Automatic calculation of load current for primary and secondary transformer windings is also performed. There is a selection of resistances, showing the transformer characteristics. Most of the transformer parameters are automatically adjusted.

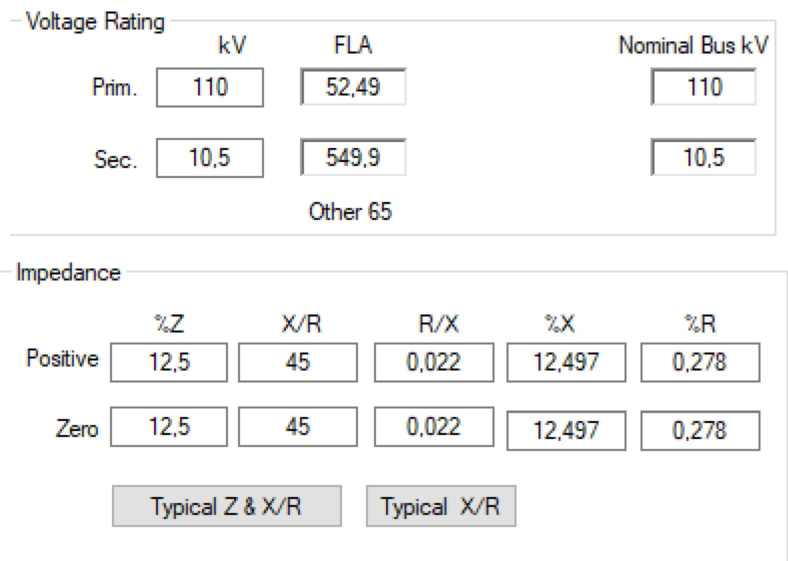

Figure 16. The parameters of the transformer T2

The following will show the values of voltages and resistances which were set when the transformer T1 was designated. Transformer T1 in this scheme is designed to reduce the voltage level from 10.5 kV to the operating voltage of the motor 6 kV. Values of resistances are calculated automatically by the program. The values are shown in Figure 17.

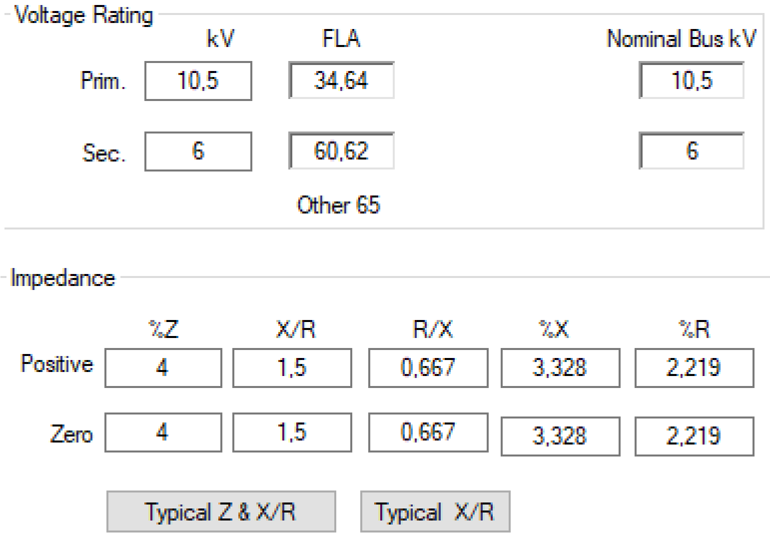

Figure 17. The parameters of the transformer T1

The consumer I have chosen as an electric motor with a rated power of 400 kW and a rated voltage of 6 kV. The load parameters are shown in Figure 18.

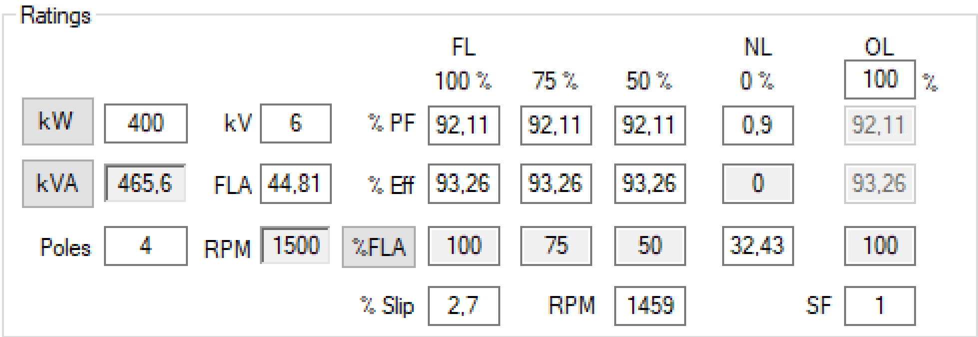

Figure 18. The parameters of the motor

4.2. Configuring Protection Parameters

Let's consider the setting of current transformer protection. Current parameters are filled in on the basis of calculated values of ratio of transformation coefficient. For the HV side the ratio is chosen 100/5, for the LV side the ratio is chosen 600/5. Parameters of current transformers are shown on Figure 19 and Figure 20 [14].

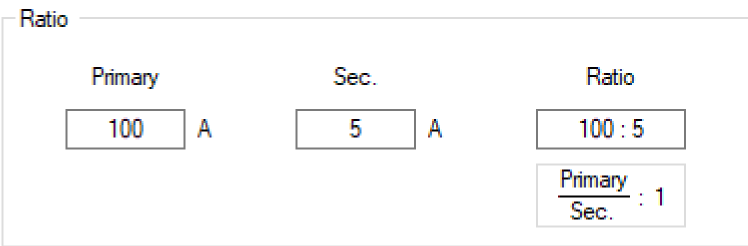

Figure 19. Parameters of the current transformer on the HV side from CT16

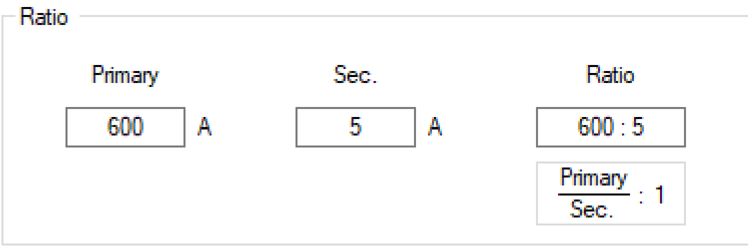

Figure 20. Parameters of the current transformer on the LV side from CT17

Then current transformers are connected to a differential relay, the setting of which is shown in Figure 21.

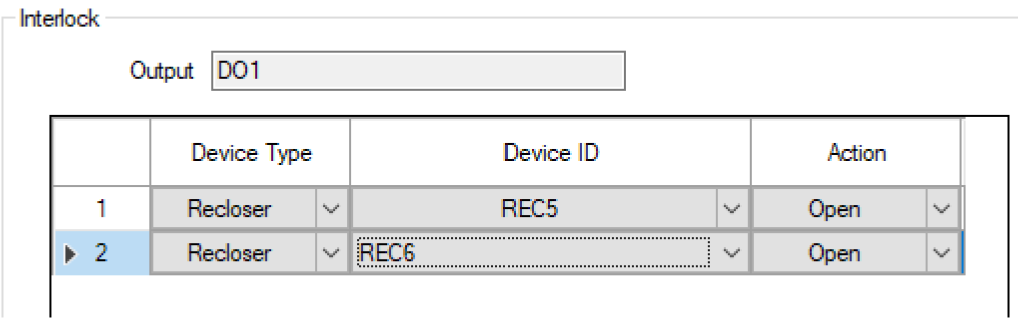

Figure 21. Setting of the parameters Relay 10

In Figure 21 shows that the shutdown signal will be fed to the high voltage switches REC5 and REC6.

The protection of the transformer T1 is applied with the fuse Fuse 4.

Selection of the values for the Fuse4 is made on the basis of calculations of the current flowing in the network, taking into account the coefficient required for the selection of protective equipment. The setting of the fuse parameters is shown in Figure 22. The fuse with the fusible link is less reliable means for providing protection of electrical equipment, but in the given project it has been chosen to show protective characteristics of various types of protection. When selecting a fuse, the main characteristics are the maximum voltage for which the fuse is designed (17.5 kV) and the current of its operation (80 A) [10].

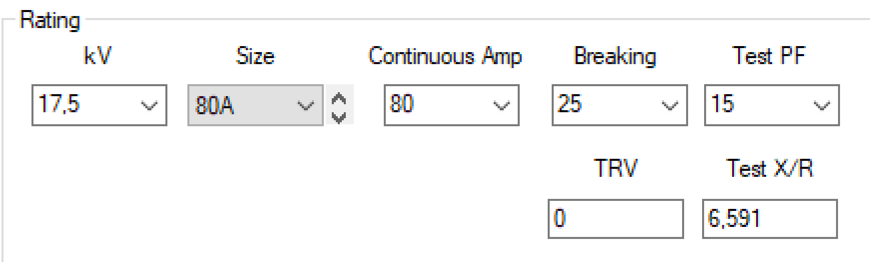

Figure 22. Settings of parameters Fuse 4

Motor protection is provided by means of maximum current protection and current cut-off. The secondary current of the relay is 2.5 A for the selected switching setting of the sensor. The primary relay current is 50 A for the selected setting of the sensor operation for overcurrent protection. For protection operating the value of primary relay current is 1200A, when the secondary relay current is equal to 60 A [15].

The values of motor protection parameters are shown in Figure 23.

Figure 23. Settings of motor protection parameters

4.3. Checking of Relay Protection Operation

To make sure that the relay protection of the equipment works correctly, it is necessary to simulate the short-circuit at different protected objects of the electric power system.

Simulation will be performed using heavy duty three-phase short-circuit. The first object of short-circuit modeling will be an electric motor. The result of the short-circuit is shown in Figure 24A. The second object of modelling is the step-down transformer T1 which protection occurs by a fuse. The result is shown in Figure 24B. The third object of short-circuit is the step-down transformer T2, protection of which occurs by differential protection. The result is shown in Figure 24C.

In the Figures, the designations with numbers one, two, and three indicate the order in which the protections are operated. From these designations it is visible, that operation of protections occurs selectively at the occurrence of short circuit that testifies about correct adjustment of protections.

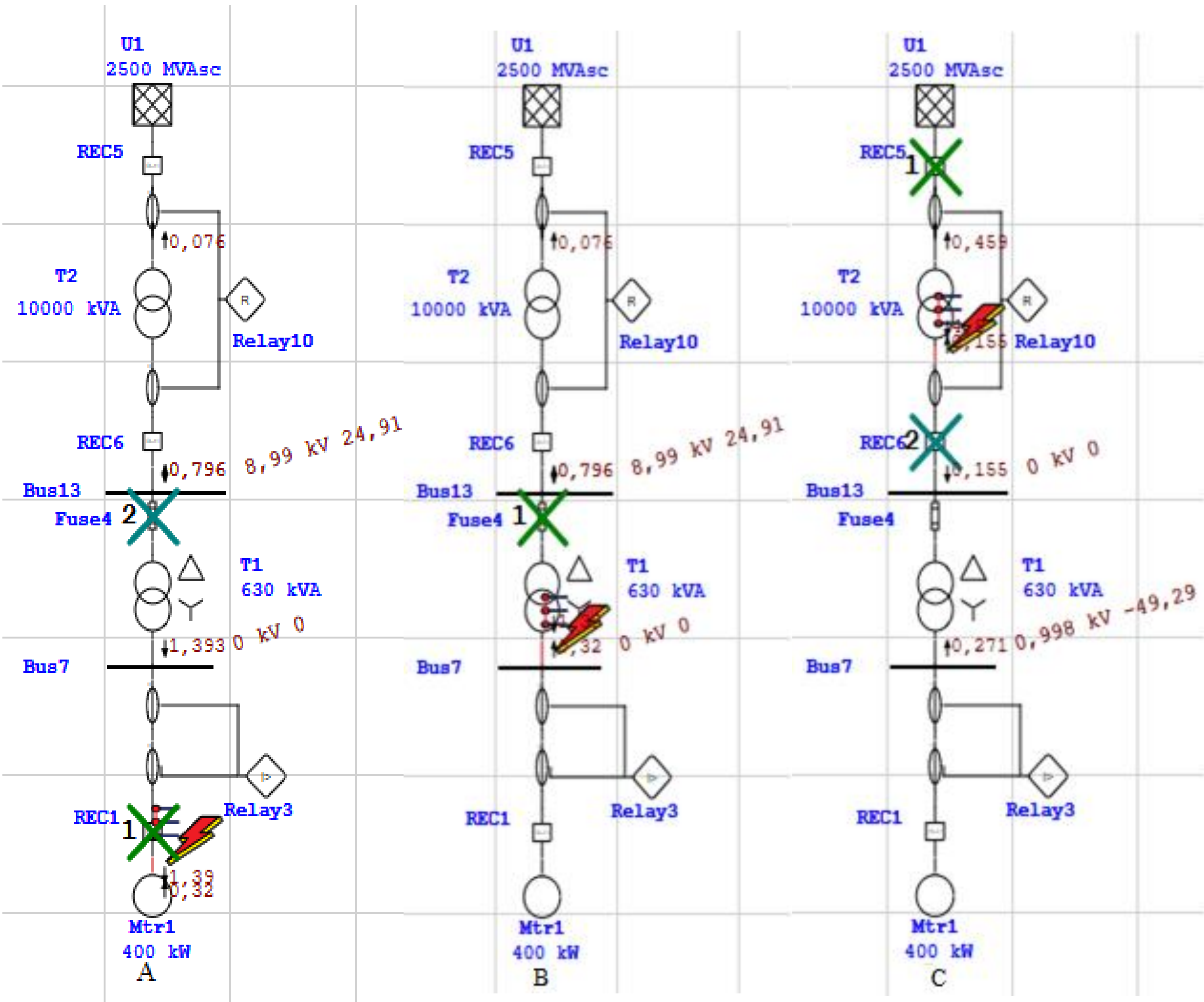

Figure 24. Selective operation of switches

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
35,0	REC1	1,393	1,0	35,0	Tripped by Relay3 Phase - OC1 - 50
35,0	Relay3	1,393	1,0	35,0	Phase - OC1 - 50
64,8	Fuse4	0,796	64,8		

Figure 25. The running time of the protection

Figure 25 shows the response time of the protections in the occurrence of a short-circuit on the motor. It is possible to notice that the first operating of protection is carried out by switches REC1 and protective relay Relay3 in 35 msec after occurrence of short-circuit. After that the Fuse4 fuse is already operated after 64.8 msec.

4.4. Selectivity of circuit breakers

For the numerical calculation it is necessary to make a selection of protective and protected equipment, which I have made in the software package ETAP.

For correct operation and adjustment of the selectivity of protection, was built a time-current characteristic, showing the correctly adjusted protective equipment. The time-current characteristic of the protection is shown in Figure 26.

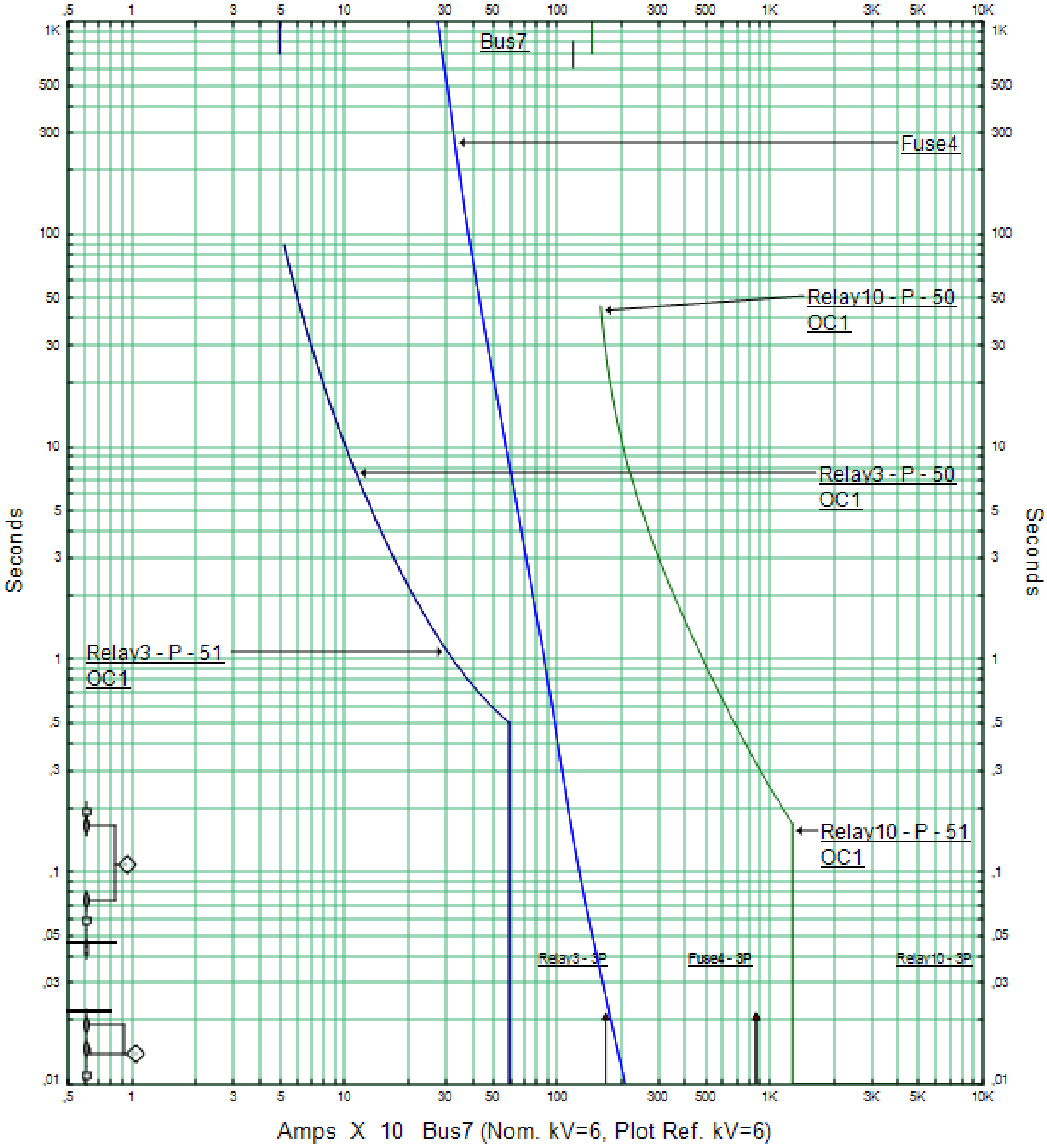

Figure 26. Time-current characteristics

Selectivity map is a set of time-current characteristics of protective equipment, constructed in the same levels, and shows the detuning from each other by current and time. Protection settings are considered selective when their time-current characteristics do not intersect and do not overlap [37]. Relay 3 has overload protection and protects the motor. The green line of Relay 10 is closer to the system, which means that the current has a higher value. The blue line, signed as Fuse 4, shows the protective characteristic of the high voltage fuse, which protects the transformer T1.

4.5. Modeling of the Grounding System

After completing the design process and calculating the parameters as well as the safe voltage limits, the software simulation can be performed. The software model is simulated in ETAP and is based on finite element analysis. This program allows you to make grounding schemes of any complexity, consisting of wires laid in three mutually perpendicular directions. The program partitions the grounding scheme into small straight segments and calculates the mutual resistances of these segments, as well as the allowable touch and step voltages on these segments.

I have chosen the average weight of the worker equal to 70 kg, and the average temperature of the ground equals $10^{\circ} C$. This parameter is used to determine the current carrying capacity of grounding conductors.

The short-circuit current is chosen on the basis of the data obtained by the simulation of the program short-circuit. The initial data for grounding system are shown in Figure 27.

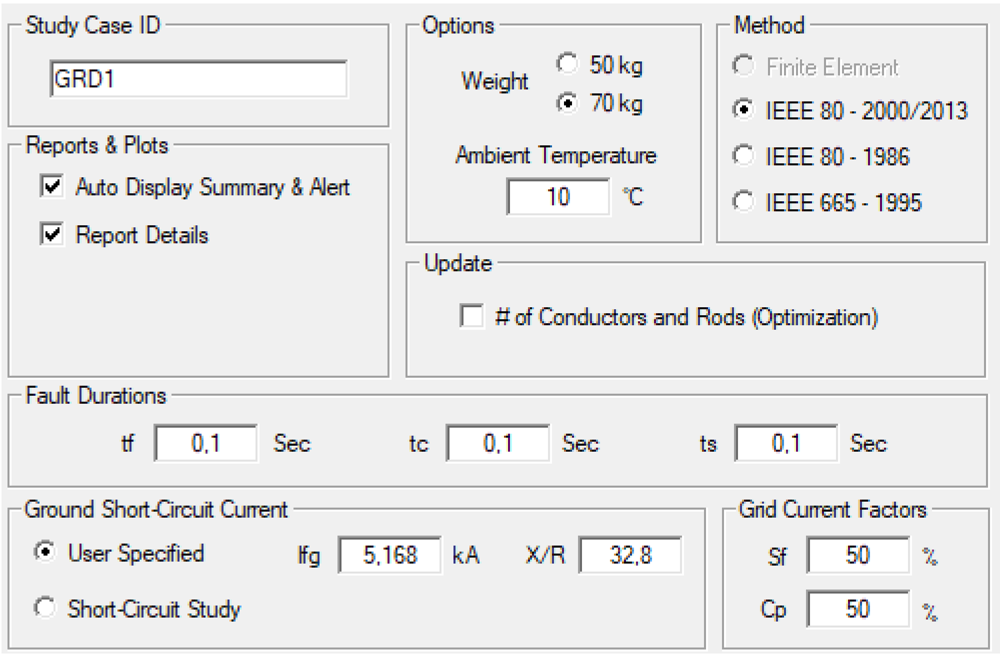

Figure 27. Data for modelling the grounding system in the ETAP software system

In the same way, Figure 28 takes into account and selects the resistivity of the ground with the depth of the layers.

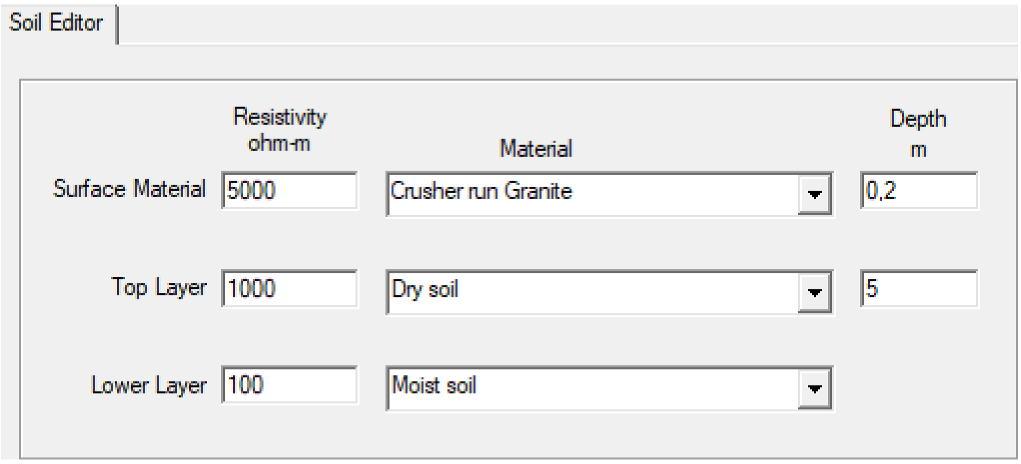

Figure 28. Data for modelling the grounding system in the ETAP software system

Figure 29 shows the test results of the grounding system.

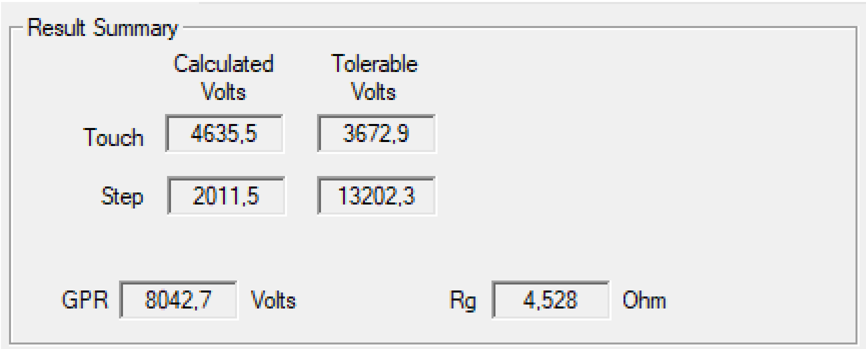

Figure 29. The result of designing the grounding system in the ETAP software system

The results show that the touch voltage value is equal to 4635.5 V, when the allowable is 3672.9 V. And the step voltage value is equal to 2011.5 V, when the allowable is 13202.3 V. According to the data, we can see that the values of touch voltage are out of the allowable values, which indicates the need to recalculate the initial data. And also, the resistance value of the earthing device is out of the permissible values.

5. Algorithm of Calculation of Protection of the Electrical Equipment

During the analytical and numerical calculations performed it was found necessary to recalculate the data, as in the numerical method when simulating the grounding system, the value of touch voltage and grounding value of the earthing device does not comply with safety standards and are outside acceptable values, which represent a risk of electric shock.

In this case, it is necessary to recalculate the data based on the following algorithm provided in Figure 30.

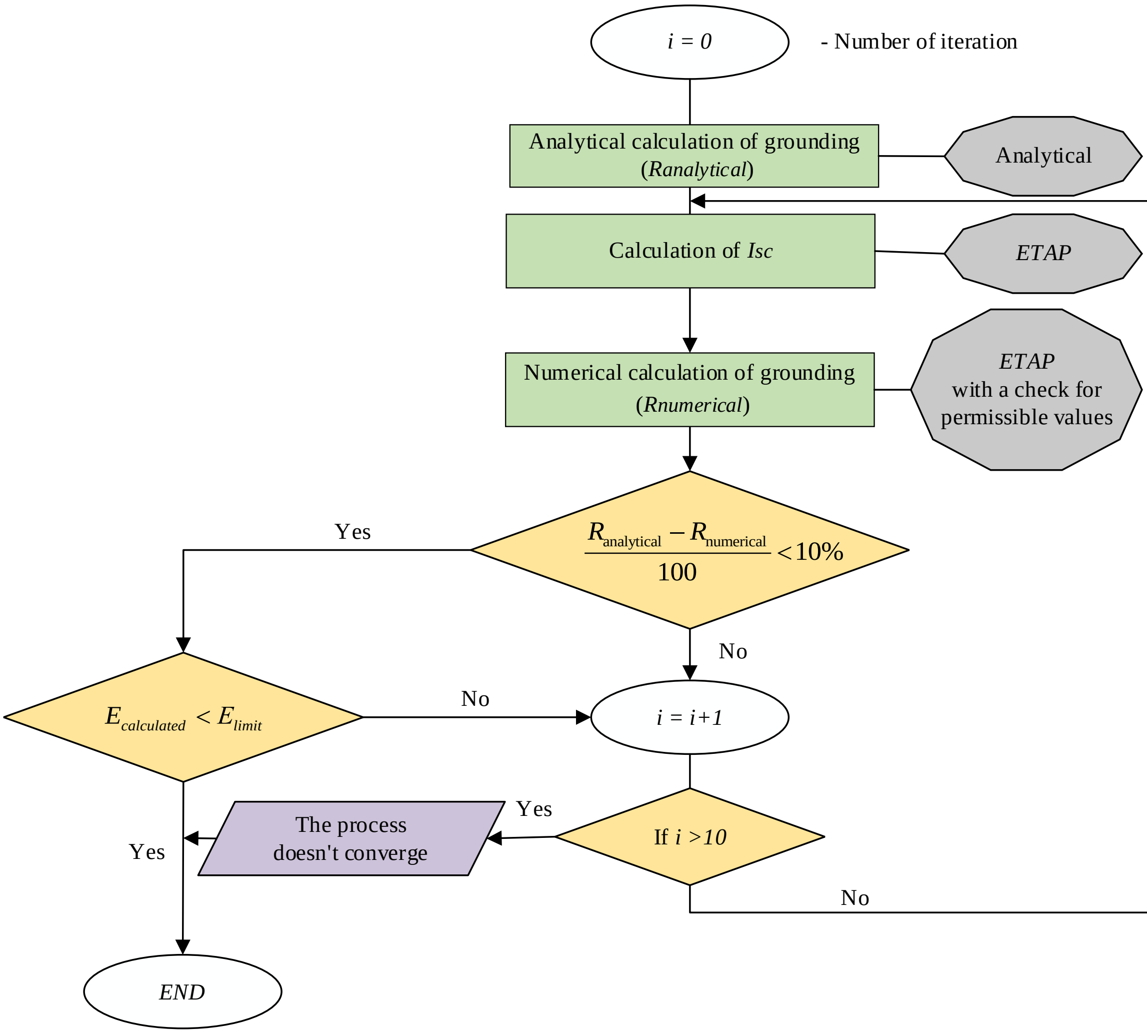

Figure 30. Calculation algorithm

After performing the zero iteration, it was determined that the values do not conform to the given limits, therefore, it is necessary to return to the beginning of the provided algorithm and make the next iteration.

Because the touch voltage values were out of limits on the last condition, it was necessary to go back through the cycle and make a numerical recalculation of the ground. When doing a numerical recalculation of the ground, there is a recalculation of the ground structure. Where there is a change in the earth's structure. In the process of which the earth resistance value changes.

In the second action the short-circuit current is recalculated with the new condition of the earth resistance value. But for this circuit its value practically does not change (remain within $\pm\ 0{,}1\,\mathrm{kA}$).

In the third step, the numerical calculation of the ground in the software system, followed by a comparison of values and finding the maximum allowable values of voltages.

The calculations were performed using the same methodology. Figure 31 shows the final results based on the numerical method.

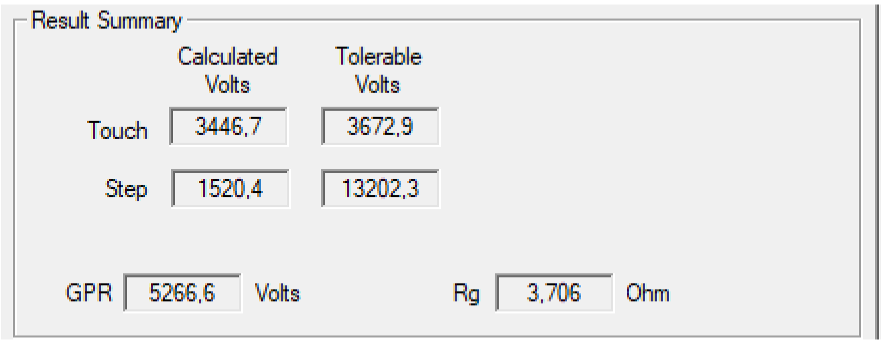

Figure 31. Results of the numerical method of 5 iterations

According to the results shown in Figure 31, you can see that the data are within the allowable values, from which we can conclude that the methodology is correct.

Table 3 provides the results of a comprehensive.

Table 3. Analytical and modeled values

<table>
<tr><th rowspan="2">Settlement system</th><th rowspan="2">Analytical values</th><th colspan="3">Numerical values</th><th rowspan="2">Error, %</th></tr>
<tr><th colspan="2">Algorithm</th><th>Direct calculation</th></tr>
<tr><td>Short circuit current</td><td>5127 A</td><td colspan="2">4804 A</td><td>4804 A</td><td>6.72</td></tr>
<tr><td>Resistance of the grounding device</td><td>3.81 Ohm</td><td colspan="2">3.706 Ohm</td><td>4.528 Ohm</td><td>2.8</td></tr>
<tr><td>Calculation of ground potential (GPR)</td><td>5274 V</td><td colspan="2">5266.6 V</td><td>8042.7 V</td><td>0.14</td></tr>
<tr><td rowspan="2">Step voltage value</td><td rowspan="2">12760 V</td><td>Limit</td><td>13202.3 V</td><td>13202.3 V</td><td rowspan="2">3.35</td></tr>
<tr><td>Calc.</td><td>1520.4 V</td><td>2011.5 V</td></tr>
<tr><td rowspan="2">Touch voltage value</td><td rowspan="2">3563 V</td><td>Limit</td><td>3672.9 V</td><td>3672.9 V</td><td rowspan="2">3.08</td></tr>
<tr><td>Calc.</td><td>3446.7 V</td><td>4365.5 V</td></tr>
</table>

The software realization of the grounding system calculation allows you to build a diagram of electromagnetic fields, which is shown in Appendix A in Figures A.3 - A.5. The diagrams show the step potential voltage limits, touch potential voltage limits and absolute voltage limits in the protected area. The diagrams are marked with color symbols that show the voltage limits, the limits of which range from 50 to 1100 V.

According to the resulting graphs, with the software simulation, the designed grounding system provides reliable protection for people and animals from physical damage due to faults.

6. Evaluation of Proposed Prediction Methods and the Cost-Benefit Analysis

The operation of the protection is very important for the company, because if the protection does not work, we will have to spend money to repair or buy new equipment. Also, the possible failure of protection leads to the danger of life of staff and animals that may be in the dangerous area. Accordingly, the lower the percentage of incorrect operation of relay protection, the more it can save money to the company, as well as save the lives and health of people and animals.

The last decade is characterized by wide application of digital (microprocessor) equipment in relay protection. This is due to the significant advantages of digital protection in comparison with analog relays. In particular, these advantages are the following:

- Increased equipment reliability, weight and size of devices due to a significant reduction in the number of blocks and connections used;
- Improved quality of protective functions (sensitivity, selectivity, static and dynamic stability of operation);
- Possibility of registering processes and events and analysis of faults occurred in the power system;
- New possibilities of protection control and transfer of information from it to more distant places

Principles of construction and algorithms used in digital relay protection differ from those used in analog relay protection, due to the significantly different technical basis and methods of information processing.

But the digital protection also has disadvantages compared to the analog protection:

- Narrow operating temperature range. In contrast to the analog protection, digital protection is demanding to comply with climatic parameters: in winter the room will have to be heated, and in summer to include air conditioners to cool the air.
- There is also a possibility of software failure. But it is worth noting that the modern software is highly stable and failure is rather an exception to the rule [7].

In this section, I will compare differential protection analog and digital from an economic point of view.

6.1. Inputs for Economic Model

The lifetime of the digital protection [29] is at least 25 years, with periodic maintenance every three - six years [30]. The periodic maintenance will be performed every five years, after the installation of the equipment [30].

The lifetime of the analog protection [31] is at least 25 years, and I will perform the periodic maintenance every five years [32].

Let's assume that this project has a reserve transformer. Which allows to minimize equipment downtime, due to the possibility of switching to the reserve transformer, in case of failure of the main transformer.

In this paper I will calculate both options using the same economic model, changing only the capital expenditures (CAPEX): the cost of equipment, its transportation, installation and maintenance costs.

To create an economic model, it is necessary to consider all the economic parameters of the model. Table 4 shows the scenarios that will be compared with each other in terms of CAPEX. For the economic evaluation of my work will take into account the possible percentage of failure of the protection, which protects the transformer. Saved money from the possible failure of the transformer and the repair of equipment and will be the benefit that will be obtained in the project. As protection is installed in order to prevent the failure of the device.

I have found and calculated the prices of protective equipment together with the providers of this equipment. After consulting with the electrical equipment company, it was decided to take the cost of delivery of the equipment equal to 15% of the cost of the equipment. As the installation of the equipment is easily accessible and installed inside the building, it will not deliver any additional costs for the installation of this equipment. The cost of installation and design of each device is assumed to be 5%. Table 4 shows the total capital investment in rubles (RUB), and the converted data values in euros (EUR).

Table 4. Total investments of the protection

Type of protection	Total investments, RUB	Total investments, EUR
Digital protection “Sirius – T”	297 808.8	3 275.9
Analog protection “EPZ 1031-90.1”	222 000	2 442

The main components of the economic model of the project are described below.

6.1.1. Calculation of Profit

To calculate the profits of the two scenarios, many aspects were considered that suggest a possible income from the installation of the protection system.

First of all, values were found according to the technique information, which specifies the possible value of non-operation of the protection. For the analog protection the value of possible failure to operate is greater than for the digital protection. This is due to the fact that the digital protection is more advanced, in comparison with the analog protection. The probability of error of digital protection will be less.

The value of the possible false disconnection of the protected transformer was also found [45]. This value was considered when calculating the benefits from the installation of protections.

As the protection is designed for frequent operation, it was decided to make a possible operation of the protection every year for 30 years. In the calculation of the cash equivalent several options for the possible repair of the transformer, if it breaks down, were considered:

1. Repair of power oil transformers with replacement of windings. Disassembly of transformer with unbuckling of the upper frame. Removal (installation) of windings and main insulation. Repair or replacement of switching devices. Drying of the active part. Restoration of corrosion-resistant coatings of internal surfaces of equipment (units). Assembly, oil filling, testing;

2. Repair of power oil transformers without changing windings. Disassembly of transformer. Inspection and repair of active part (without disassembly). Assembly, oil filling, testing;

3. Transformer replacement (disassembly and assembly).

Leakproofing of the dismountable transformer. Dismantling of removable component assemblies. Installation of transport fixtures of nodes on the active part and preservation of dismantled component assemblies. Sealing. Unsealing of the mounted transformer. Examination of the active part and elimination of detected defects, removal of nodes securing the transport units. Disassembly and installation of component parts. Sealing, oil pouring, testing;

4. Dismantling of the transformer.

Unsealing. Dismantling of removable component assemblies. Installation of transport fixing nodes on the active part and preservation of component parts;

5. Transformer installation.

Unsealing. Inspection of the active part and elimination of detected defects, removal of transport fasteners of nodes. Disassembly and installation of component parts. Sealing, oil pouring, testing [42].

As a benefit, it was decided to take the most difficult possible repair, which could be avoided, because the protection was operated. The price of repair of the first hard scenario is 196748 rubles, or 2164.23 euros [42].

The benefit was also considered, which will be obtained from the fact that the main transformer was switched, after the operation of the protections to the reserve transformer. Which allowed to reduce the downtime of electricity and continue to supply it to the consumer.

Since the protection of expensive equipment is taking place, I decided once to consider the possible worst-case outcome. When the transformer completely fails during a fire, in which case it is necessary to spend money for the elimination of fire, the replacement of damaged equipment, the purchase, delivery and installation of a new transformer, which in total amounted to 6 270 000 rubles or 68 970 euros [43].

6.1.2. Maintenance Cost

Protection maintenance includes external inspection of the protection, dust removal, checking the technical fastening of elements, checking the insulation resistance, checking or first adjustment of settings, checking under load, taking readings diagrams, checking the sensitivity of protections, etc. Costs for maintenance and repair were assumed to be 2% of the cost of equipment per year.

6.1.3. Inflation

Inflation is the rise in prices of goods and services. Inflation depreciates money and reduces the purchasing power of the population [38].

At this time, making inflation calculations is quite problematic because of the pandemic at the moment. The market is not stable and the inflation forecast can be unreliable.

6.1.4. Discount rate

The discount rate is some value, expressed as a percentage, which allows forecasting the value of future money as of the current time.

This project will not borrow money from the bank. The investor has his own money and will buy the equipment at his own expense.

The economic approach defines the following principles for the discount rate.

The risk-free rate of return is the same for all investors. It is subject only to the risks of the economic system.

All risks of the investment project are assessed and accepted by each investor privately.

The risk-free rate is the expected return on capital without its own financial risk. For example, these are investments in financial instruments, the profitability of which is guaranteed by the state. However, here there are risks of economic system, depending on political events, macroeconomic factors, changes in legislation, emergencies, natural disasters, etc. [39].

For this project, I have assumed discount rate as risk-free rate of Government bonds in Russia 7.56 % [33] plus premium risk which equal 2.13% [41]. The value of discount rate is equal 9.69%.

6.1.5. Net present value

Net present value (NPV) of an investment project allows you to determine how much income the investor will receive in monetary terms as a result of his investment. The NPV of a project shows the amount of financial income as a result of investment in the investment project, taking into account the associated costs, i.e. - net discounted income [35]. NPV is determined by the formula (33) [34]:

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+r_i)^t} = \sum_{t=1}^{n} \frac{CF_t}{(1+r_i)^t} - INV, \tag{33}$$

where CF_t is Cash flow in time period *t*,

r_i is Discount rate,

INV is Investment,

n is the number of periods,

t is time period.

For the two scenario projects, Table 5 shows the NPV values found.

NPV values for both scenarios are positive, so both projects are profitable for the company. But the analog protection is more profitable compared to the digital protection, because its NPV is higher.

Table 5. Calculation results of the NPV

Type of protection	Digital protection "Sirius – T"	Analog protection "EPZ 1031-90.1"
Investment, EUR	3 725.9	2 380.7
Lifetime, year	30	30
NPV, EUR	442.04	1 268.27

6.1.6. Payback Period

The payback period (PP) of a project is determined by calculation of the number of years required for the cumulative cash flow and the initial investment to be equal [34].

The equation of PP (34) [34]:

$$PP = \frac{INV}{\frac{\sum_{t=1}^{n} CF_t}{n}}, \tag{34}$$

where CF_t is Cash flow in time period t,

INV is Investment,

n is the number of periods,

t is time period.

6.1.7. Internal Rate of Return

The internal rate of return (IRR) is a standard method of comparing the efficiency of different investment alternatives, which is independent of the discount rate. The IRR corresponds to the discount rate when the present value of future cash flow coincides with the value of investments. The equation of IRR (35) [34]:

$$NPV = \sum_{t=1}^{n} \frac{CF_t}{(1+IRR)^t} - INV, \tag{35}$$

where CF_t is Cash flow in time period *t*,

NPV is Net Present Value,

r_i is Discount rate,

INV is Investment,

n is the number of periods,

is time period.

The criterion for acceptance of a project is that the IRR exceeds the discount rate ($IRR > r_i$). If several projects are compared, the projects with higher IRR values are more preferable.

6.1.8. Profitability index

The ratio of NPV to initial investment is known as the profitability index. The equation of Profitability index (36) [35]:

$$P = \frac{NPV}{INV}, \tag{36}$$

where NPV is Net Present Value;

INV is Investment;

If the profitability index is greater than one, then the project is efficient from an investment point of view. Projects with higher profitability index are preferable among several projects.

6.2. Evaluation of economic parameters

Table 6 presents the parameters calculated based on paragraph 6.1.

Table 6. Economic evaluation parameters

Parameter	Digital protection	Analog protection
NPV, EUR	442.04	1 268.27
IRR, %	11.1%	14.7%
Payback period, years	8.09	6.03
Profitability index	0.13	0.52

I can conclude, analyzing table 6, that the analog protection is more profitable, because the NPV, IRR, payback period and profitability index are better than the digital protection. But it is necessary to take into account not economic indicators. in terms of technical characteristics, digital protection is more comfortable to work, because of following features:

- The ability to accurately measure electrical quantities;
- speed of protection response;
- Compactness;

- The possibility of fixing the occurring faults;
- Display of circuit diagrams;
- Probability of failure is less.

For both projects, I can conclude that the NPV is positive and the IRR is greater than the discount rate. This indicates that both projects are profitable.

6.3. Sensitivity analyzes

In this section I have analyzed the effect of the parameters on the NPV value. Sensitivity analysis is an assessment of the impact of changes in the initial parameters of the project on its final characteristics.

Dependence of NPV on discount rate is presented in Figure 32.

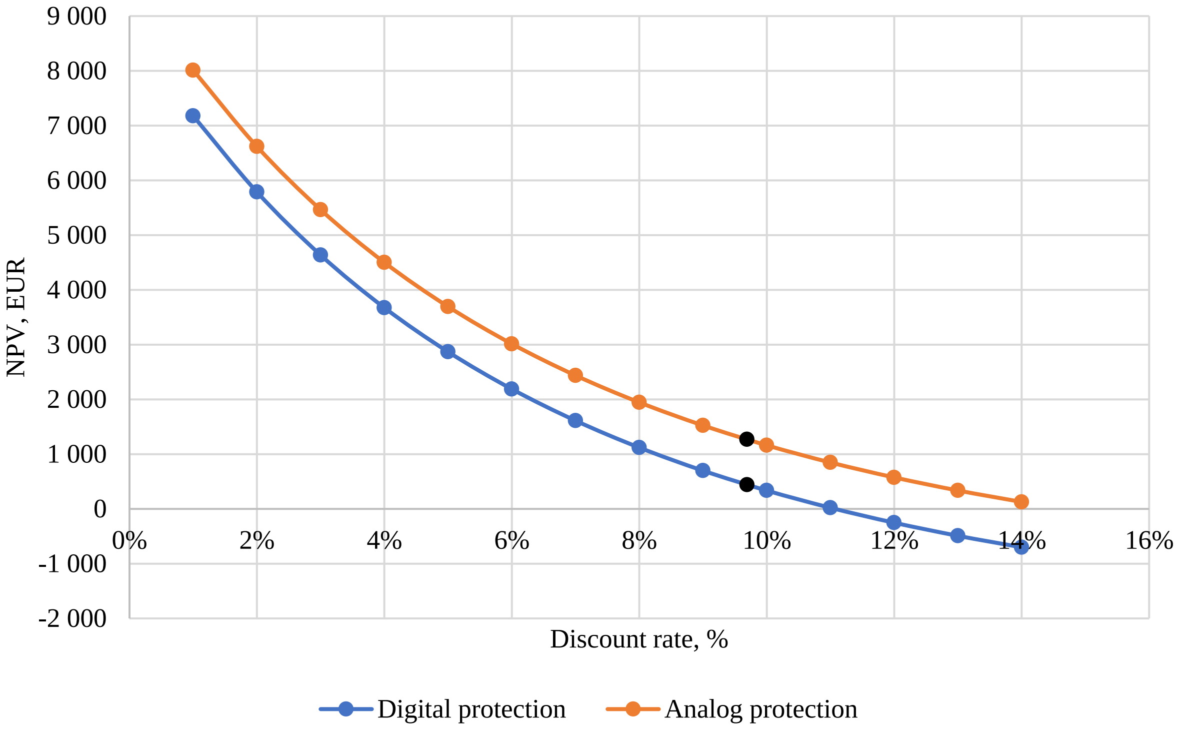

Figure 32. Dependence of NPV on discount rate

The graph shows that as the value of the discount rate increases, the NPV value will decrease. This dependence is explained by formula (33). I can also notice that the IRR values determined graphically coincide with the values found using the EXCEL program.

Dependence of NPV on investment is presented in Figure 33.

The graph shows that as the value of the investment increases, the NPV value will decrease. This dependence is explained by formula (33).

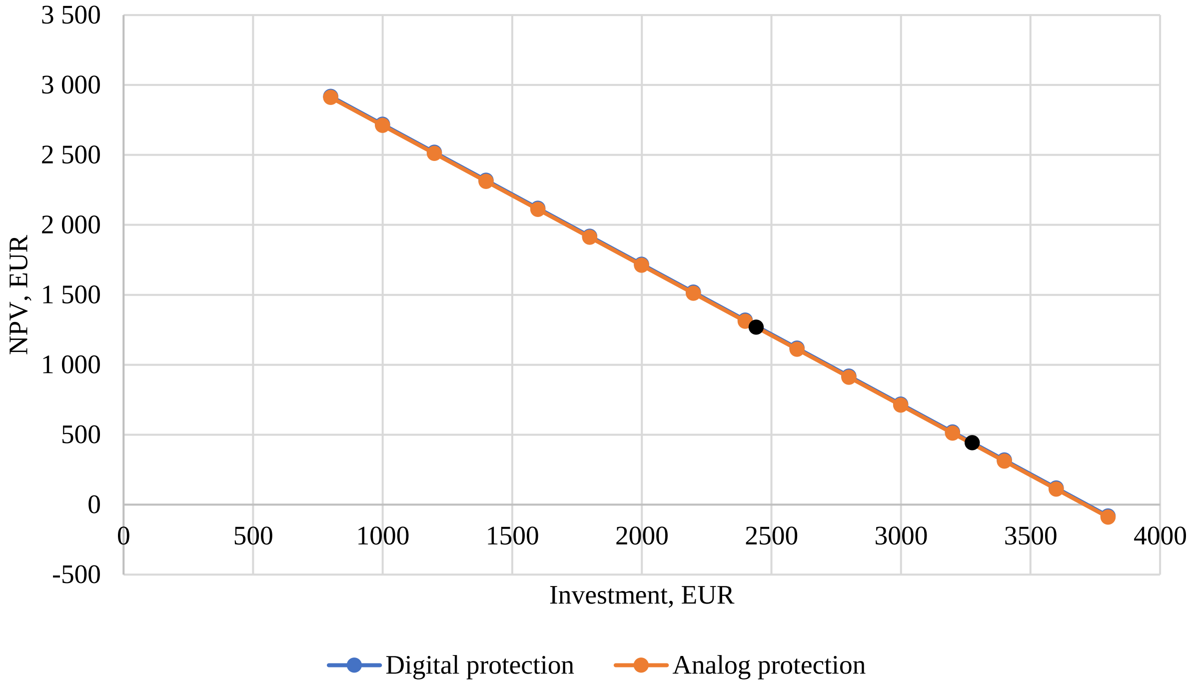

Figure 33. Dependence of NPV on investment

Dependence of NPV on probability of failure of transformer is presented in Figure 34.

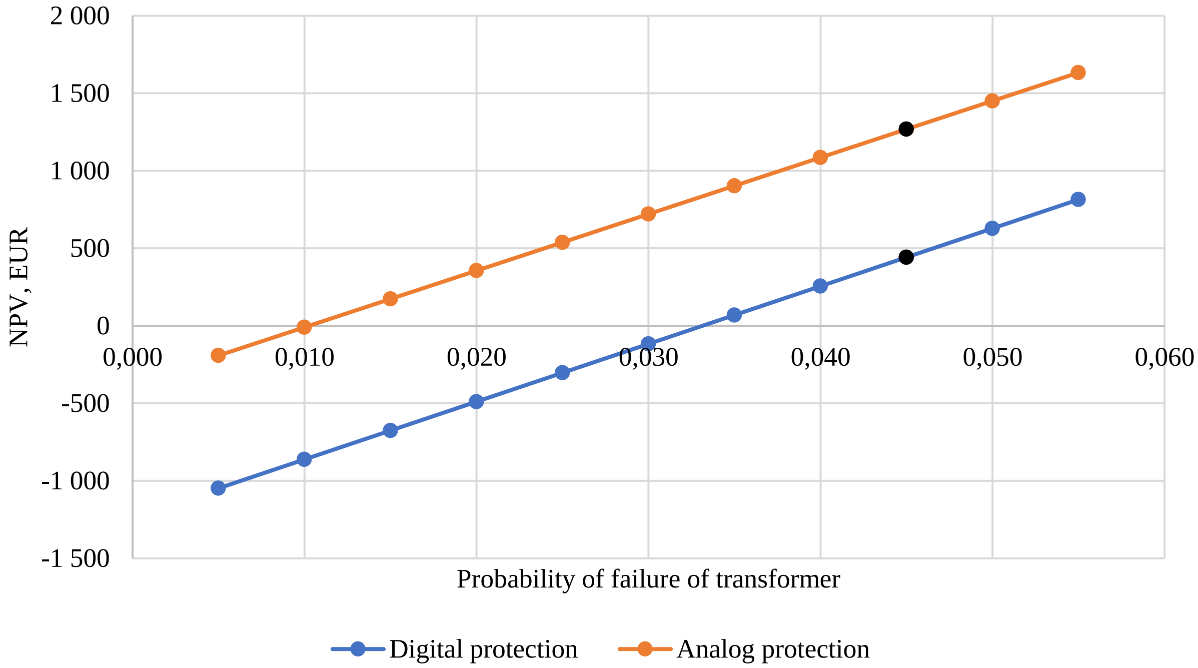

Figure 34. Dependence of NPV on probability of failure of transformer

This graph illustrates that the greater the possibility of the protection working correctly (i.e. there is no need to repair the transformer) increases the NPV of this project. This is due to the fact that we do not incur additional costs for repairs and there is no power downtime, due to the possibility of switching to a reserve transformer.

Dependence of NPV on lifetime of protection is presented in Figure 35.

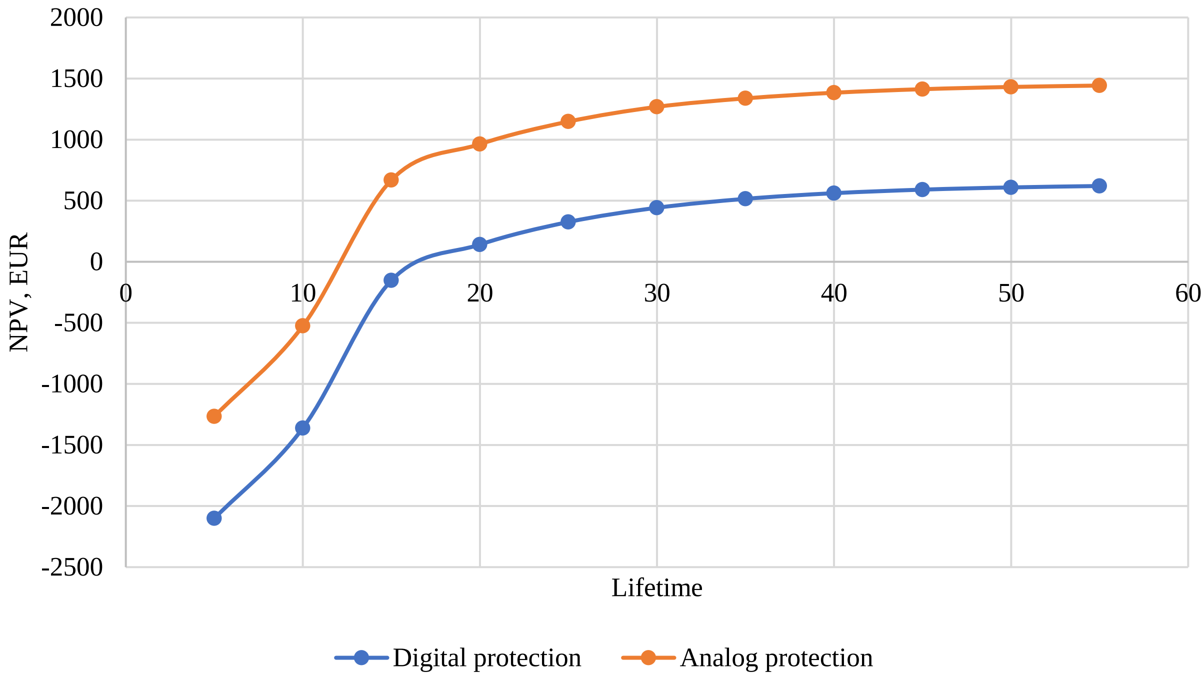

Figure 35. Dependence of NPV on lifetime of protection

This graph shows that the CF values are positive and with increasing project time. Due to this occurs NPV increases.

Conclusion

In this master's thesis, the necessity of installation of protections for electrical equipment, which will also protect humans and animals from possible short-circuit currents, on the simulated system was considered.

And also the main elements of electrical equipment to be simulated in the electrical power system were selected: two step-down transformers and an electric motor.

The following types of grounding systems were studied: TN-C, TN-S, TN-C-S, TT and IT. It was found that protection of electrical equipment can be provided by high voltage fuse, overcurrent protection and differential protection.

After that the parameters of short-circuit and grounding system I have calculated with two methods: analytical and numerical.

- The analytical method allows a simple and easy analysis of the results. The following values were obtained: the short-circuit current produced on the bus between the two transformers is 5127A, the resistance of the grounding device is 3.81 Ohm, the calculation of ground potential (GPR value) is 5274 V, and the values of step voltage and touch voltage were calculated, the allowable values of 12760 V and 3563 V, respectively.
- A direct numerical calculation using analytical data is less time-consuming and has less analytics. From the results it was seen that the touch value is equal to 4635.5 V, when the allowable 3672.9 V, and the step voltage value is equal to 2011.5 V, when the allowable 13202.3 V. In the same way was calculated short-circuit current 4804 A, the resistance of the grounding device, which is equal to 4.528 Ohm, as well as the calculation of the earth potential 8042.7 V. Analyzing the results, we can say that the numerical calculation does not confirm the analytics on the parameter of contact voltage, because the values of contact voltage are out of the maximum allowable values, which is dangerous for the personnel.
- Under the integrated solution was proposed an algorithm for the operation of the integrated calculation of the ground and protection with the control of the main parameters: the selectivity of protection, the value of short-circuit current, touch voltage and step electricity. Using the complex method, five iterations were performed, which led to the desired result. The analytical touch value is equal to 3563 V, the numerical recalculation at five iterations the touch value is equal to 3446.7 V. Which is within the permissible limits of 3672.9 V. And the resistance of the grounding device is 3.706 ohms, which satisfies the operating conditions.

This grounding system meets the necessary safety requirements as the data is within the allowable limits. The use of this protection ensures safety for animals and people on the territory of the EES during short-circuit.

In constructing the possible costs and benefits of the two types of transformer protections analog and digital protection, I have made the following conclusions:

- Digital protection has both advantages and disadvantages. One of its main disadvantages is the high cost compared to the analog protection. But do not underestimate its advantages, which were described in paragraph 6. In calculating the profitability of installing digital protection, the following values were found NPV 442.04 euros, the IRR value for this scenario is equal to 11.1%. Payback period for this protection will be no more than eight years. According to the obtained values, I can conclude that the project is profitable, and it will fully recoup the investment.

- The analog protection was also calculated to compare the two protections. The NPV value of this project is more than zero, which indicates its payback. In calculating the profitability of installing digital protection, the following values were found NPV 1268,27 euros, the IRR value for this scenario is equal to 14,7%. Payback period for this protection will be no more than six years.

According to the obtained results, I concluded that the digital protection, although it has a high cost of investment, but in the end, it will be able to recoup the investment. Although according to economic data, digital protection is not as profitable as analog protection, I should not forget about its greater capabilities. Digital protection is a more advanced protection, which contains more functions, has the ability to fix network failures, is compact. Also, a significant improvement in relay reliability is achieved due to the fact that the use of fewer components leads to fewer connections and reduced component failures.

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Appendix A

Figure A. 1. High-voltage fuse [40]

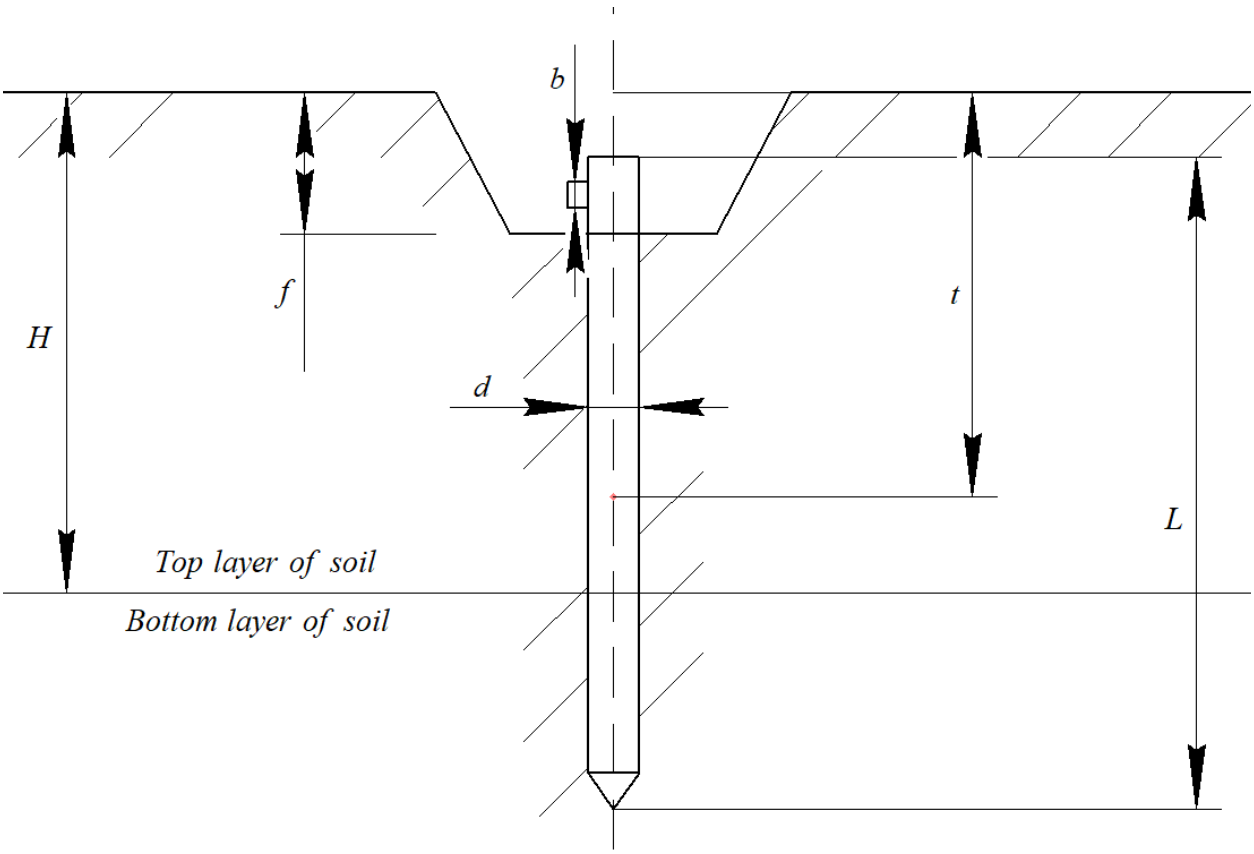

Figure A. 2. Installation of vertical electrode [18]

Table A. 1. Data for season coefficients [19]

Climate zone	Conductor type		Additional information
	Vertical	Horizontal	
I	1,9	5,8	Vertical conductors layout depth 0,5 – 0,7 m
II	1,7	4,0	Horizontal conductors layout depth 0,5 – 0,7 m
III	1,5	2,3	
IV	1,3	1,8	

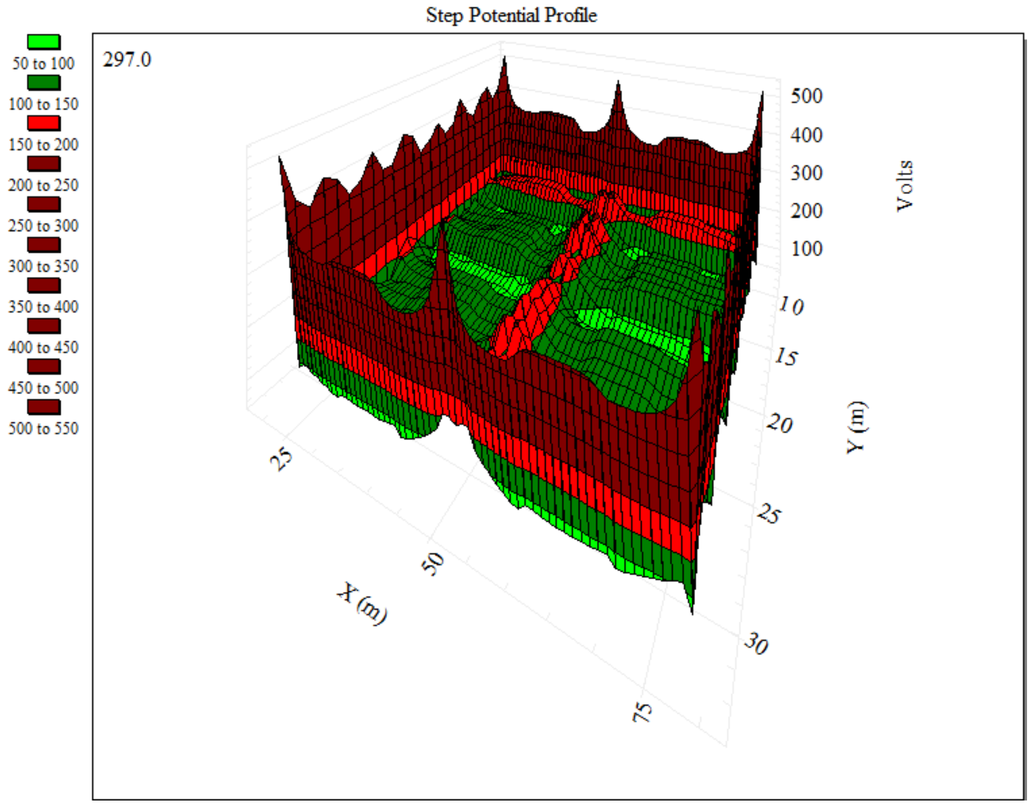

Figure A. 3. Diagram of electromagnetic fields of the step voltage

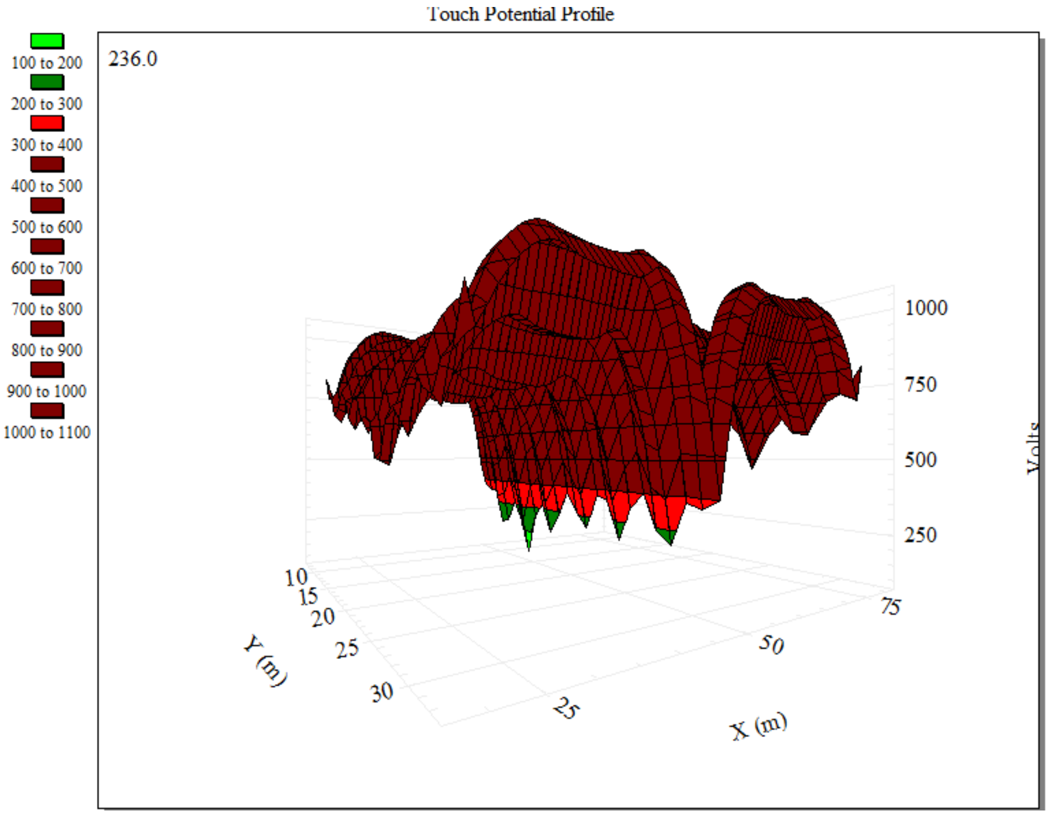

Figure A. 4. Diagram of electromagnetic fields of the touch voltage

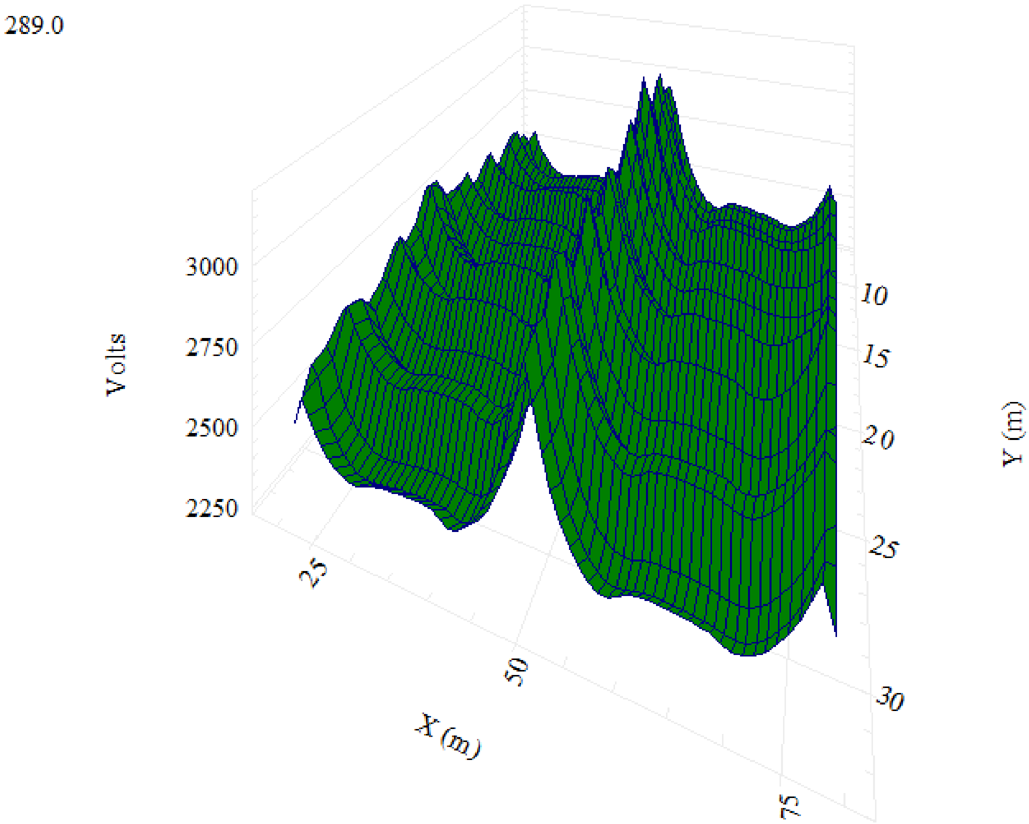

Figure A. 5. Diagram of electromagnetic fields of the absolute voltage