CZECH TECHNICAL UNIVERSITY IN PRAGUE
FACULTY OF ELECTRICAL ENGINEERING
DEPARTMENT OF ECONOMICS, MANAGEMENT AND HUMANITIES

Master’s thesis

Study program: Electrical engineering, Power engineering and Management

Field of study: Economy and Management of Power engineering

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MASTER‘S THESIS ASSIGNMENT

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1. Describe the design of the grounding and lightning protection systems. 2. Make an analytical calculation of protection systems. 3. Calculate the protections and their implementation in the studied model. 4. Asses the technical and economical results and make the conclusions.

Bibliography / sources:

1. DEHN + SÖHNE: Lightning Protection Guide 3rd updated edition, DEHN + SÖHNE GmbH, 2014 2. Brealey R. A., Myers S. C., Allen F.:Principles of Corporate Finance, 10th edition, McGraw-Hill, 2011 3. Kabyshev A. V.: Lightning Protection of Electrical Installation Systems, TPU Tomsk, 2006

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Topic registration form:

Student: Vladimir Konusarov

Study program: Electrical engineering, Power engineering and management

Topic: Overvoltage protection of power supply facilities

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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 an optimal overvoltage protection for an indoor transformer substation 10/0,4 kV of city electrical power distribution network. Lightning strikes and fault currents can pose a serious threat to living beings life and health. In addition to physical damage, these currents create risk of electrical systems failure and risk of fire. Designing technical reliable and cost effective LPS is highly important both for the protection of living beings and equipment. The solution of the problem is based on solution of the following tasks:

- Designing and analytical calculation of protection system;
- Risk management, that enables to assess risk values and allows ascertaining if the protection system optimization is required.
- Economical assessment, that enables to estimate the profitability of protection measures

At the end of the paper, conclusions are made about the effectiveness of the developed overvoltage protection. The result of this work can be used for solution of similar tasks.

Key words

Air-termination system, earth-termination system, down-conductor, earth rod, touch voltage, step voltage, damage, loss, risk, sensitivity analysis.

Contents

Introduction

There are many factors in electrical networks capable to incapacitate an electrical equipment and disrupt power supply. These factors also lead to occasion a risk of threat to life and human health. One of these factors is overvoltage. Overvoltage is divided to two types: natural, which occurs due to lightning strikes and artificial, which occurs due to faults. Both types can be the source of dangerous event, which causes economic losses.

Reliable operation of electrical installations for the production and distribution of electricity is achieved by performing a number of organizational and technical measures. Overvoltage protection occupies an important place among them. Nowadays, the problem of overvoltage protection is becoming progressively relevant due to increase in the number of consumers sensitive to electromagnetic pulses in electrical networks. Creation a properly working overvoltage protection is only possible with detailed design of its internal and external systems. Sometimes even a small deviation in overvoltage protection system coordination can cause an explosion, fire or injures to large number of people.

This work is dedicated to design of overvoltage protection system for 10/0,4 kV indoor transformer substation of Tomsk city distribution network. Considered substation supplies consumers of residential buildings. For convenience overvoltage protection system is called LPS in this work. LPS of the considered structure performs protection functions from both external and internal overvoltage.

There is no ideal protection which guarantee 100 % effectiveness. Reliable protection can make possible risks less than tolerable level, which sets the minimal probability of losses occurrence due to damage event. Calculation of possible risks is the task of risk management. In addition to risk management the economical assessment of protection measures is applied. There may be cases of structures when installation of protection is not profitable. Nowadays in Russia, risk management and economic evaluation are often have been neglected in engineering of overvoltage protection, despite the fact that they have a significant impact on the final results. Thus, the purpose of this work is designing of LPS for the indoor transformer substation with implementation of risk and financial management.

Through this work a reader will face the following structure. The thesis starts from theoretical description of lightning discharge. Then, the types of LPS are considered and the detailed description of external and internal LPS components is given. In addition the existed neutral grounding modes are examined and recommendations about choosing the mode are given.

After theoretical description the design calculation of LPS for the researched structure is presented. This part includes analytical calculation and program modeling of grounding device used for touch and step voltages estimation. Calculations include optimization of initially created model as well. Then, the risk management is presented. Here risks calculation and decision process about choosing the best protection measure are shown. In economic assessment part the financial comparison of total costs for the protection measure and costs of possible losses in the structure without the protection measures is introduced. Feasibility of models is described during the sensitivity analysis.

At the end of the work obtained results are discussed and recommendations are given.

List of abbreviations

LPS – Lightning protection system

LPL – Lightning protection level

HVI – High voltage insulated

MEB – Main earthing busbar

SPD – Surge protection device

PEN – Protective earth and neutral

RSD – Residual current device

CGD – Central grounding device

LEMP – Lightning electromagnetic pulse protection

MSDS – Main stepdown substaition

HVSG – High voltage switch gear

LVSG – Low voltage switch gear

LPZ – Lightning protection Zone

EUR – Euro

NPV – Net Present Value

WACC – Weighted Average Cost of Capital

1. Description of grounding and lightning protection systems

1.1 Description of overvoltage protection systems

Normal operation of electrical installations is defined by competent combination of technical and organizational measures. Overvoltage protection take an important place among them. High increase in the electric field strength can be dangerous both for insulation state of an electrical equipment and for people that are in the vicinity of an installation or line during this process. The most dangerous type of overvoltage is lightning discharge. LPS is used to protect people and installations from lightning strikes. LPS also protects from overvoltage occurs in operation process, the faultless operation of overvoltage protection is achieved with detailed study and implementation of external and internal LPS. Slight deviation in coordination of these systems can cause critical overvoltage and electromagnetic interference leading to malfunction or failure of the equipment and injures of life beings [1].

1.1.1 Main characteristics of lightning discharge

Lightning is an electrical discharge in the atmosphere, developing between thunderclouds or thundercloud and earth. Lightning is usually generated by thunderstorm that occurs when warm moisture air masses are transported to a great altitude. The lightning discharge starts with leader appearance – a glowing plasma channel with a high conductivity. According to the direction of leader movement, flashes are divided into two types: downward flashes (cloud-to-earth) and upward flashes (earth-to-cloud) [1].

An intensity of thunderstorm activity is characterized by the average number of thunderstorm hours or days per year. The thunderstorm map and density of lightning strikes for Russia is shown in the Appendix 1 [2]. In most regions of Russia, excluding southern areas, the number of thunderstorm hours does not exceed 100 per year. For example, in Tomsk region, the number of thunderstorm hours is on average 40-60 per year. The amount of thunderstorm hours in Russia comprises around 0,067 discharges per 1 km^2 [3].

Lightning current consists of long (with duration more than 2 ms) and short strokes (with duration less than 2 ms) components. It could be different combinations of these components depending on type of lightning flash and lightning polarity. The waveform definition of short and long lightning currents are shown in the fig. 1.1, 1.2.

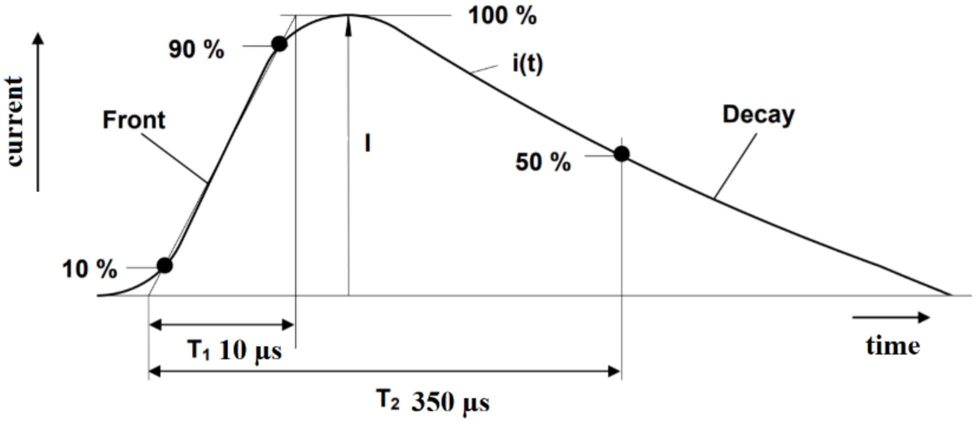


Figure 1.1 Definition of short stroke current components, where T_1 – time of current rise, T_2 – time of current decay to half of peak value [4]

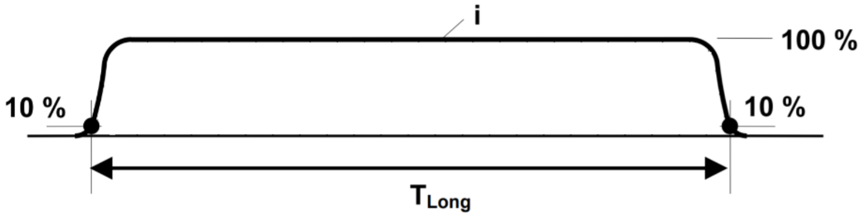


Figure 1.2 Definition of the long stroke current components, where T_{long} – time of component duration [4]

There are some parameters of lightning current important for lightning protection calculation can be noted:

- The peak value of a lightning current – I
- The steepness of lightning current rise – $\frac{di}{dt}$
- The lightning current charge – Q
- Specific potential energy of the lightning current – W

The main quantitative characteristic of a lightning discharge is the peak value of lightning current. Lightning currents vary widely from units to hundreds of kA. The average rated lightning current is 15 kA. When lightning is discharged, in addition to the lightning conductor and power lines, substations, power stations, residential buildings, etc. can be affected. The flow of lightning current through conductive parts causes the appearance of a voltage drop, which can destroy the insulation of electrical devices [5]. In the simplest case the relationship between lightning current and voltage can be described using Ohm’s Law [6]:

$$U = I \cdot R \qquad (1)$$

where I – peak value of a lightning current,
R – conductive part resistance.

If lightning current appears at the point of homogeneous conductive structure, the area of potential gradient arises. This effect also occurs when lightning strikes the homogeneous ground surface, fig. 1.3.

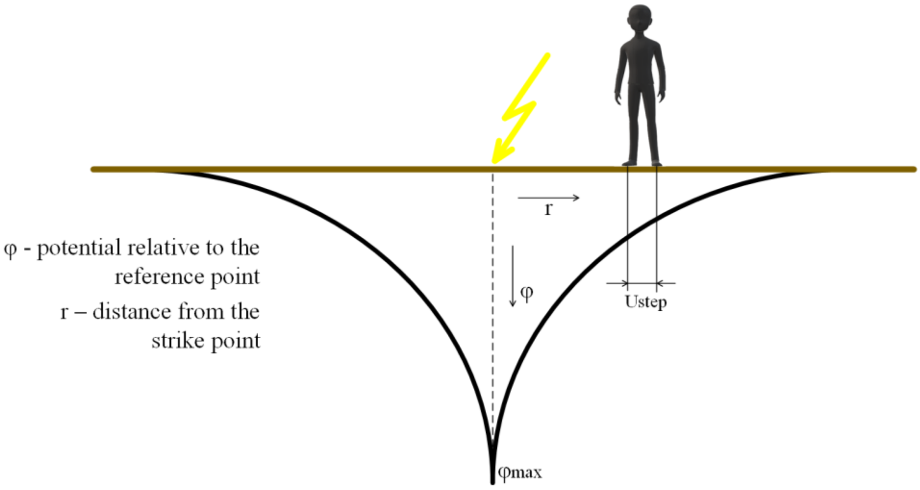


Figure 1.3 Distribution of potential in case of lightning strikes to homogeneous ground layer

If humans or animals are in the potential gradient area, step voltage is formed. Step voltage can cause electric shock and bring a serious health damage. The higher the ground conductivity the sharper is potential gradient area and the risk caused by step voltage increase. Step voltage defined in more detail in paragraph 1.3.4. In case of lightning strikes in the building equipped with lightning protection, the current flows through earth-termination system of the building and voltage drop via the earth-termination system resistance R_E, fig. 1.4. Creation of the fig. 1.4 was inspired by source [6]. As far as all conductive parts of the building are raised to the same potential value, there is no risk of electric shock [6]. Thus, the implementation of proper designed earth termination system is very important.

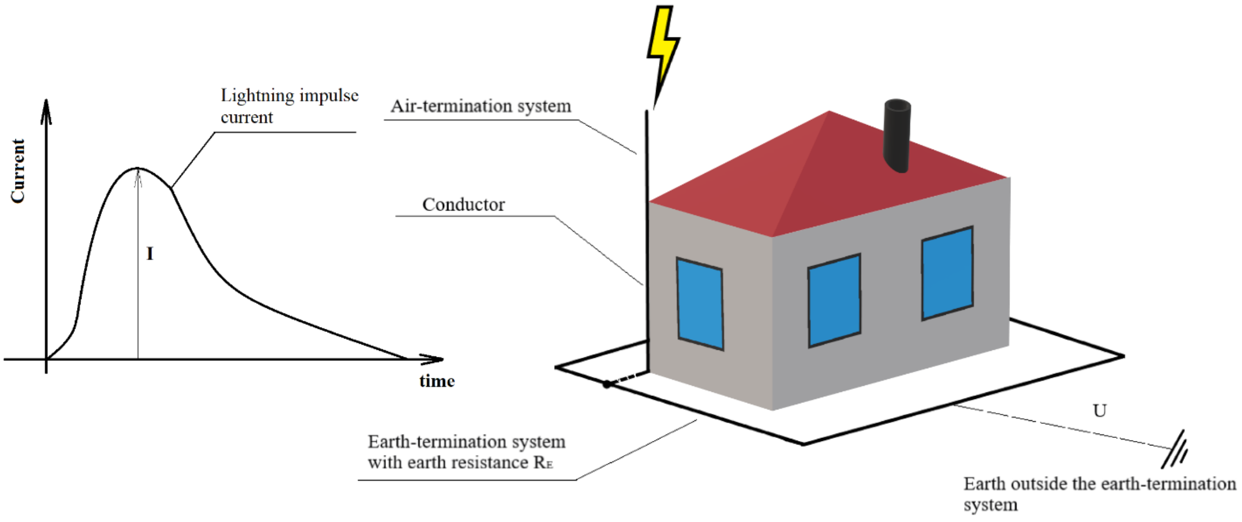


Figure 1.4 Potential rise of the building's earth-termination system respect to earth outside of the protection system caused by the peak value of lightning current

Electrical installations and buildings have many conductors in their structure used for electrical supply, data links or as parts of construction. These conductors can form different loops: open and closed. The steepness of lightning current rise defines the value of electromagnetically induced voltage in these loops [4]. The induced voltage can be determined by the next formula:

$$U = M\frac{di}{dt} \qquad (2)$$

where M – mutual inductance of the loop,

$\frac{\Delta i}{\Delta t}$ – steepness of the lightning current rise.

The transmitted charge of lightning current responsible for melting effect at the point of lightning strike. It can be defined by the formula [6]:

$$Q = \int i dt = Q_{short} + Q_{long} \qquad (3)$$

where Q_{short} – charge of the short stroke components,

Q_{long} – charge of the long stroke components

The amount of energy input at the base point of arc is defined through charge value and anode/cathode voltage drop on the insulating gap can be calculated by the next formula [6]:

$$W = Q \cdot U_{A,C} \qquad (4)$$

where Q – Charge of the lightning current,

$U_{A,C}$ – Anode/cathode voltage.

The specific energy is relevant for mechanical forces between conductors carrying lightning current as well as heating effect is expressed by the following formula [4]:

$$\frac{W}{R} = \int i^2 dt \qquad (5)$$

where $\frac{W}{R}$ – specific energy,

R – resistance of the conductor.

Table 1.1 shows some parameters of lightning discharges for flat terrain.

Table 1.1 – Lightning discharge parameters
(based on data from [7])

Parameter	Most frequent value	Registered value	
		The greatest	The smallest
Polarity	up to 80% negative	–	–
Peak value of current, kA	up to 20	200–300	0,5
Lightning charge, C	up to 20	100	0,5
Current pulse duration, mcs	10–30	100	Less than 10
Pulse front duration, mcs	1,5-10	80–90	Less than 1
Steepness of lightning current rise, A/mcs	5000	50000	–
Number of impulses in the discharge	2–3	20	1
Duration of discharge, s	0,2–0,6	1,33	–

In mountainous areas, due to the reduction in the distance from the clouds to the surface of the earth, the amplitude values of the lightning current are reduced about two times. Lightning occurs with smaller charge of clouds [3].

Lightning protection systems aim to protect building and power stations from dangerous effect of all possible lightning strikes. Depending on the object to be protected, specially designed protection system is used. A prerequisite for effective operation of lightning protection system is developing of good earth-termination system. There are structures where lightning protection must be installed, such as power station, substation, hospitals, etc. under the terms of the law. The entire list of structures required the implementation of lightning protection are given in [2].

1.2 Design of lightning protection system

LPS is divided on external and internal. According to [11] LPS includes the next components:

1. External LPS:
    - Air-termination system,
    - Earth-termination system,
    - Down-conductor system.
2. Internal LPS:
    - Separation bounding,
    - Lightning equipotential bounding.

The purpose of external LPS is to intercept direct lightning strikes with the air-termination system, conduct the lightning current via the down-conductor system and then distribute it through the earth-termination system. The function of internal LPS is to prevent dangerous sparking and overvoltage inside of the protected structure. This is achieved by installation of surge devices or setting of equipotential and separation bounding between LPS and parts of the protected structure [6].

External LPS are divided into four security levels (I, II, III, IV) to protect the object from direct lightning strikes; the first level has highest requirements for protection reliability, the forth one imposes the least reliability requirements for protection measures [12]:

I. The first level of lightning protection is used toward industrial buildings and structures that belong to dangerous areas (facilities where mining or processing of explosive substances occurs). Dimensioning and positioning of air-termination system is determined by industry regulation documents.
II. The second level of lightning protection is applied to objects with enhanced fire safety containing flammable or explosive substances. Also, objects of the second level of protection include electronic equipment sensitive to atmospheric phenomena.
III. The third level of lightning protection is applied to buildings and structures to prevent fires, destruction, as well as injuries and death of people, from the destructive effects of lightning strikes. The examples of objects with the third level of LPS are kindergartens, schools, cottages, boiler rooms, pipes of enterprises, water towers, hotels, train stations,

public residential and administrative buildings with a height of 25 meters or more, which exceed the average height of the surrounding buildings within a radius of 400 meters.

IV. The fourth level of lightning protection is used toward small non-residential facilities located in rural areas. Due to minor regulatory requirements, the fourth level is practically not applied.

Lightning protection of each structure has its specific features, so the next description of LPS design mostly will be related to the researched object of this paper. The researched object of this work is the indoor transformer substation of Tomsk city distribution network. This type of substations are protected from direct lightning strikes if the number of thunderstorm hours per year exceeds 20. Indoor substations made with metal coatings and conducted materials must be protected by earthing of this constructive parts. For the indoor substations without conductive parts the protection must be accomplished by installation of detached lightning rods and meshed conductors on the substation's roof [13]. Lightning protection is connected through the down-conductors to the earth-termination system. Typically, a transformer substation consists of three rooms: a switchgear of higher voltage, a switchgear of lower voltage and a transformer chamber. Sometimes the switchgears are combined in one common room. All conductive parts of electrical installations in substation rooms, not energized in normal working mode, are grounded by MEB, which runs along the walls. Main earthing bus is also connected to the earth-termination system. Surge arresters are used to protect the insulation of substation equipment.

In the following parts of this chapter will be considered in more detail the description of methods for external LPS designing and the features of the internal LPS engineering.

1.3 External LPS

1.3.1 Air-termination system

The function of earth-termination system is to prevent direct lightning strikes that could damage for protected structure. Correct designing, dimensioning and positioning of air-termination system allows to significantly reduce the risk of lightning strikes, it especially important for power supply facilities.

Air-termination system consist of the following components [14]:

- Meshed conductors
- Rods
- Tensioned cables and wires

Air-termination system rods must sustain the thermal and electrical effects of lightning current. Cross-section of tensioned cables and wires are usually 50 – 100 mm^2. Section of meshed conductors must be not less than 35 mm^2 [3].

Engineering and dimensioning of air-termination system depend on given reliability of protected structure. For determining the position of air-termination system geometric, electro-geometric and probabilistic methods are used. Wherein the protection reliability is determined by the object protection level and set within 0,90 – 0,99 [15].

At the present time, there are three approaches used for arrangement and positioning of air-termination systems: rolling sphere method, protective angle method and mesh method. When designing, any approach can be chosen, but practice shows the expediency of using certain methods in the following cases of protected structures up to 60 m [16]:

- Rolling sphere method is most reliable and universe method. Rolling sphere method gives good results for geometrically complicated forms of air-terminations systems.
- Protective angle method is used for simple structures or for separate small parts of large structures.
- Mesh method is advisable in the general case, especially for the flat roof protection.

The essence of rolling sphere method is determining the areas of the structure that need a protection by rolling the sphere radius – *r*, depending on the level of protection (tab. 1.2), around and along the top of the building in all possible directions. The basic idea of this method is shown in the fig. 1.5.

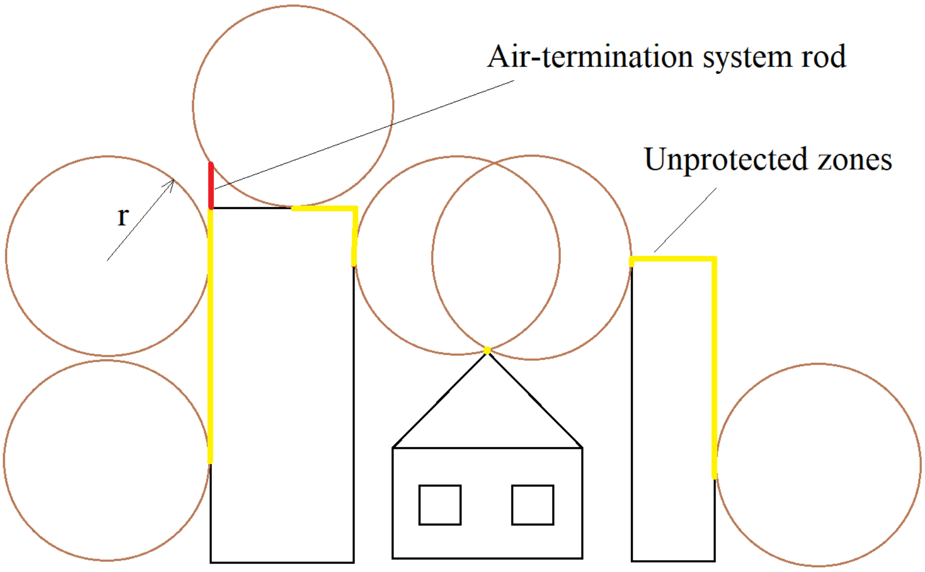


Figure 1.5 Application of the rolling sphere method for air-termination system arrangement

The method of protective mesh is as follows: to protect structure surfaces use a metal mesh, laid on the roof of the structure and protects the entire surface, fig 1.6. This method involves the following conditions [17]:

- The air-termination system conductors are laid along the edge of the structure roof, if the roof extends beyond the overall dimensions of the structure.
- The system's conductors are positioned along the ridge of the roof, if the slope of the roof exceeds 5,7˚.
- No metal parts should protrude beyond the outer contours of the air-termination system.
- The mesh sizes do not exceed the values are given in table. 1.2.

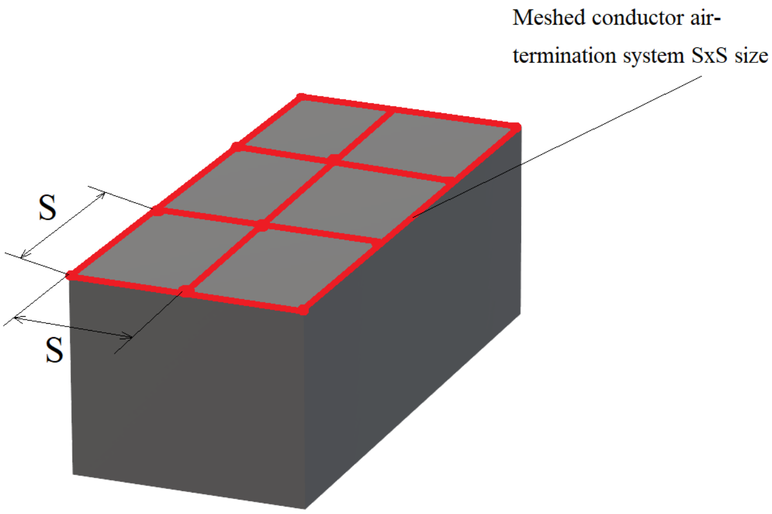


Figure 1.6 Application of the mesh method

The protective angle method assumes that all parts of the structure are being in the protection zone formed by an angle between the tip of vertical rod and the line projected to the surface where this rod installed, fig. 1.7. The protective angle method is mathematical simplification of the rolling sphere method and can be derived from it. The protective angle method is not used if the structure height – *h* is greater than the radius of the rolling sphere, according to the table 1.2, for a corresponding protection level.

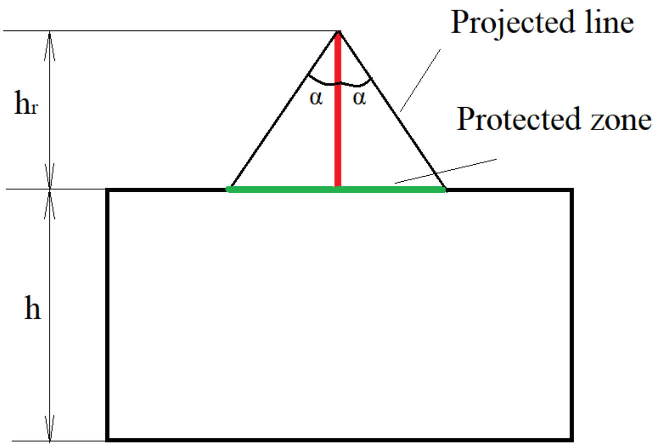


Figure 1.7 Application of the protective angle method; *h* – height of the protected structure, h_r – height of air-termination system, *α* – protective angle

he values of the angles at the top of the protection zone, the radii of the rolling sphere, as well as the maximum allowable grid cell spacing for objects up to 60 m high are given in the table 1.3 for protection levels I – IV.

Table 1.2 – Maximum values of rolling sphere radius, protective angles and mesh size corresponding to the LPS class
(based on data from [17])

Protection level	Reliability of protection P	Rolling sphere radius r (m)	Angle α (°) at the top of the air-termination system for buildings of different heights, h (m)				Mesh size, m
			20	30	45	60	
I	0,99	20	25	*	*	*	5×5
II	0,97	30	35	25	*	*	10×10
III	0,95	45	45	35	25	*	15×15
IV	0,90	60	55	45	35	25	20×20

* In these cases, only the rolling spheres or mesh methods are applicable.

1.3.2 Down conductor system

Down conductors provide an electrical connection of air-termination and earth-termination systems. The down conductors function is to conduct the lightning current without damage to the protected structure.

The down conductor system usually consist of several conductors in order to reduce the current density. It allows lowering the risk of sparking and decrease electromagnetically induced voltage inside the structure loops. To avoid the damage by lightning discharge, the down conductor system must meet the following requirements [11]:

- The length of current path should be as short as possible. It is achieved by using straight vertical conductors without excess loops.
- Multiple path. It means using more than one conductor.
- Spacing and bounding. Down conductors can be connected with conductive parts of the structure to be protected.
- Insulation of down conductors in order to prevent touch voltage risk.

The number of down conductors depends on LPS class of the structure to be protected, its area and constructive features. Spacing between down conductors and the structure can vary; the minimum distance according to LPS class is shown in the table 1.4.

Table 1.4 – Spacing between down conductors
(based on data from [18])

Class of LPS	Typical distance, m
I	10
II	10
III	15
IV	20

Down conductors can be installed directly on the structure walls or even inside them when walls materials are flame-redundant. If walls are made from combustible materials, so the lightning current increases the temperature and it could create the fire hazard. In this case down conductors should be separated from the structure surface. The separation distance can be calculated by the following formula [6]:

$$s = \frac{k_i k_c}{k_m} \cdot l \qquad (8)$$

where k_i – coefficient depending on the LPS class,

k_c – factor depending on the lightning current flows through conductors,

k_m – factor depending on conductors insulation,

l – length of down conductor in m, from the point where separation distance is set to the earth-termination system.

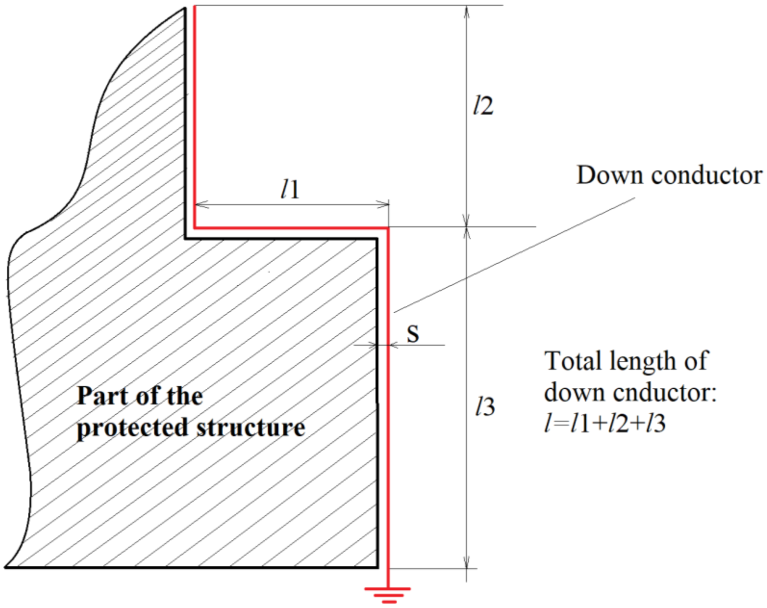


Figure 1.8 Down conductor installation

Separation distances are also referred to internal LPS, when it is important to protect internal installations from dangerous sparking. It is especially important in case of electronic equipment. Sometimes it is impractical to set separation distance in new structures from aesthetic or technical reasons. Protection of structure elements from dangerous flashovers without putting separation distance is performed by HVI conductors. The basic principle of HVI conductors is that they are covered with insulating material to ensure the required separation distance [6].

Natural components of the structure can be used as parts of down conductor system, it decreases the number of mounted conductors and saves the investments. For examples the metal gutters, construction metal frameworks and walls reinforcement can carry lightning current, if they are connected to earth-termination system and meet the down conductor requirements.

1.3.3 Earth-termination systems

Earth-termination system is part of external LPS used to disperse lightning current into the earth. It consists of one or several conductive parts in contact with the ground. In total, these conductors form grounding device. Installation of grounding device is mandatory in case of power stations and substations [19]. The researched object of this work is indoor transformer substation, therefore, further earth termination system and grounding device terms will have the same meaning.

A good earthing should have the following characteristics [20]:

- Low earth resistance. The lower the earth resistance the more likely that the lightning current will flow down this way, allowing the current to be conducted safely to the earth and then dissipate in. There is no specified value of earth resistance for each protection system, but in general, the resistance measured with low frequency should be no more than 10 Ohm.
- Good corrosion resistance. The choice of material for electrodes and their connections has significant importance. It will be buried in the earth for many years, so system has to be reliable.

It is acceptable to distinguish two types of earth-termination system arrangement: Type *A* and Type *B* [11]:

- **Type A** design consists of individually arranged earthing rods and/or surface earth electrodes which is connected to down conductor and installed outside the protected structure, fig 1.9. The arrangement of Type *A* requires at least two electrodes. One earth electrode is enough only in case of separate positioned air-termination rod.
- **Type B** earth-termination system arrangement is ring electrode encircling the protected structure, fig. 1.9. It is also possible to include the conductive parts of the object inside the ring, for example pipelines, reinforced concrete foundations. The ring electrode must be in direct contact with soil for at least 80% of its overall length and should be installed at the approximately 1 m distance of the protected structure walls.

Type *B* is recommended in case of objects located in places with low soil conductivity, such as rocky or arid areas, or structures with a high risk of fire. This approach is also preferable, because it provides the equipotential bounding between the down conductors. Type *B* system is highly recommended for the structures with non-conductive walls, such as wood or bricks, and without connection to reinforcing foundation [11].

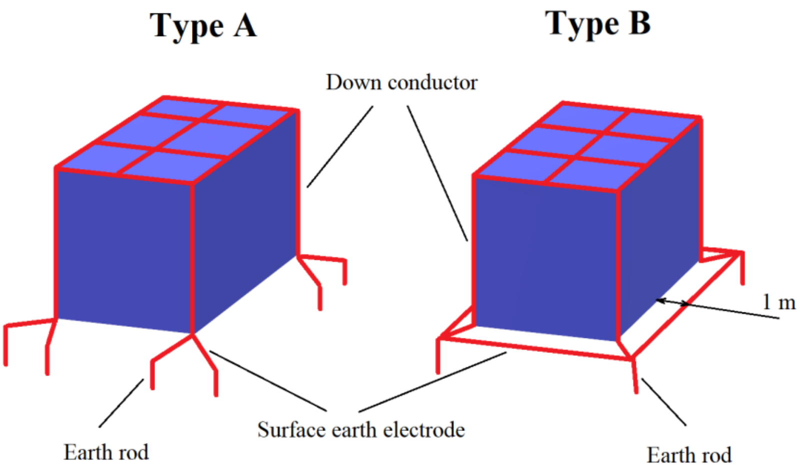


Figure 1.9 Arrangement of Type *A* and Type *B* earth-termination system

There are many possible variants of air-termination system construction for both types. The choice of a particular design consists of the satisfaction of technical and economic requirements. The technical requirements include provision of low network resistance, long-term system performance and minimization of step and touch potential risk. Economic requirement is the choice of the least cost option, subject to the technical requirements.

1.3.4 Step and touch voltage

Touch voltage occurs between two points of current flow circuit, which is closed by person simultaneous touch. One of this point usually is the down conductor under the lightning strike or an electrical installation case under the voltage due to phase conductor fault on it. The second point is the conductive surface with zero potential. Step voltage is resulted from current flowing through the earth and means a potential difference between two points of the ground located at the distance in one step considered equal to one meter. Step and touch voltage depends on earth potential gradient as shown in the fig 1.10. The greater the distance from the point with maximum potential, the less risk of electric shock [13].

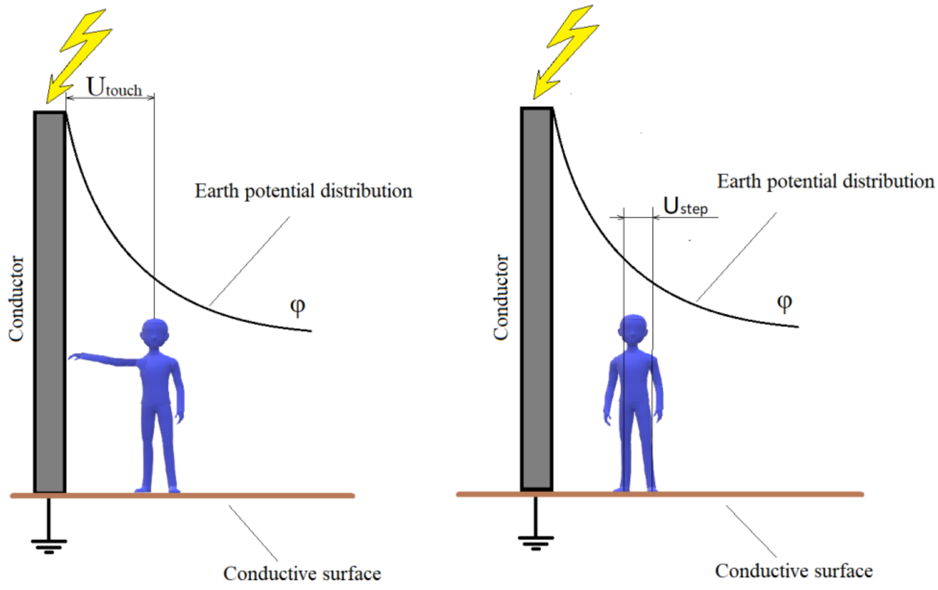


Figure 1.10 Demonstration of touch and step voltage arising

In the event a fault or lightning strike many equipotential surfaces appear on the protected structure territory. Depending on the voltage class of the protected structure and neutral operation mode the touch voltage has different maximum permissible values and durations of exposure. For example in case of emergency mode of industrial electrical installations with voltage up to 1 kV with a low-ground or insulated neutral and above 1 kV with an insulated neutral, touch voltage 20 V is acceptable value with an unlimited duration of exposure [21]. Protection of human from electric shock hazard, when touch or step voltage occur, is the task of earth-termination system proper designing and dimensioning. Properly functioning earth-termination system and relay protection should defend humans, electrical equipment and material assets in case of faults or overvoltage.

1.4 Internal LPS

Internal LPS includes equipotential bounding and separation distances. The purpose of equipotential bounding is to prevent dangerous sparking and touch potential voltage risk inside the structure to be protected by potential equalization. Equipotential bonding is necessary for all electrical installation indoors. It can be performed by direct connection to the MEB or using SPDs, fig. 1.11. MEB is interconnected to the external LPS through terminals. Separation and insulation of structure elements from the LPS is maintained by setting distances through non-conductive medium. For calculation separation distances the same approach can be applied as was shown in part 1.2.2. Equipotential bounding for feeder cables should be installed on the entrance to the structure [22].

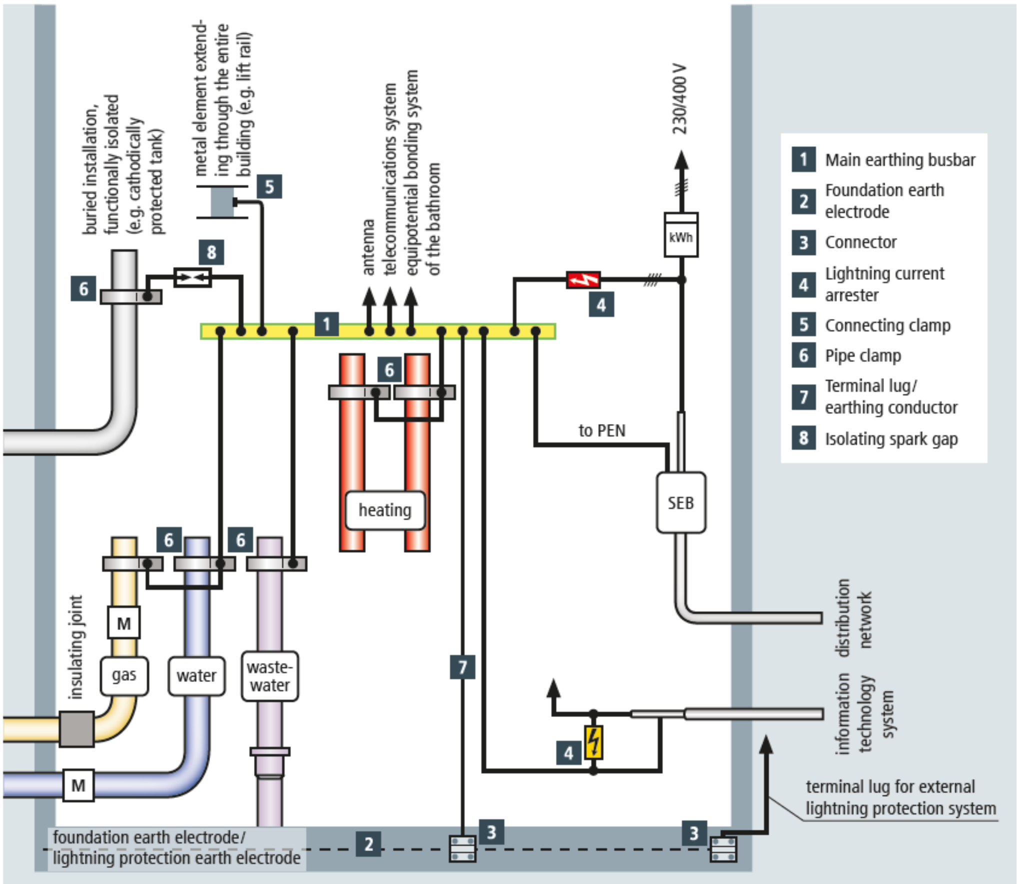


Figure 1.11 The principle of internal LPS organization [6]

The equipotential conductors, as they performs a protective function, are marked in yellow-green color. These conductors can be bare, because they do not transfer operation current. The minimum cross-sections of bonding conductors are shown in the table 1.5

Table 1.5 – The minimum cross-sections of protective bounding conductors (based on [23])

Class of LPS	Material	Cross section (mm^2)
I – IV	Coper	6
	Aluminum	16
	Steel	50

MEB is generally installed on the ground floor, it binds all clamps and equipotential conductors. Earthing bar is connected to foundation earth electrode, which must provide proper earth resistance and when this electrode installed cost effectively it can be used as a part of earth-termination system. MEB should be reliable and corrosion resistant [6]. The minimum requirements to MEB are set by standard and may vary in different countries, usually it is flat or round conductor.

Connection of the installations to MEB via bonding conductors must be constant and reliable. Protected structure may contain some internal installations, for example: electrical and electronic equipment that should be connected to equipotential bounding system via SPDs. Installation of SPDs is explained by the next reasons:

- Providing protection to the structure electrical/electronic equipment against impulses from direct or indirect flashes to the services [24];
- Eliminating potential differences to service conductors and thereby reducing the risk of flashover and resulting fire [20];
- Correctly located and installed protection (coordinated protection) will also reduce the risk of equipment damage from impulses generated by switching or faults within the electrical circuits;
- Is a key part of the LEMP measures.

The issue of SPDs installation is quite difficult and covered by many standards requirements. It is planned to give detailed description to the SPDs problem in the third chapter of this paper.

1.5 Neutrals grounding modes in 0,4 kV networks

The technical features of electrical installations and the electrical networks supplying them determine the use of various types of grounding systems. Type of grounding system is understood as an indicator characterizing the relation to earth of the open neutral conductive parts of electrical energy receiver and neutral in electrical installations up to 1 kV [3].

Grounding mode of the neutral is usually denoted by two letters: the first letter indicates the grounding state of the power source relative to the ground (power transformer 10/0,4 kV), the second letter defines the state of open conductive parts relative to the ground.

The notations use the first letters of the French words:

- **T** – grounded (*terre* – ground);
- **I** – isolated (*isole* – isolated);
- **N** – neutral (*neuter* – neutral) – connected to the power source neutral.

For electrical installations with a voltage of up to 1 kV, the International Electrotechnical Commission provides three modes of neutrals grounding [3]. The specified modes are summarized in the table 1.6.

Table 1.6 – Neutral operation mode
(based on [25])

Grounding mode	Description
TN	System in which the power supply source neutral is solidly grounded, electric installation cases are connected to the neutral wire.
TT	System in which the power supply source neutral and electric installation cases are solidly grounded. Neutrals can be connected to different grounding devices.
IT	System in which the supply equipment neutral is insulated or grounded through high-resistance devices, electric installation cases are solidly grounded.

In turn, the grounding mode of the neutral – *TN* can be of three types, table 1.7.

Table 1.7 – Types of the of *TN* neutrals operation modes
(based on [25])

Grounding mode	Description
TN-C	*TN* system in which protective – ***PE*** and neutral – ***N*** conductors are combined into one conductor along the whole length of system. Combined conductor is called ***PEN***.
TN-S	*TN* system in which protective and neutral conductors are isolated from each other.
TN-C-S	*TN* system in which protective and neutral conductors are grouped into one conductor at the advance section, but further they are separated.

Neutral grounding mode names are often assigned to networks, so for convenience the network and neutral grounding mode will have the same meaning.

It should be noted that the neutral operation modes are largely determine [3]:

- Safety conditions of work in electrical networks, protection against the threat of electric shock;
- Overvoltage values and ways to limit them;
- Electromagnetic compatibility in normal and emergency modes;
- Fire safety (probability of fire occurrence due to faults);
- Currents at single-phase short circuits, damageability and selection of electrical equipment;
- Uninterrupted power supply;
- Network design and operation process.

It will be noted the advantages and disadvantages of the existing neutral operation modes in 0,4 kV networks, the characteristics listed above are chosen as comparison criteria.

1.5.1 TN–C network

Networks with this neutral operation mode are most common in Russia. The network scheme is shown in the fig. 1.12.

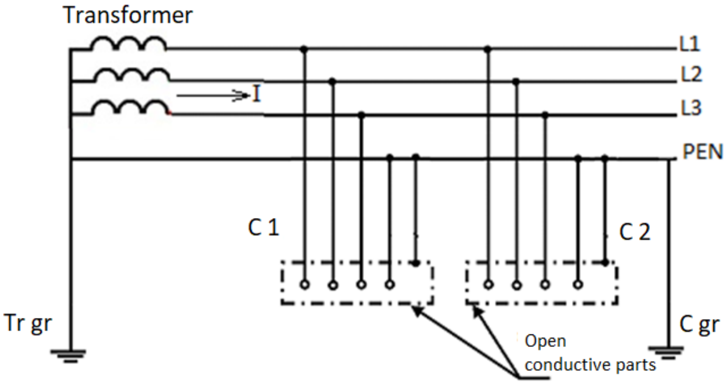


Figure 1.12 Scheme of an electrical network with *TN-C* neutral grounding mode; C 1, C 2 – consumers of electrical power, Tr gr – transformer grounding, C gr – consumers grounding

Electrical safety during housing contact in this case is provided by circuit breaker or fuse switching off a one-phase short circuit to the housing. If the fault is remote from the source, its elimination time increases, in this case the danger of electric shock of human or animal increases. To ensure electrical safety in 0,4 kV network, short-circuit protection must be switched off within a time less than 0,2 seconds, which is provided with fuses and circuit breakers only in case [3]:

$$I_{\text{fault}} = [6\ ;\ 10]\cdot I_{\text{nom}} \qquad (9)$$

Thus, with the housing contact during remote faults, the TN-C neutral is not safe, because fault current ratio has values lower the specified range. It should be noted that designing this type of networks demands to measure or calculate the resistances of all connections and phase-zero loops for protection settings, and when the network parameters are being changed, it is necessary to recalculate protection thresholds to ensure their reliability.

The biggest disadvantage of the *TN-C* network is the inability to install residual current devices (RCDs) [3]. RCD is one of the main components of automation used to protect the electrical network, it controls the electrical circuit and works when leakage currents occur in case of fault.

Fire safety of this network is low. This is due to the significant currents of single-phase short circuit and as mentioned above with the weak sensitivity of protections for remote faults. Uninterrupted power supply of consumer, in case of faults is not provided for *TN-C* neutral mode. For *TN-C* networks, the appearance of electromagnetic disturbances is typical which amplify during lightning strikes, even in normal operation mode a voltage drop occurs in neutral wire [3].

This grounding system was used in the Soviet Union and now it can be found in houses belonging to the old buildings. Today it is also used in networks of street lighting, where the level of risk is minimal.

1.5.2 TN–S network

TN-S networks are characterized by separation of working and protective neutral conductors, fig. 1.13.

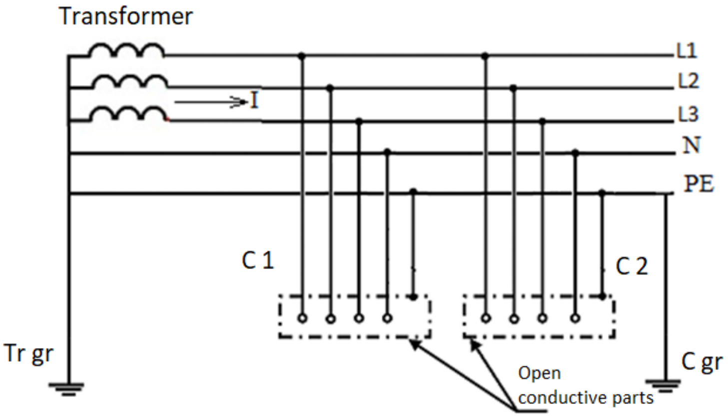


Figure 1.13 Scheme of an electrical network with *TN-S* neutral grounding mode; C 1, C 2 – consumers of electrical power, Tr gr – transformer grounding, C gr – consumers grounding

The advantage of this neutral mode is the ability to use the RCDs. It increases electrical safety of the network. Fire safety of *TN-S* networks, due to implementation of the RCDs is significantly higher in comparison with the *TN-C* networks. *TN-S* and *TN-C* networks are similar in terms of uninterrupted power supply. In the normal operation mode of *TN-S* network, electromagnetic disturbances lower than in *TN-C* due to the isolation of *N* and *PE* conductors.

In terms of designing, configuring and maintaining protection, *TN-S* networks do not have significant advantages over *TN-C* networks, besides they are significantly more expensive due to the installation of the RCDs and the presence of a fifth wire. *TN-S* neutral mode was first appeared in Europe and it is still used in Europe countries. In Russia *TN-S* neutral mode is used in the construction of multi-storey buildings.

1.5.3 TN–C–S network

TN-C-S network is a combination of *TN-C* and *TN-S* networks. *TN-C-S* network is characterized by all the advantages and disadvantages noted above for two previous neutral modes, fig. 1.14.

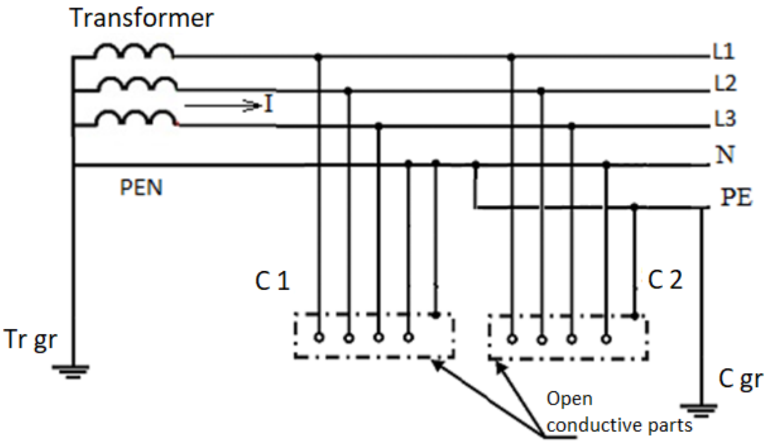


Figure 1.14 Scheme of an electrical network with *TN-C-S* neutral grounding mode; C 1, C 2 – consumers of electrical power, Tr gr – transformer grounding, C gr – consumers grounding

TN-C-S neutral mode is used in urban buildings construction; the conductors are separated in basement of the building and running separately in rises.

1.5.4 TT network

TT networks are characterized by the fact that the neutral of the power source and the conductive parts of power consumers are connected to the ground through separate conductors, the network scheme is shown in the fig. 1.15.

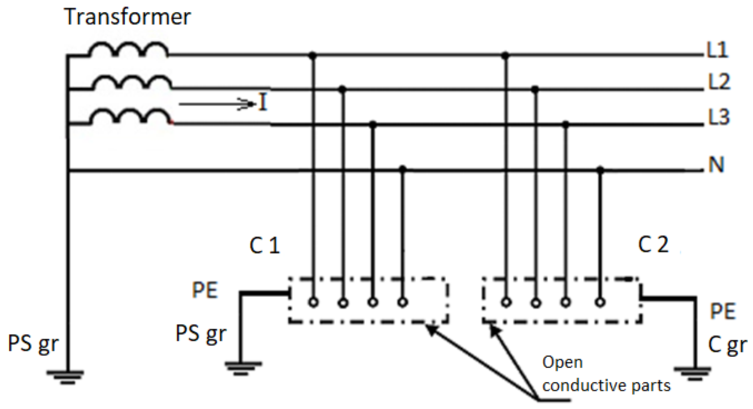


Figure 1.15 Scheme of an electrical network with *TT* neutral grounding mode; C 1, C 2 – consumers of electrical power, Tr gr – transformer grounding, C gr – consumers grounding

In case of single phase short circuit on conductive housing of electrical receiver the dangerous fault voltage occurs. Electrical safety of *TT* network in this case can be achieved by installation of the RCDs.

Fire safety of networks of this type is higher than in *TN-C* networks. This is due to the lower values of the single-phase fault current and use of the RCDs. Uninterrupted power supply is not ensured. There are no electromagnetic disturbances in *TT* networks in normal mode, since no currents flow through the protective conductor [3]. Often, due to economy, the cases of several electrical receiver are united by one PE conductor.

In terms of design, the use of RCDs eliminates the problem of limiting the length of PE conductor, there is no need to know the impedance of the phase-zero loop, it is possible to expand the network without recalculation of short-circuit currents. *TT* networks are widespread in rural areas, because of poor quality of power transmission line supports; they are also used in private buildings and in urban conditions to electrify temporary consumers.

1.5.5 IT network

IT network, in other words, can be called a network with isolated neutral. The scheme of the *IT* network is shown in the fig. 1.16. Transformer neutral in the *IT* network is also can be grounded via resistors (hundreds or thousands kOhm).

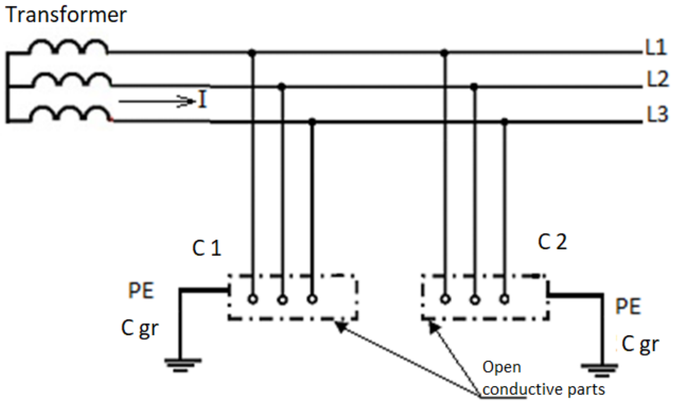


Figure 1.16 Scheme of an electrical network with *IT* neutral grounding mode; C 1, C 2 – consumers of electrical power, Tr gr – transformer grounding, C gr – consumers grounding

IT networks are most electrical safety; touch voltage in case of housing contact is practically equals to zero, it is connected with small value of one-phase short circuit current. Fire safety of these networks is much higher, compared with other neutral grounding modes; it is once again connected with small values of the fault current. *IT* networks are characterized by uninterrupted operation, single-phase fault to ground or conductive equipment housing does not require immediate shutdown.

It should be noted that during the operation of the network, difficulties might occur, related to the location of the fault. Today they are widely used in dangerous industries, where electrical and fire safety is very important. In addition, *IT* networks are often used in construction of private houses.

1.5.6 Recommendations for choosing the type of network

As the suggestions for choosing the type of network, the following recommendations can be drawn:

1. *TN-S* and *TN-C-S* networks are characterized by a low level of electrical safety, fire safety and significant electromagnetic disturbances.
2. *TN-S* networks can be recommended for selection in case of network project with long lifetime period without planning to change it.
3. *TT* networks should be used to supply temporary or changeable electrical installations.
4. *IT* networks are recommended to use if it is absolutely necessary to ensure uninterruptible power supply.

Each neutral grounding mode is not universal and choice of exact mode usually based on standards. In cases when it is not standardized it should be based on technical end economical requirements.

1.6 Neutrals grounding modes in 10/0,4 kV substation

In city distribution networks, electrical installations at 10/0,4 kV substation can operate in following modes [2]:

- Solid-grounded or effectively grounded neutral;
- Insulated neutral or grounded through an arc-suppression reactor or resistor with high resistance.

Use of the *TN-C* neutral grounding mode is prohibited in the construction of single-phase buildings with direct or alternating current [26].

Protective grounding of all electrical equipment at 10/0,4 substations is performed common. The common grounding device installed in the substation is called the central grounding device (CGD) or the main earth-termination system. The CGD, in most cases, consists from interconnected horizontal and vertical steel conductors of a certain diameter. Usually, vertical conductors are steel rods up to 10 m long and 12-16 mm in diameter; angle steel – 2,5-3 m; steel pipes with a diameter of 30-50 mm [27]. The choice of vertical conductor types depends on climatic conditions and type of soil at site of the designed grounding device. Horizontal conductors are usually steel strips or round steel conductors. Overall, the electricity consumer grounding resistance should be no more than 4 Ohms [13].

In general, all schemes for the implementation of protective ground networks at the substations can be divided into three groups [28]:

- Local (individual) – electrical receivers are not connected to a common ground network. Performed by grounding, located near the objects to be grounded.
- Trunk – electrical equipment are attached to the CGD. The CGD is common for a group of the receivers to be grounded.
- Ring – one part of receivers are connected to the CGD and other part is connected to local grounding.

All these schemes are used for grounding electrical equipment installed at the substation and determined by neutral grounding mode on 10 and 0,4 kV sides.

2. Designing of overvoltage protection system

2.1 Steps of overvoltage protection designing

There is no ideal LPS that can guarantee 100% effectiveness, but proper designing is able to make it high reliable. A system designed according to standards is an issue of risk management and sequential projecting of its parts.

The LPS design process is determined by steps based on information from [11] and shown in the fig. 2.1. The process of designing can be iterative. It depends on meeting safety requirements for protected structure. An important part of designing is fulfilment of separation distance requirements that applies both internal and external LPS. Separation distances are determined by the LPL, the numbers of down conductors and position of the designed LPS. Sometimes, an alternative location or additional number of down conductors are required to correspond the separation distance requirement [11].

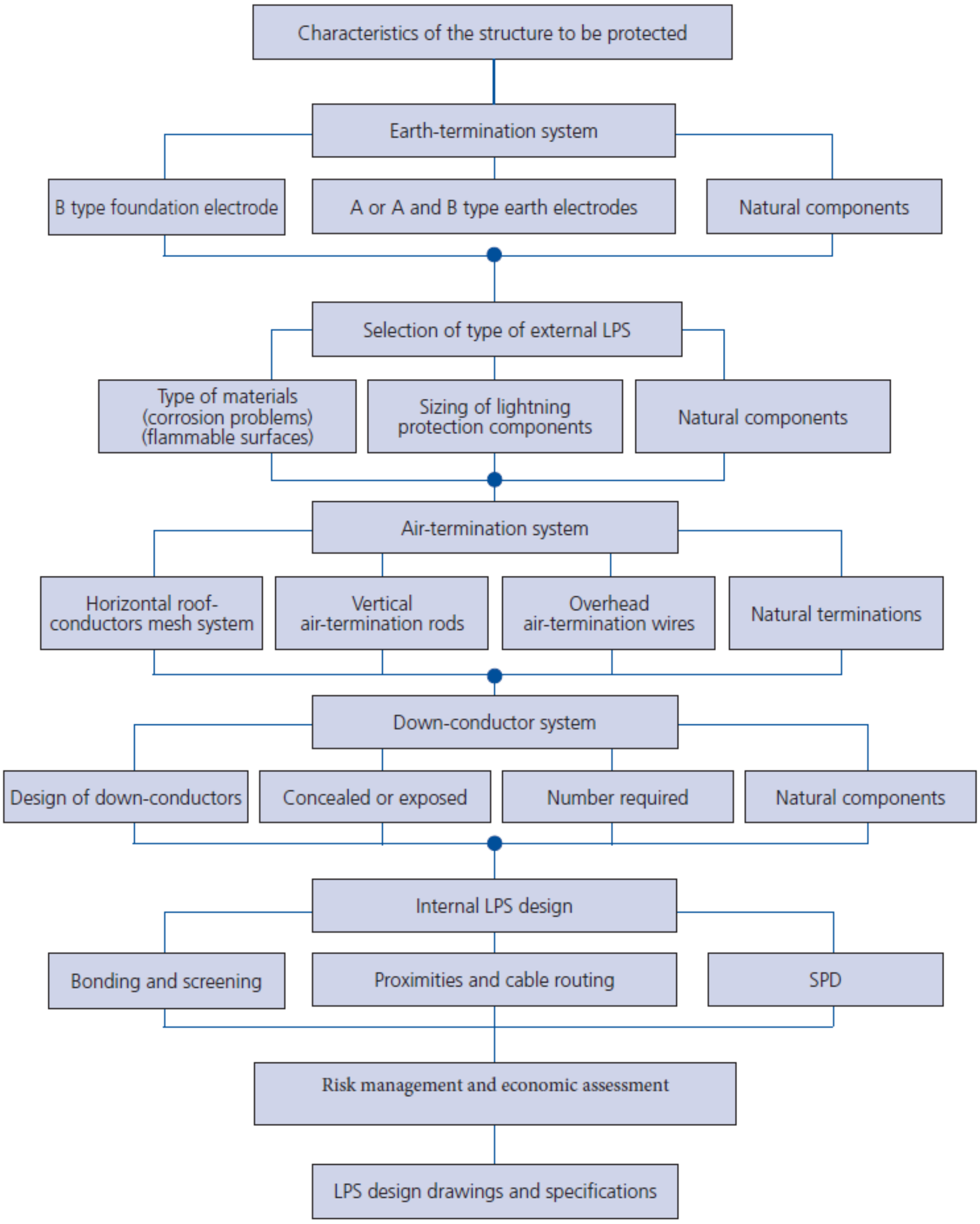


Figure 2.1 LPS design process

Further design steps of LPS will be performed in accordance with the sequence shown in the fig. 2.1. The First step is a detailed description of the step-down substation, which is the object to be protected.

2.2 Description of the protected structure

As was mentioned in the chapter 1, the researched object is indoor stepdown transformer substation 10/0,4 kV of Tomsk city distribution network. For visual representation, a fragment of the Tomsk city distribution network is shown below, fig. 2.2.

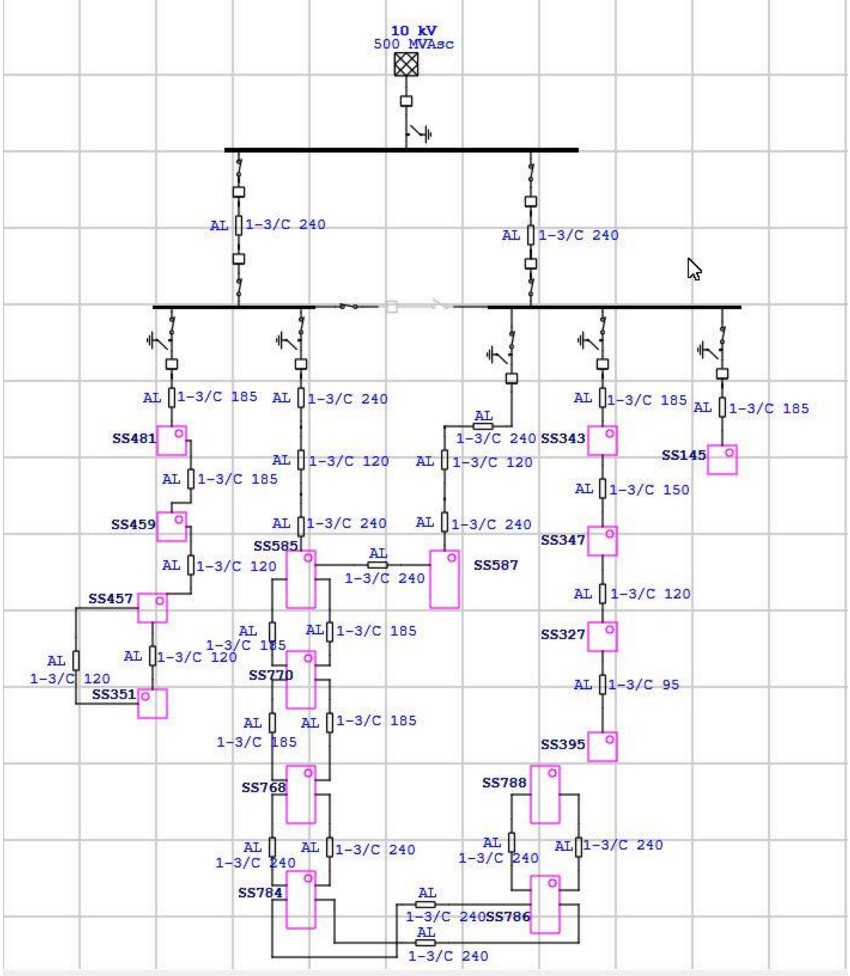


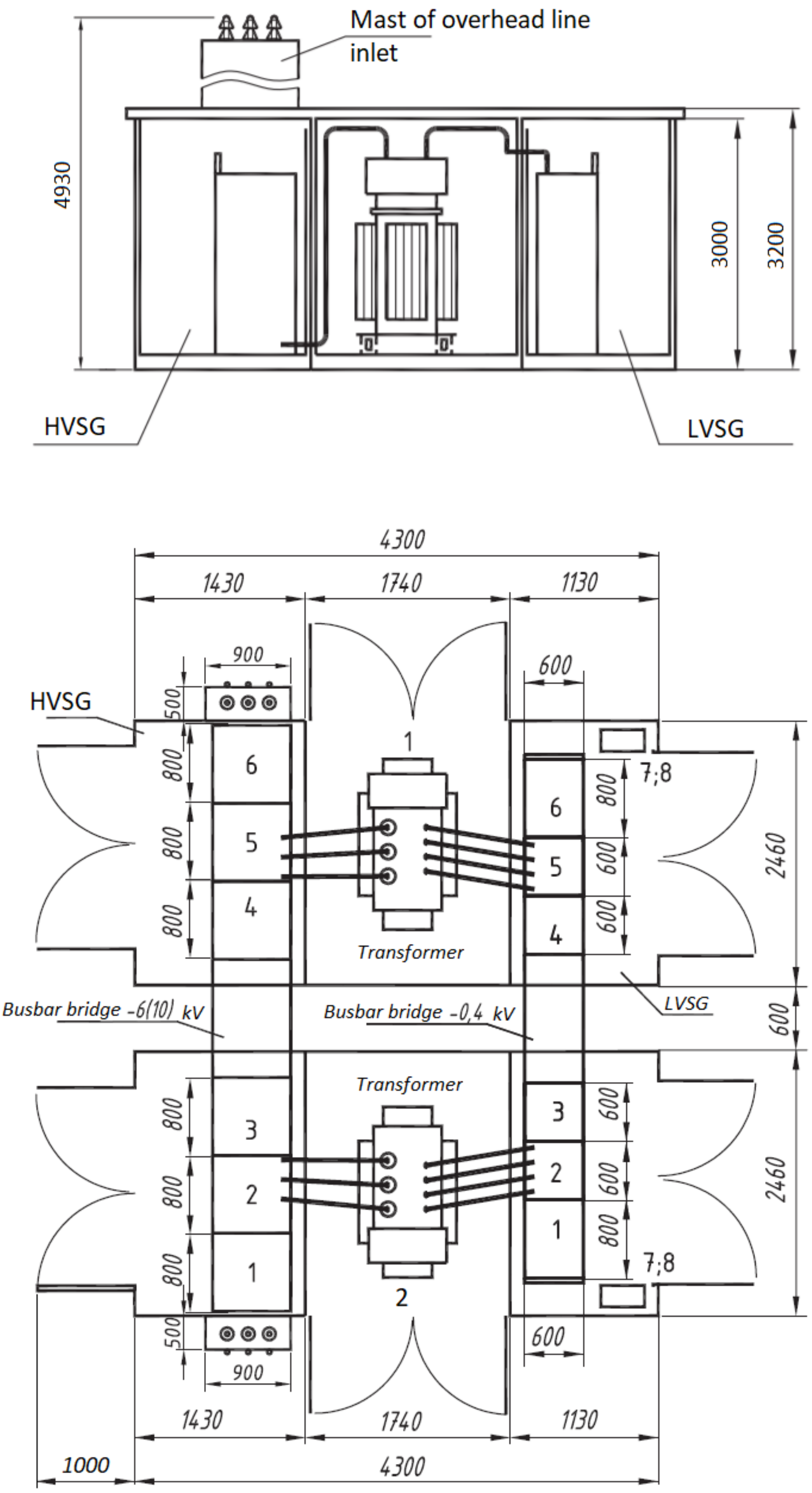
Figure 2.2 Fragment of Tomsk city distribution network: SS### – transformer substation designation, Al 1-3/C ### – caconnections between transformer substations

In this figure, number of 10/0,4 kV substations feeding consumers is operating on a single, partitioned bus system. Substation neutrals operate in the same mode.

Considered substation consists of following main components:

- Two power oil transformers for 630 kVA;
- Medium and low voltage switchgears 10 and 0,4 kV respectively;
- Medium and low voltage interconnections;
- Auxiliary equipment (lightning, heating, signalization).

The substation is structurally divided into 3 compartments: section of HVSG, section of LVSG and transformer sections partitioned both HV and LV side. The substation is connected to the mains through an overhead power line, consumers are supplied via cable lines. Considered transformer substation is standard, its scheme, shown in fig. 2.3, is based on [29]. There is operational staff building located very close to protected substation and it should be considered as connected structure in risk management calculations and economic assessment. The layout and dimensions of researched substation and adjacent building are shown in fig. 2.4.



Cells designation

HVSG:

1,6 – inlet
2,5 – line entrance to transformer
3,4 – bus-tie switch

LVSG:

1,4,6 – linear to consumers
2,5 – transformer output
3 – sectional
7 – meters cabinet
8 – auxiliary cabinet

Figure 2.3 The layout and dimensions of standard indoor transformer substation with air inlet and sectioning on HV side

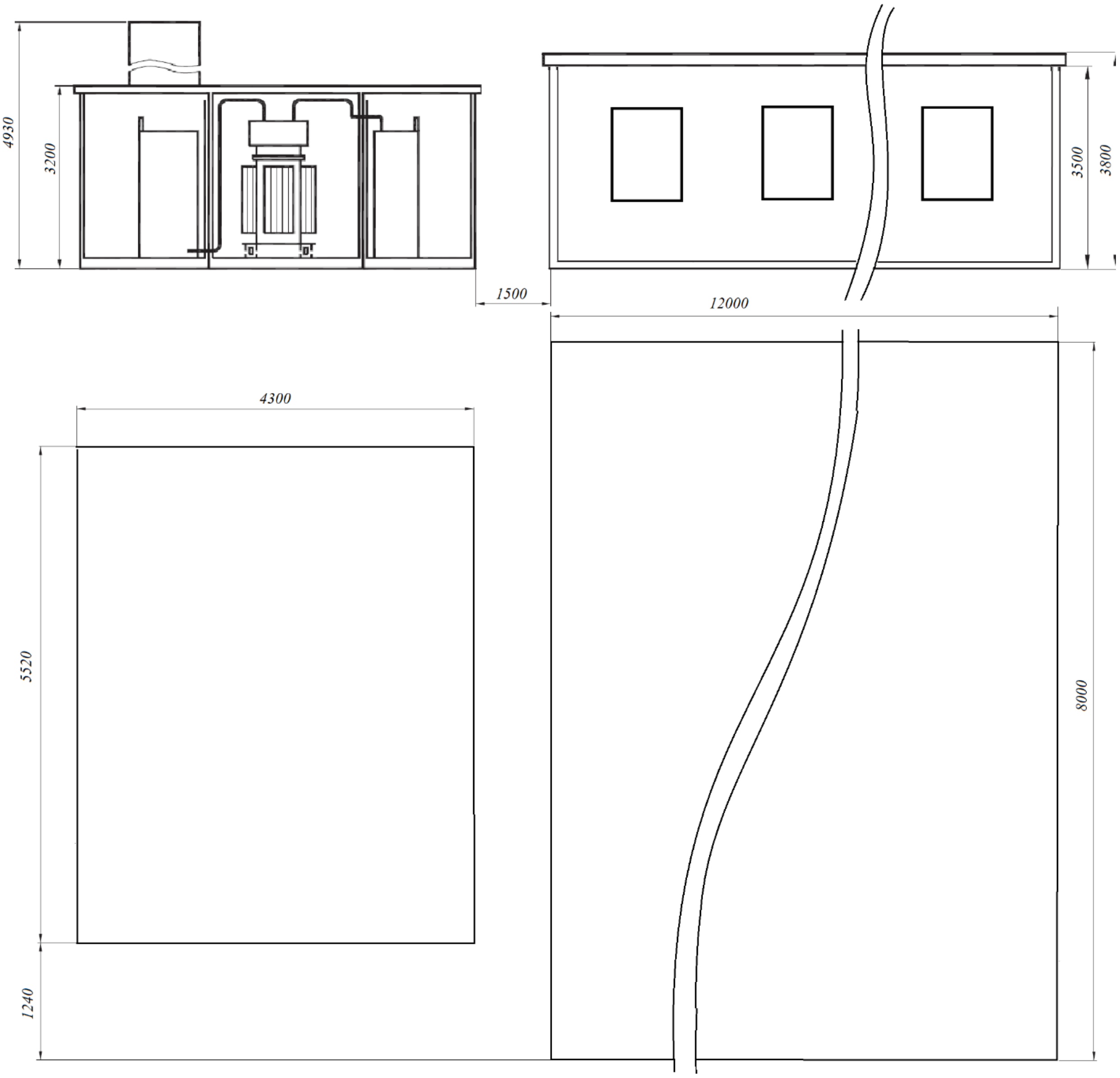


Figure 2.4 The layout and dimensions of standard indoor transformer substation and adjacent building

Considered electrical installation works with isolated neutral on the 10 kV side and *TN-S* neutral operation mode on the 0,4 kV side. Networks with an isolated neutral are characterized by low currents during single-phase earth faults, no more than 20 A at voltage level of 10 kV. On the 0,4 kV side, working with a solidly-grounded neutral, the value of fault currents mainly depend on the connection circuit of the supply transformer windings [30]. The chosen neutral grounding mode for protected substation can be explained by two reasons:

- The use of *TN-S* mode in city networks is recommended by standard [26];

- Isolation of the transformers neutral on 10 kV side is permitted according to standards [13] and it is the cheapest variant for designing. This neutral mode is applied in 80 % of Russian networks 6–35 kV [31].

The connection of the step-down transformers windings on the 10 kV side is made according to the Δ scheme. On the 0,4 kV side, the winding connection is made according to the Y scheme.

Substation is installed on the prepared concrete base platform. Internal and external LPS are common for both 10 and 0,4 kV facilities. Calculation of the external LPS will be made in the following clauses of this work. A metal cover of the stepdown substation is used as internal LPS for equipotential bounding. All metallic non-conducting parts that may be energized are attached to substation cover by welding or bolting. Each substation section has two platforms for connection to an earth-termination system [32].

To the internal LPS are attached:

- Transformer neutral on the LV side
- Transformer housing
- Metal parts of the HVSG and LVSG not energized in normal mode
- Metal non-current-carrying parts of the auxiliary equipment

Since the protected substation includes oil transformers, in the event of fault or lightning strike, they can become a source for a fire or explosion. Also the protected object includes electronic equipment, sensitive to atmospheric phenomena. In this case it is decided to set LPL – II.

It should be noted that since the installation of an earth-termination system is mandatory for transformer substation, the calculation of grounding device does not depend on the risk management and economic assessment results and will be conducted in first turn. Furthermore in the indoor transformer substations with metal cover the roof can serve as air-termination system and metallic walls as down conductors [13]. In this instance grounding device for this type of substation is the main part of LPS.

2.3 Analytical calculation of grounding device for 10/0,4 kV substation

To perform grounding protection vertical and horizontal conductors used, which together form the grounding device.

The grounding device serves for the next purposes:

- To ensure the safety of service personnel;
- For connection of electrical neutrals;

- For connection of lightning protection equipment and dispersion of lightning current into the earth.

All the listed functions are performed by the same grounding device, therefore, its choice is determined by the most stringent requirements and, as a result of the calculation, it must meet all of the above purposes. In this work, the protected substation has trunk grounding network scheme with branches, neutrals and protective conductors of all electrical installations and all electrical equipment attached to the CGD. A model of the protective grounding device is shown in the fig. 2.5.

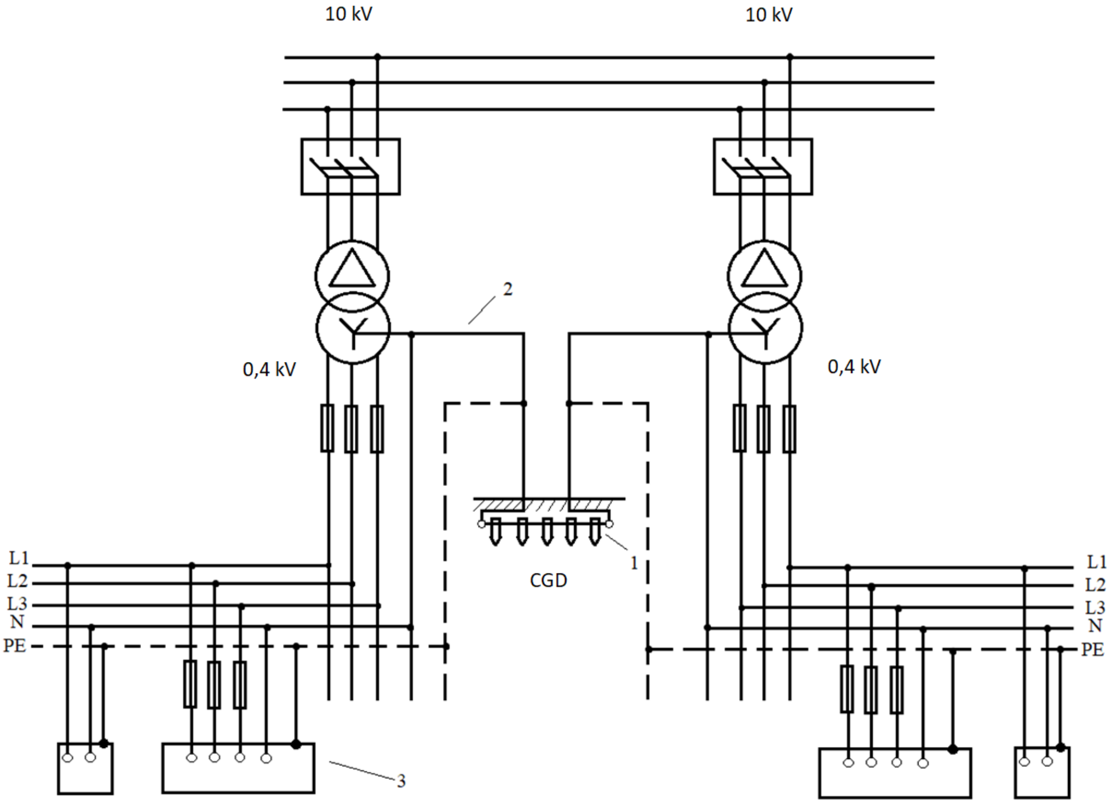


Figure 2.5: Protective grounding scheme; 1 – site of CGD installation, 2 – neutral grounding bus, 3 – an electrical receiver

In electrical installations with insulated neutral, the calculation of the grounding device is performed by the following sequence:

1. **Designing of grounding device:**
    - Determination of short circuit current and required resistance of the grounding device;
    - Determination of the estimated soil resistance;
    - Choice the number of electrodes and determination their resistance;
2. **Clarification of grounding device configuration:**
    - Determination of conductors utilization rate;

- Determination of the vertical and horizontal conductors number;
- Determination of the vertical and horizontal conductors resistance;
- Calculation of the grounding device resistance;

3. **Calculation of allowable values of step and touch voltages.**

As a grounding device circuit, the electrode layout shown in the fig. 2.6 will be taken. The earth-termination system arrangement is Type *A*.

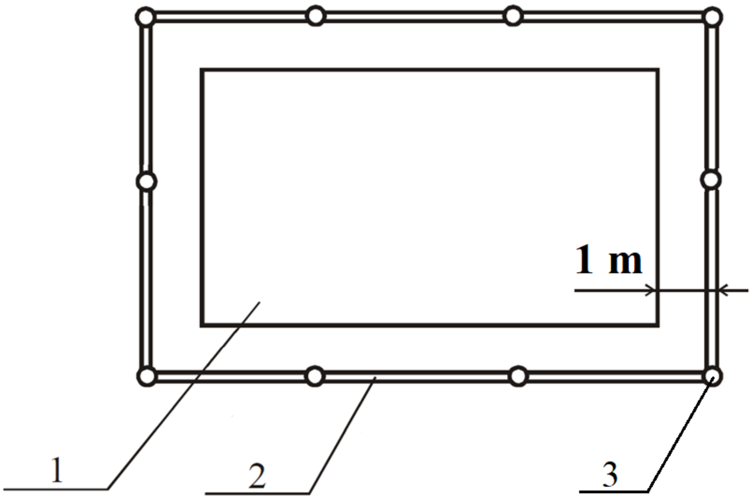


Figure 2.6 Grounding device plan: 1 – the area occupied by installations (4,3×5,5) m ; 2 – horizontal conductor; 3 – vertical rod

It should be noted that when designing a grounding device, its layout may be different. The only requirement to grounding device is to ensure the reliable protection of people and equipment.

It is supposed to create the grounding device in the form of vertical rods with 5 m length and 12 mm cross section – $l_{rod} = 5$ m, $d = 20$ mm. The distance between the vertical rods is 2,3 m – $a = 2{,}3$ m, the primary number of rods is 12. Vertical rods are connected by horizontal steel tape with 40 mm width – $b = 40$ mm, the overall tape length can be found according to the grounding device plan:

$$l_{tape} = (4{,}3 + 2) \cdot 2 + (5{,}5 + 2) \cdot 2 \approx 27{,}6 \qquad (10)$$

Short circuit current for 10 kV side approximately can be determined by the expression [3]:

$$I_{sc} = \frac{U_{nom} \cdot (35 \cdot L_c + L_{ol})}{350} = \frac{10 \cdot (35 \cdot 0 + 525)}{350} = 15\,A \qquad (11)$$

where L_c – total length of 10 kV cable lines,

L_{ol} – total length of 10 kV cable lines, Resistance of grounding device for 10 kV electrical installations [3]:

$$R_{GD} = \frac{125}{I_{sc}} = \frac{125}{15} = 8,3\ Ohm \qquad (12)$$

The required resistance of grounding device is used both for electric installations with voltage up and higher of 1 kV should be not more than 4 Ohm [13]. In this case the grounding device resistance is taken equal to 4 Ohm – R_{GD} = 4 Ohm.

The soil resistivity is determined by the formula [10]:

$$\rho_{soil} = k_{seas}\rho \qquad (13)$$

where ρ is the soil resistivity measured for normal amount of moisture,
k_{seas} is the seasonality fluctuation coefficient that takes into consideration the soil freezing and drying.

Soil at the substation for which is designed the grounding device is loamy. The ground resistivity is taken as ρ = 50 Ohm·m [33]. Seasonality fluctuation coefficient for the first climate zone, which is the zone with the most frigid climate, is taken as (Appendix 1, table 2):

$k_{seas\ v}$ = 1,9 is the seasonality fluctuation coefficient for the vertical ground conductor;

$k_{seas\ h}$ = 5,8 is the seasonality fluctuation coefficient for the horizontal ground conductor;

$$\rho_{soil\ rod} = k_{seas\,v} \cdot \rho = 1,9 \cdot 50 = 95\,Ohm \cdot m$$

$$\rho_{soil\ h} = k_{seas\,h} \cdot \rho = 5,8 \cdot 50 = 290\,Ohm \cdot m$$

The laying depth of the vertical ground conductor is f = 0,7 m (Appendix 1, table 2). The vertical ground conductor resistance is determined by the next formula [34]:

$$r_{rod} = \frac{\rho_{soil\ rod}}{2\pi l_{rod}}(\ln\frac{2l_{rod}}{d} + \frac{1}{2}\ln\frac{2t + \frac{l_{rod}}{2}}{2t - \frac{l_{rod}}{2}}) = \frac{95}{2 \cdot \pi \cdot 5}(\ln\frac{2 \cdot 5}{20 \cdot 10^{-3}} + \frac{1}{2}\ln\frac{2 \cdot 2,2 + \frac{5}{2}}{2 \cdot 2,2 - \frac{5}{2}}) = 20,7\,Ohm \qquad (14)$$

where t is the depth from ground surface to the middle of vertical conductor,

$$t = f + \frac{l_{в}}{2} = 0,7 + \frac{3}{2} = 2,2\,m \qquad (15)$$

The ratio of the vertical ground conductor length to the distance between rods is equal to 0,5 – $a/l \approx 0,5$, utilization rate has the following values [3]:

ŋ$_{rod}$ = 0,52 – utilization rate for the vertical ground conductors;

ŋ$_{h}$ = 0,32 – utilization rate for the horizontal ground conductors;

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

$$R_{rod} = \frac{r_{rod}}{\eta_{rod}} = \frac{20,7}{0,52} = 39,9\,Ohm \qquad (16)$$

According to the calculation the necessary number of vertical rods is 5.

The resistance of horizontal steel tape in grounding devise loop is determined by the formula [27]:

$$r_h = \frac{\rho_h}{\pi l_h} \ln \frac{1,5 \cdot l_{tape}}{\sqrt{b \cdot t}} = \frac{290}{\pi \cdot 27,6} \ln \frac{1,5 \cdot 27,6}{\sqrt{40 \cdot 10^{-3} \cdot 0,7}} = 18,432\,Ohm \qquad (17)$$

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

$$R_h = \frac{r_h}{\eta_h} = \frac{18,432}{0,32} = 57,6\,Ohm \qquad (18)$$

The required resistance of vertical rods is:

$$R'_{rod} = \frac{R_h \cdot R_{GS}}{R_h - R_{GS}} = \frac{57,6 \cdot 4}{57,6 - 4} = 4,3\,Ohm \qquad (16)$$

The refined number of vertical conductors:

$$N'_{rod} = \frac{R_{rod}}{R'_{rod}} = \frac{41,4}{4,3} = 9,3 \rightarrow 10 \qquad (17)$$

Thus the clarified number of vertical ground conductors is 10. Two rods at the sides of the grounding device loop are not installed, fig. 2.6. Utilization rate in this case is 0,55 – η_{rod} = 0,55 [3]. The vertical conductors resistance in this case:

$$R''_{rod} = \frac{r_{rod}}{N'_{rod} \cdot \eta'_{rod}} = \frac{21,5}{10 \cdot 0,55} = 3,8\,Ohm \qquad (18)$$

The grounding device resistance will be determined as:

$$R_{GS} = \frac{R_h \cdot R''_{rod}}{R_h + R''_{rod}} = \frac{57,6 \cdot 3,8}{57,6 + 3,8} = 3,5\,Ohm \qquad (19)$$

Impulse currents (lightning strikes current) passing through the grounding device makes specific conditions that change earth-termination system static resistance [35]. This change is taken into account by the introduction of a pulse coefficient – α_{imp} .

Pulse coefficient can be estimated by the formula for lightning currents from the range (5 – 150 kA):

$$\alpha_{imp}^{5kA} = \sqrt{\frac{1500\sqrt{S}}{(\rho+320)\cdot(I_{strike}+45)}} = \sqrt{\frac{1500\sqrt{6,3\cdot 7,5}}{(50+320)\cdot(5+45)}} = 0,747 \quad (20)$$

$$\alpha_{imp}^{100kA} = \sqrt{\frac{1500\sqrt{S}}{(\rho+320)\cdot(I_{strike}+45)}} = \sqrt{\frac{1500\sqrt{6,3\cdot 7,5}}{(50+320)\cdot(100+45)}} = 0,378 \quad (21)$$

Impulse resistance of the grounding device:

$$R_{imp} = (\alpha_{imp}^{5kA} \div \alpha_{imp}^{100kA})\cdot R_{GD} = (0,747 \div 0,378)\cdot 3,7 = 2,6 \div 1,3\,Ohm \quad (22)$$

The calculated grounding device resistance is less than standard value. It means that the earth-termination system is reliable for electrical equipment protection. Furthermore, it is necessary to assess the reliability of human protection. For this purpose in the next paragraph step and touch voltages will be calculated and program model will be created based on the results of CGD analytical calculation.

2.4 Step and touch voltages calculation and program model implementation

Safety of a human depends on preventing the critical amount of shock energy from being absorbed before the fault is cleared and the system de-energized. The maximum driving voltage of any accident circuit should not exceed the limits defined below [36].

The tolerable limits for the step voltages calculated for 50 and 70 kg body weight:

$$E_{step\ for 50kg} = (1000 + 6\cdot C_s \cdot \rho)\cdot \frac{0,166}{\sqrt{t_s}} \quad (23)$$

$$E_{step\ for 70kg} = (1000 + 6\cdot C_s \cdot \rho)\cdot \frac{0,157}{\sqrt{t_s}} \quad (24)$$

where t_s is duration of fault in seconds, according to the condition of protection adjustment this time should be equal to 0,1 seconds [37],

C_s – surface layer coefficient,

ρ – soil resistivity.

Surface layer coefficient can be calculated by the formula:

$$C_s = 1 - \frac{0,09 \cdot (1 - \frac{\rho}{\rho_{s\,layer}})}{2h_{s\,layer} + 0,09} \qquad (25)$$

where $h_{s\text{ layer}}$ –thickness of the surface layer in meters,

$\rho_{s\,layer}$ –resistivity of the surface layer, Ohm·m,

ρ - soil resistivity under the surface layer, Ohm·m.

According to the project of the substation, the surface layer is concrete 0,2 m thick, its specific resistance is 1500 Ohm·m.

$$C_s = 1 - \frac{0,09 \cdot (1 - \frac{\rho}{\rho_{s\,layer}})}{2h_{s\,layer} + 0,09} = 1 - \frac{0,09 \cdot (1 - \frac{50}{1500})}{2 \cdot 0,2 + 0,09} = 0,822$$

The tolerable step voltage values:

$$E_{step\ for 50kg} = (1000 + 6 \cdot 0,822 \cdot 50) \cdot \frac{0,166}{\sqrt{0,1}} = 654V$$

$$E_{step\ for 70kg} = (1000 + 6 \cdot 0,822 \cdot 50) \cdot \frac{0,157}{\sqrt{0,1}} = 619V$$

The tolerable limits for the touch voltages calculated for 50 and 70 kg body weight:

$$E_{touch\ for 50kg} = (1000 + 1,5 \cdot C_s \cdot \rho) \cdot \frac{0,166}{\sqrt{t_s}} = (1000 + 1,5 \cdot 0,822 \cdot 50) \cdot \frac{0,166}{\sqrt{0,1}} = 557V \qquad (26)$$

$$E_{touch\ for 70kg} = (1000 + 1,5 \cdot C_s \cdot \rho) \cdot \frac{0,157}{\sqrt{t_s}} = (1000 + 1,5 \cdot 0,822 \cdot 50) \cdot \frac{0,157}{\sqrt{0,1}} = 527V \qquad (27)$$

After the designing process and calculations of the CGD parameters as well as the safety voltage limits are finished, software simulation can be performed. Program model is simulated in *ETAP* program and based on the finite element analysis. This program can run the grounding device configurations of any complexity, consisted from the conductors laid in three mutually perpendicular directions. Program divides the grounding device layout into small straight segments and calculates the mutual resistances of these segments and tolerable touch and step voltages on this plots. Then it summarizes the calculated results to obtain the resistance of CGD and plot voltage distribution graphs. Voltage graphs for 70 kg weight shown in the Appendix 1, fig. 2, 3.

According to obtained graph during the program simulation the designed earth-termination system provides reliable protection of people and animals from physical damage due to faults.

3. Risk management

The main goal of risk assessment is to determine if additional protection required or not. If it is required than to define protection measures. Protection measures can be implemented even when the risk management shows that it is not necessary. Risk analysis consist of following steps [38]:

- Identify the structure environment;
- Evaluating loss types (*L1 – L3*) and associated risks (*R1 – R3*);
- Comparing *R1 – R3* with the tolerable risk – $R_{T\,1\text{-}3}$;
- Evaluating risks $R1 - R3 \leq R_{T\,1\text{-}3}$.

Risk assessment process can be introduced as a flow chart shown in the fig. 3.1

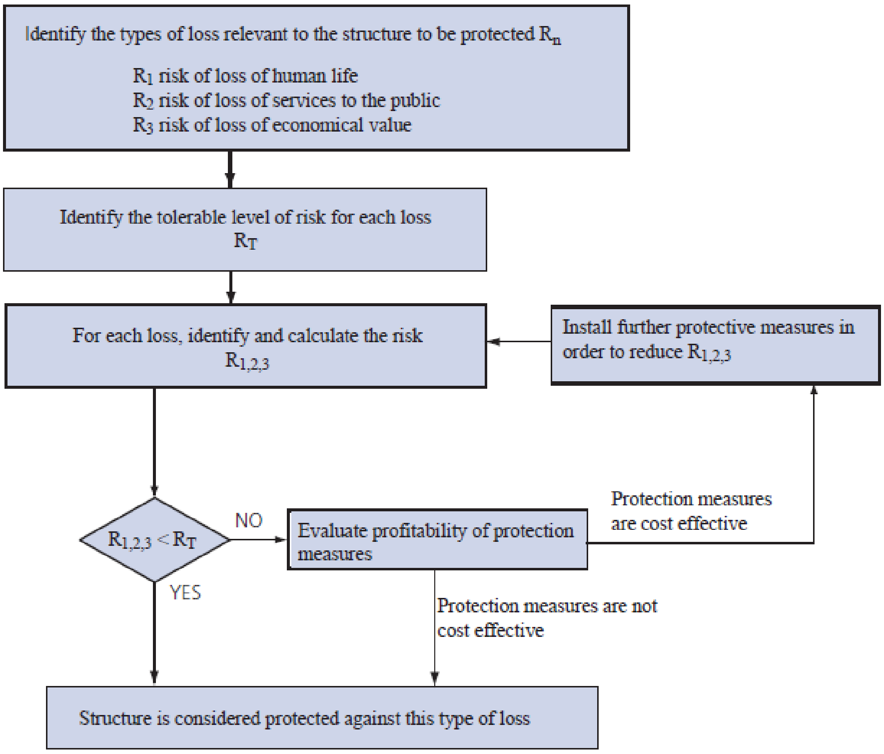


Figure 3.1 Flow diagram for determining the need of protection and for selecting protection measures

Reliable protection system requires all evaluated risks to be less than tolerable values. If it is not possible to eliminate risk it should be covered by insurance.

It is important to understand sources, types of damages and possible losses due to this damages in order to evaluate risks consider the protected structure, services and its environment, table 3.1.

Table 3.1 – Damage and losses of the structure depending on the point of strike (based on [38])

Point of strike	Type of damage	Type of loss
S1 – Lightning strike to the structure	D1 – injury of living due to touch and step voltages	$L1._{A}$ – Loss of human life $L3._{A}$ – Economic loss
	D2 – damage due to fire, explosions and chemical reactions	$L1._{B}$ – Loss of human life $L2._{B}$ – Loss of public service $L3._{B}$ – Economic loss
	D3 – failure of electrical and electronic systems due to lightning impulse	$L1._{C}$ – Loss of human life $L2._{C}$ – Loss of public service $L3._{C}$ – Economic loss
S2 – Lightning strike near the structure	D3 – failure of electrical and electronic systems due to lightning impulse	$L1._{M}$ – Loss of human life $L2._{M}$ – Loss of public service $L3._{M}$ – Economic loss
S3 – Lightning strike to incoming line	D1 – injury of living due to touch and step voltages	$L1._{U}$ – Loss of human life $L3._{U}$ – Economic loss
	D2 – damage due to fire, explosions and chemical reactions	$L1._{V}$ – Loss of human life $L2._{V}$ – Loss of public service $L3._{V}$ – Economic loss
	D3 – failure of electrical and electronic systems due to lightning impulse	$L1._{W}$ – Loss of human life $L2._{W}$ – Loss of public service $L3._{W}$ – Economic loss
S4 – Lightning strike near incoming line	D3 – failure of electrical and electronic systems due to lightning impulse	$L1._{Z}$ – Loss of human life $L2._{Z}$ – Loss of public service $L3._{Z}$ – Economic loss

The risk R that the lightning damage occurs is the sum of risks components that can be defined by the following formula [38]:

$$R_x = N_x \cdot P_x \cdot L_x \qquad (28)$$

where R_x – individual risk component,

N_x – number of dangerous events (the frequency of lightning strikes in a year),

P_x –probability of damage,

L_x – loss factor (quantity evaluation of damage).

Therefore, to define the risk function it is necessary to determine the three parameters N_x , P_x and L_x for all relevant risk components R_x.

3.1 Calculation of dangerous events frequency

Frequency of dangerous incidents caused by direct lightning strikes to the structure can be calculated by the next formula [6]:

$$N_D = N_G \cdot A_D \cdot C_D \cdot 10^{-6} = 4 \cdot 1001 \cdot 0,5 \cdot 10^{-6} = 2 \cdot 10^{-3} \qquad (29)$$

where A_D – the equivalent collection area of the structure, fig 3.2,

C_D = *0,5* – location factor (consider the influence of the surrounding objects), (Appendix 2, table 1),

N_G – number of lightning strikes in year per 1 km^2. Based on data from Appendix 1, table 1, $N_G \approx 4$.

The collection area can be calculated by the following formula [11]:

$$\begin{aligned} A_D &= L \cdot W + 2 \cdot (3 \cdot H) \cdot (L + W) + \pi \cdot (3 \cdot H)^2 = \\ &= 5,52 \cdot 4,3 + 2 \cdot (3 \cdot 4,93) \cdot (5,52 + 4,3) + \pi \cdot (3 \cdot 4,93)^2 = 1001\ m^2 \end{aligned} \qquad (30)$$

where *L*, *W*, *H* – length, width and height of the structure respectively.

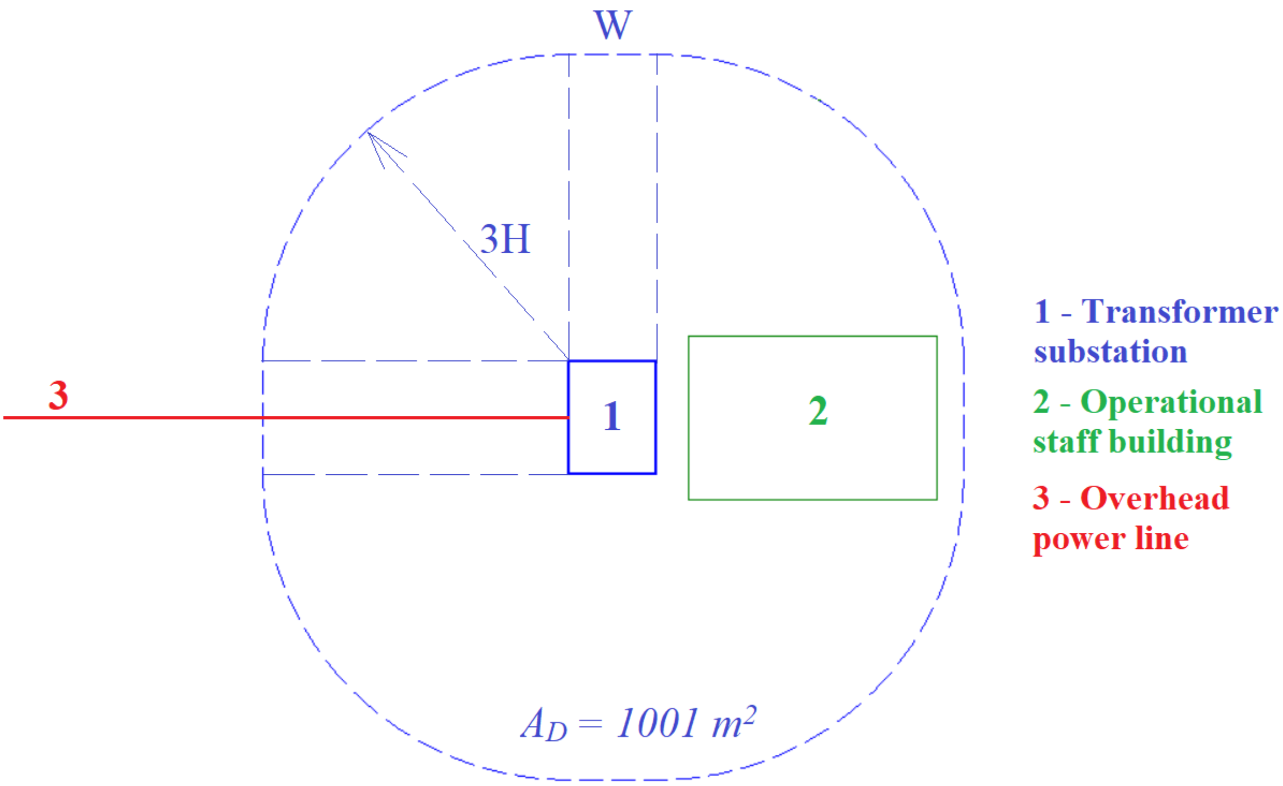


Figure 3.2 Equivalent collection area of the protected structure in case of direct lightning strike

Frequency of dangerous incidents caused by lightning strikes near the structure is described by the next formula [11]:

$$N_M = N_G \cdot A_M \cdot 10^{-6} = 4 \cdot 7952 \cdot 10^5 \cdot 10^{-6} = 3,2 \qquad (31)$$

where A_m – area obtained by drawing the line on the 500 m distance from the structure – M = 500 m.

A_m can be calculated by the formula [11]:

$$\begin{aligned} A_M &= L \cdot W + 2 \cdot M \cdot (L+W) + \pi \cdot (M)^2 = \\ &= 5,52 \cdot 4,3 + 2 \cdot 500 \cdot (5,52+4,3) + \pi \cdot (500)^2 = 7952 \cdot 10^5\ m^2 \end{aligned} \qquad (32)$$

Frequency of dangerous incidents caused by lightning strikes to incoming line is calculated by the next formula [11]:

$$N_L = N_G \cdot A_L \cdot C_I \cdot C_E \cdot C_T \cdot 10^{-6} = 4 \cdot 40 \cdot 10^3 \cdot 1 \cdot 0,1 \cdot 0,2 \cdot 10^{-6} = 3,2 \cdot 10^{-3} \qquad (33)$$

where N_L – number of surges in line section per year,

$C_I = 1$ – installation factor of the line (Appendix 2, table 2),

$C_E = 0,1$ – environmental factor (Appendix 2, table 3),

$C_T = 0,2$ – line type factor (Appendix 2, table 4),

$A_L = 40 \cdot L_{line}$ – collection area of the line of 1000 m length.

Frequency of dangerous incidents caused by lightning strikes near incoming line can be calculated by the next formula [11]:

$$N_I = N_G \cdot A_I \cdot C_I \cdot C_E \cdot C_T \cdot 10^{-6} = 4 \cdot 4000 \cdot 1 \cdot 0,1 \cdot 0,2 \cdot 10^{-6} = 0,32 \qquad (34)$$

where A_I – area obtained by drawing the square with 4000 m – width and L_{line} = 1000 m – length.

It should be noted that transformer substation has two incoming lines, but these lines are located close to each other relative the collection areas width, thus in calculations it can be considered as one line section.

3.2 Calculation of damage probabilities

Probability of damage defines the probability of dangerous events caused by lightning strike and it can have maximum value of one. There are the following eight possible probabilities:

1. Probability of damage in case of direct lightning strikes (*S1*):
    - P_A – probability of human or animal will be injured;
    - P_B – probability that describes measures against physical damage due to fire and explosions, $P_B = 1$ (Appendix 3, table 2);
    - P_C – probability of internal systems failure.

2. Probability of damage in case of lightning strike near the structure (*S2*):
    - P_M – Failure of electrical or electronic systems.
3. Probability of damage in case of lightning strike to incoming line (*S3*):
    - P_U – Injury to living beings;
    - P_V – Physical damage (fire, explosion);
    - P_W – Failure of electrical or electronic systems.
4. Probability of damage in case of lightning strike near incoming line (*S4*):
    - P_Z – Failure of electrical or electronic systems.

Probability of damage in case of *S1* [9]:

$$P_A = P_{TA} \cdot P_B = 10^{-2} \cdot 1 = 10^{-2} \qquad (35)$$

$$P_C = P_{SPD} \cdot C_{LD} = 1 \cdot 1 = 1 \qquad (36)$$

where $P_{TA} = 10^{-2}$– probability that describes protection measures against touch and step voltages, (Appendix 3, table 1);

$P_{SPD} = 1$ – probability that describes protection measures depending on SPDs presence and LPL, (Appendix 3, table 3);

$C_{LD} = 1$ – factor considering insulation and earthing conditions of supplying line, (Appendix 3, table 4).

Probability of damage in case of *S2* [14]:

$$P_M = P_{SPD} \cdot (K_{S1} \cdot K_{S2} \cdot K_{S3})^2 = 1 \cdot (0,276 \cdot 1 \cdot 0,01)^2 = 7,6 \cdot 10^{-6} \qquad (37)$$

where K_{S1} –factor of shielding effectiveness of the structure;

K_{S2} – factor depends on the rated impulse withstand voltage of the system to be protected;

$K_{S3} = 0,01$ – factor depends on internal wiring, (Appendix 3, table 5).

K_{S1} and K_{S2} can be calculated by the formulas [15]:

$$K_{S1} = 0,12 \cdot a = 0,12 \cdot 2,3 = 0,276 \qquad (38)$$

$$K_{S2} = \frac{1}{U_W} = \frac{1}{1} = 1 \qquad (39)$$

where $a = 2,3\ m$ – distance between the metal rods of the *CGD* in meters (Paragraph 2.3),

$U_W = 1\ kV$– rated impulse withstand voltage of the system to be protected in kV.

Probability of damage in case of *S3*:

$$P_U = P_{TU} \cdot P_{EB} \cdot P_{LD} \cdot C_{LD} = 10^{-1} \cdot 1 \cdot 1 \cdot 1 = 0,1 \qquad (40)$$

where $P_{TU} = 10^{-1}$ – probability that describes protection measures against touch and step voltages, (Appendix 3, table 6);
$P_{EB} = 1$ – probability that depends on equipotential bounding and LPL, (Appendix 3, table 7);
$P_{LD} = 1$ – probability that structure would fail due to lightning strike to supplying line, (Appendix 3, table 8).

Probability that physical damage would occur due to a lightning strike to a line entering the structure:

$$P_V = P_{EB} \cdot P_{LD} \cdot C_{LD} = 1 \cdot 1 \cdot 1 = 1 \qquad (41)$$

Probability of internal systems failure as the result of S3:

$$P_W = P_{SPD} \cdot P_{LD} \cdot C_{LD} = 1 \cdot 1 \cdot 1 = 1 \qquad (42)$$

Probability of internal systems failure in case of S4:

$$P_Z = P_{SPD} \cdot P_{LI} \cdot C_{LI} = 1 \cdot 1 \cdot 1 = 1 \qquad (43)$$

where P_Z – probability that lightning strikes near the supplying line will failure the structure;
$P_{LI} = 1$ – probability of structure failure due to lightning strikes that depends on line features, (Appendix 3, table 9);
$C_{LI} = 1$ – factor that considers features of the line, (Appendix 3, table 4).

3.3 Calculation of damage losses

Loss of human life (*L1*) divided up to eight losses relevant to the structure that can be defined by the formulas [6]:

$$L_{1A} = L_{1U} = \frac{r_t \cdot L_t \cdot n_z}{n_t} \cdot \frac{t_z}{8760} = \frac{10^{-3} \cdot 10^{-2} \cdot 10}{10} \cdot \frac{1900}{8760} = 2,169 \cdot 10^{-6} \qquad (44)$$

$$L_{1B} = L_{1V} = \frac{r_p \cdot r_f \cdot h_z \cdot L_F \cdot n_z}{n_t} \cdot \frac{t_z}{8760} = \frac{0,2 \cdot 10^{-1} \cdot 1 \cdot 10^{-1} \cdot 10}{10} \cdot \frac{1900}{8760} = 4,338 \cdot 10^{-4} \qquad (45)$$

$$L_{1C} = L_{1M} = L_{1W} = L_{1Z} = \frac{L_0 \cdot n_z}{n_t} \cdot \frac{t_z}{8760} = \frac{10^{-1} \cdot 10}{10} \cdot \frac{1900}{8760} = 0,022 \qquad (46)$$

where $L_T = 10^{-2}$– typical mean percentage of injured people or animals by *D1*, (Appendix 4, table 1);

$L_F = 10^{-1}$ – typical mean percentage of injured people or animals by *D2*, (Appendix 4, table 1);

$L_0 = 10^{-1}$ – typical mean percentage of injured people or animals by *D3*, (Appendix 4, table 1);

$r_t = 10^{-3}$ – factor that reduces *L1* depending on type of the floor, (Appendix 4, table 2);

$r_p = 0,2$ – factor that reduces *L1* depending on measures taken to reduce the fire consequences, (Appendix 4, table 3);

$r_f = 10^{-1}$ – factor that reduces *L1* depending on the risk of fire and explosions, (Appendix 4, table 4);

$h_z = 1$ – factor increases the relative value of a loss for type of loss *L1* when a special danger exist, (Appendix 4, table 5);

$n_z = 10$ – number of people in the protected zone, assume n_z equals to 10;

$n_t = 10$ – number of people in the structure, n_t equals to n_z;

$t_z = 1900\ h$ – number of hours per year during which people stay in the zone, assume it equal to 1900 hours (number of working hours during a year).

Loss of public services (L2) divided up to six losses relevant to the structure that can be defined by the formulas:

$$L_{2B} = L_{2V} = \frac{r_p \cdot r_f \cdot L_F \cdot n_z}{n_t} = \frac{0,2 \cdot 10^{-1} \cdot 10^{-1} \cdot 2000}{4000} = 1 \cdot 10^{-3} \qquad (47)$$

$$L_{2C} = L_{2M} = L_{2W} = L_{2Z} = \frac{L_0 \cdot n_z}{n_t} = \frac{10^{-2} \cdot 2000}{4000} = 5 \cdot 10^{-3} \qquad (48)$$

where $L_F = 10^{-1}$ – typical mean percentage of unserved users due to *D2*, (Appendix 4, table 6);

$L_0 = 10^{-2}$ – typical mean percentage of unserved users due to *D3*, (Appendix 4, table 6);

$n_z = 2000$ – number of served users in the (supply) zone, assume n_z equals to 2000;

$n_t = 4000$ – number of served users by the structure, assume n_t equals to 4000.

Economic loss (*L3*) is divided up to eight losses relevant to the structure that can be defined by the formulas [6]:

$$L_{3A} = L_{3U} = \frac{r_t \cdot L_t \cdot c_a}{c_t} = \frac{10^{-2} \cdot 10^{-2} \cdot 0}{300} = 0 \qquad (49)$$

$$L_{3B} = L_{3V} = \frac{r_p \cdot r_f \cdot L_f \cdot (c_a + c_b + c_c + c_s)}{c_t} = \frac{0,2 \cdot 10^{-1} \cdot 1 \cdot 10^{-2} \cdot 10^{-2} \cdot 300}{300} = 0,02 \qquad (50)$$

$$L_{3C} = L_{3M} = L_{3W} = L_{3Z} = \frac{L_0 \cdot c_s}{c_t} = \frac{10^{-1} \cdot 0,7 \cdot 300}{300} = 0,07 \qquad (51)$$

where $L_T = 10^{-2}$ – percentage of damaged equipment by *D1,* (Appendix 4, table 7);

$L_F = 1$ – percentage of damaged equipment by *D2,* (Appendix 4, table 7);

$L_0 = 10^{-2}$ – percentage of damaged equipment by *D3*, (Appendix 4, table 7);

c_a – value of injured animals,

c_b – value of the building related to the zone,

c_c – value of the external equipment in the zone,

c_s – value of the internal equipment in the zone,

c_t – total value of the structure, assume equal to 300 EUR/m^2 [38],

The values of c_a , c_c , c_s , c_t are typically provided by the owner of the structure. In many cases, these values are not available, this project is not an exception. In this case a simplified procedure to implement the risk management can be applied [38]. For the protected structure based on Russian market value of the equipment, they can be estimated as:

- $c_a = 0$;
- $c_b = 0,2 \cdot c_t$;
- $c_c = 0,1 \cdot c_t$;
- $c_s = 0,7 \cdot c_t$;
- $c_t = 300$ EUR/m^2 .

It should be noted that economic losses connected with power outage of consumers do not taken into account, because considered transformer substation supplies consumers of the third group. For this group it is possible to interrupt the power supply for 24 hours, it is supposed that the malfunction will be repaired no later than this time. [13]

3.4 Calculation of risks

Depending on the sources and types of damage, there are the following risk components, table 3.2.

Table 3.2 – Risk components for different points of strike and types of damage

Source of damage	Type of damage	Risk Component	Formula	Value
S1	D1	R_{1A}	$N_D \cdot P_A \cdot L_{1A}$	$4{,}34 \cdot 10^{-11}$
		R_{3A}	$N_D \cdot P_A \cdot L_{3A}$	0
	D2	R_{1B}	$N_D \cdot P_B \cdot L_{1B}$	$8{,}7 \cdot 10^{-7}$
		R_{2B}	$N_D \cdot P_B \cdot L_{2B}$	$2{,}0 \cdot 10^{-6}$
		R_{3B}	$N_D \cdot P_B \cdot L_{3B}$	$4{,}0 \cdot 10^{-5}$
	D3	R_{1C}	$N_D \cdot P_C \cdot L_{1C}$	$4{,}3 \cdot 10^{-5}$
		R_{2C}	$N_D \cdot P_C \cdot L_{2C}$	$1{,}0 \cdot 10^{-5}$
		R_{3C}	$N_D \cdot P_C \cdot L_{3C}$	$1{,}4 \cdot 10^{-4}$
S2	D3	R_{1M}	$N_M \cdot P_M \cdot L_{1M}$	$5{,}26 \cdot 10^{-7}$
		R_{2M}	$N_M \cdot P_M \cdot L_{2M}$	$1{,}2 \cdot 10^{-7}$
		R_{3M}	$N_M \cdot P_M \cdot L_{3M}$	$1{,}7 \cdot 10^{-6}$
S3	D1	R_{1U}	$N_L \cdot P_U \cdot L_{1U}$	$6{,}9 \cdot 10^{-10}$
		R_{3U}	$N_L \cdot P_U \cdot L_{3U}$	0
	D2	R_{1V}	$N_L \cdot P_V \cdot L_{1V}$	$1{,}4 \cdot 10^{-6}$
		R_{2V}	$N_L \cdot P_V \cdot L_{2V}$	$3{,}2 \cdot 10^{-6}$
		R_{3V}	$N_L \cdot P_V \cdot L_{3V}$	$6{,}4 \cdot 10^{-5}$
	D3	R_{1W}	$N_L \cdot P_W \cdot L_{1W}$	$6{,}9 \cdot 10^{-5}$
		R_{2W}	$N_L \cdot P_W \cdot L_{2W}$	$1{,}6 \cdot 10^{-5}$
		R_{3W}	$N_L \cdot P_W \cdot L_{3W}$	$2{,}2 \cdot 10^{-4}$
S4	D3	R_{1Z}	$N_I \cdot P_Z \cdot L_{1Z}$	$6{,}9 \cdot 10^{-3}$
		R_{2Z}	$N_I \cdot P_Z \cdot L_{2Z}$	$1{,}6 \cdot 10^{-3}$
		R_{3Z}	$N_I \cdot P_Z \cdot L_{3Z}$	$2{,}2 \cdot 10^{-3}$

The tolerable values for the three types of loss are shown in the table 3.2

Table 3.2 – Typical tolerable risk values R_T
(based on [38])

Type of loss	R_T, 1/year
L1	10^{-5}
L2	10^{-3}
L3	10^{-3}

Risk of loss of human life or injury of living beings caused by electric shock can be calculated as a sum of following risk components:

$$R_1 = R_{1A} + R_{1B} + R_{1C} + R_{1M} + R_{1U} + R_{1V} + R_{1W} + R_{1Z} = 7,1 \cdot 10^{-3} \qquad (52)$$

Risk of loss of services can be calculated as a sum of following risk components:

$$R_2 = R_{2B} + R_{2C} + R_{2M} + R_{2V} + R_{2W} + R_{2Z} = 1,6 \cdot 10^{-3} \qquad (53)$$

Risk of loss of economic value can be calculated as a sum of following risk components:

$$R_3 = R_{3A} + R_{3B} + R_{3C} + R_{3M} + R_{3U} + R_{3V} + R_{3W} + R_{3Z} = 22,9 \cdot 10^{-3} \qquad (54)$$

Comparison of obtained results with standard requirements shows that calculated risks exceed tolerable values for all types of loss. It means that protection measures should be taken.

3.5 Protection measures estimation and sensitivity analysis

There are several protection measures can be implemented for reduction of risk, each of them has different impact on risk components [6]. Possible protection measures for indoor transformer substation and they relative influence on risk components for each type of risk R_{1-3} are shown in the table 3.3 – 3.5. The protection measure which gives the highest reduction off risk should be taken, it is also supposed to set the level of indifference equal to 10 % (the influence of protection measures is considered equal, if the difference in overall risk reduction with these protective measures is less than 10 %).

Table 3.3 – Possible protection measures and they influence on the risk R_1 components

Protection measures	**R1a**	**R1b**	**R1c**	**R1m**	**R1u**	**R1v**	**R1w**	**R1z**	**ΣR$_i$**	**Value of R1 possible reduction**
	$2,20 \cdot 10^{-10}$	$4,30 \cdot 10^{-6}$	$2,20 \cdot 10^{-4}$	$2,60 \cdot 10^{-6}$	$3,50 \cdot 10^{-9}$	$6,90 \cdot 10^{-6}$	$3,50 \cdot 10^{-4}$	$3,50 \cdot 10^{-2}$	%	$7,06 \cdot 10^{-3}$
	Influense on the risk components (R1$_i$ / R1), %									
Physical restrictions, insulation, warning notice	0,000				0,000				0,000	$7,37 \cdot 10^{-10}$
Lightning protection system (LPS)	0,000	0,012	0,615	0,007	0,000	0,020			0,655	$4,62 \cdot 10^{-5}$
Coordinated SPD system			0,615	0,007			0,984	98,362	99,968	$7,05 \cdot 10^{-3}$
Spatial shielding			0,615	0,007					0,623	$4,39 \cdot 10^{-5}$
Routing precautions			0,615	0,007					0,623	$4,39 \cdot 10^{-5}$
Equipotential bonding network			0,615						0,615	$4,34 \cdot 10^{-5}$

Table 3.4 – Possible protection measures and they influence on the risk R_2 components

Protection measures	R2a	R2b	R2c	R2m	R2u	R2v	R2w	R2z	ΣRi	Value of R2 possible reduction
		$2,00\cdot 10^{-6}$	$1,00\cdot 10^{-5}$	$1,20\cdot 10^{-6}$		$3,20\cdot 10^{-6}$	$1,60\cdot 10^{-4}$	$1,60\cdot 10^{-2}$	%	$1,63\cdot 10^{-2}$
	Influense on the risk components ($R3_i$ / R3), %									
Physical restrictions, insulation, warning notice	0,000				0,000				0,000	0,00
Lightning protection system (LPS)	0,000	0,123	0,613	0,007	0,000	0,196			0,939	$1,53\cdot 10^{-5}$
Coordinated SPD system			0,613	0,007			0,981	98,080	99,681	$1,63\cdot 10^{-3}$
Spatial shielding			0,613	0,007					0,620	$1,01\cdot 10^{-5}$
Routing precautions			0,613	0,007					0,620	$1,01\cdot 10^{-5}$
Equipotential bonding network			0,613						0,613	$1,00\cdot 10^{-5}$

Table 3.5 – Possible protection measures and they influence on the risk R_3 components

Protection measures	R3a	R3b	R3c	R3m	R3u	R3v	R3w	R3z	ΣRi	Value of R3 possible reduction
	0,00	$4,00\cdot 10^{-5}$	$1,40\cdot 10^{-4}$	$1,70\cdot 10^{-6}$	0,00	$6,40\cdot 10^{-5}$	$2,20\cdot 10^{-4}$	$2,20\cdot 10^{-3}$	%	$2,76\cdot 10^{-3}$
	Influense on the risk components ($R3_i$ / R3), %									
Physical restrictions, insulation, warning notice	0,000				0,000				0,000	0,00
Lightning protection system (LPS)	0,000	1,501	5,252	0,064	0,000	2,401			9,217	$1,50\cdot 10^{-4}$
Coordinated SPD system			5,252	0,064			8,253	82,530	96,099	$1,57\cdot 10^{-3}$
Spatial shielding			5,252	0,064					5,316	$8,67\cdot 10^{-5}$
Routing precautions			5,252	0,064					5,316	$8,67\cdot 10^{-5}$
Equipotential bonding network			5,252						5,252	$8,57\cdot 10^{-5}$

The results from table 3.3 – 3.5 are summarized in the table 3.6.

Table 3.6 – Possible protection measures and they influence on the risks R_{1-3}

Protection measures	R1, %	R2, %	R3, %
Physical restrictions, insulation, warning notice	0,000	0,000	0,000
Lightning protection system (LPS)	0,657	0,939	9,217
Coordinated SPD system	99,969	99,681	96,099
Spatial shielding	0,626	0,620	5,316
Routing precautions	0,626	0,620	5,316
Equipotential bonding network	0,618	0,613	5,252

After calculating the possible risk reduction with each protection measure it is obvious that coordinated SPD system hard dominates, fig. 3.3. It means that SPDs should be installed.

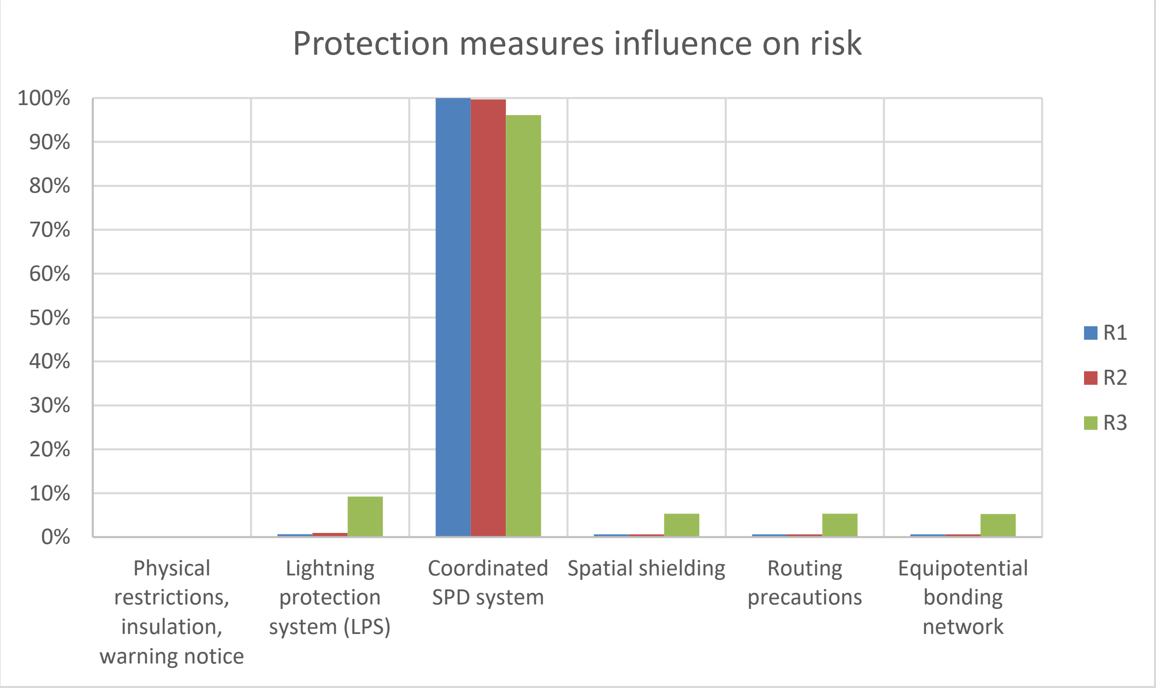


Figure 3.3 Possible protection measures and they influence on the risks R_{1-3}

3.6 SPDs installation

For 10 kV side it is decided to install arresters on the overhead line inners. The choice of arrester is based on its following characteristics:

- Surge arrester must withstand a certain level of voltage for a long time. For *10 kV* network with isolated neutral mode the maximum long-term operating voltage of the arrester equals to *12 kV* [39];
- Time characteristic – the dependence of the allowable voltage on the time of its impact. Since a network with an isolated neutral mode can operate for a long time

in single-phase fault regime, the time of withstand voltage duration should be chosen as long as possible;

- Protective levels of the device when exposed to overvoltage are determined by the current-voltage characteristic specified in the catalog;
- The energy intensity of the arrester – the value of the energy absorbed by the arrester during the transient process, supposed to be equal to *3 kJ/kV* [3].

Based on defined characteristics the surge arresters type: *3EP5 010 - 1 P C 2 1 – 1* are chosen for installation [40]. The average market price of this surge arrester is 100 EUR per unit in Russia.

To protect the substation on the 0,4 kV side working with the *TN–S* neutral mode, in accordance with the recommendations of [41], two types of surge protection devices are used, which are installed according to the following scheme, fig. 3.4.

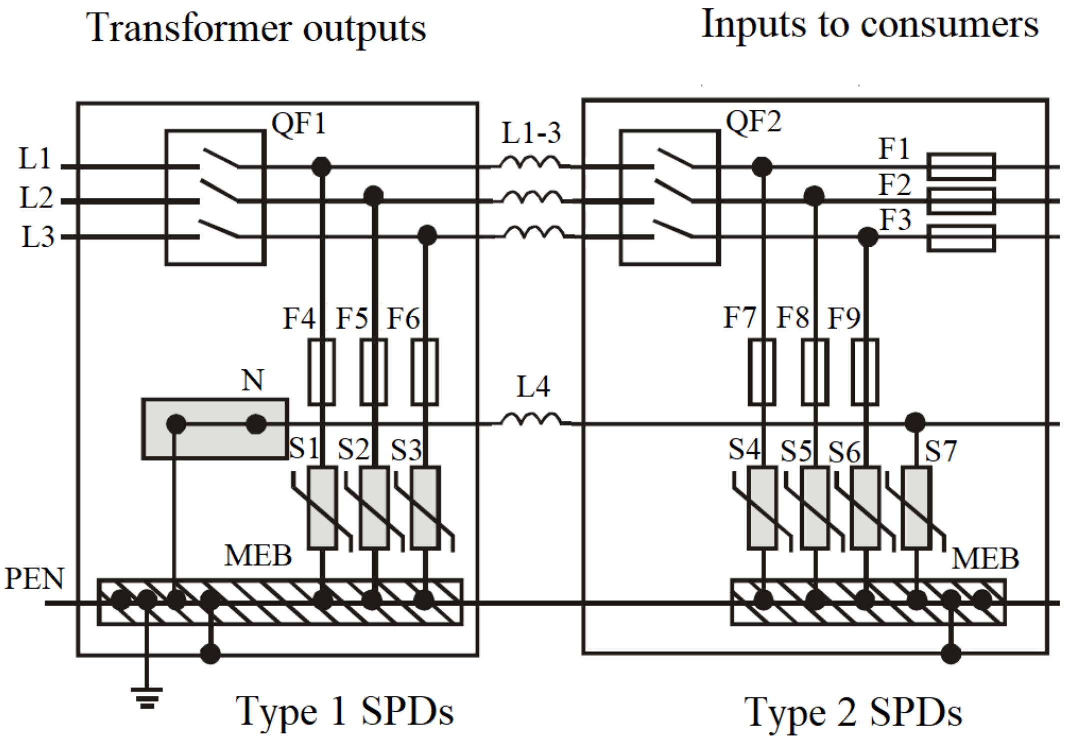


Figure 3.4 Installation scheme of SPDs in *TN–S* network; QF1-2 – circuit breaker, F1-9 – fuse, S1-S7 – SPDs, L1-4 – disconnecting chokes

Disconnecting chokes are used to ensure the selectivity of protection operation, since the distance between different types of SPDs is less than *10 m*. Disconnecting chokes create a time delay for the rise of an overvoltage impulse at the next protection stage, the resistance of the choke is selected in the range of *6-15* μH.

One of the main parameters of the SPD for 0,4 kV is the maximum value of the voltage drop on the device, which occurs due to impulse discharge current flow – U_p. This parameter characterizes the ability of SPD to limit overvoltage. SPDs for 0,4 kV can be made on the basis of discharge gaps and varistors. SPDs on the varistors base have better characteristics and widely used, so it is decided to take varistors SPDs. Generally the first type of SPDs on varistors base have $U_p = 2{,}5\ kV$. They provide the reliable protection for impulse current amplitudes $I_{imp} = 50\ kA$ and duration $t_{imp} = 10/350\ mcs$. The second type of SPDs on varistors base have $U_p = 1{,}5\ kV$ [3]. They provide the reliable protection for impulse current amplitudes $I_{imp} = 20\ kA$ and duration $t_{imp} = 8/20\ mcs$ [3].

Based on required parameters the next SPDs are chosen for installation:

- *5SD7 411* SPDs are chosen for the first type. The average Russian market price of this device is 200 EUR per unit [42].
- *5SD7 461* SPDs are chosen for the second type. The average Russian market price of this device is 100 EUR per unit [42].

To protect electrical equipment against short circuit current, fuses with a *gG* characteristic [43] are used. These fuses are designed to protect current-carrying conductors and switching devices from overloads and short circuit. The rated current of the fuses depends on the characteristics of the selected SPDs. It is planned to install the following types of fuses:

- *OFAF0H50* fuses for the first type SPDs. The average Russian market price of this fuse is 10 EUR per unit.
- *OFAF0H20* fuses for the second type SPDs. The average Russian market price of this fuse is 8 EUR per unit.

3.7 Calculation of the remaining loss if protection measurement is taken

Following the same process of risk calculation, shown in details in paragraphs 3.2 – 3.4 of this work, but changing factors used in formula corresponding to considered type of protection the new risk values are obtained, table 3.7.

Table 3.7 – Residual values of risk if coordinated SPD system installed

R1	R2	R3
$1{,}615 \cdot 10^{-6}$	$3{,}724 \cdot 10^{-6}$	$5{,}213 \cdot 10^{-5}$

Comparison of obtained results with standard requirements (table 3.2) shows that calculated risks are less than tolerable values for all types of loss and in case of SPDs installation structure is sufficiently protected.

4. Economical assessment

After finding the optimum protection measure for the considered structure it has to be compared whether the SPDs installation make economic sense. The economic sense is determined as follows: how does the total cost for the protection measures match to the costs of possible losses in the structure without the protection measures. For this purpose the NPV of two variants costs are calculated. Then, by comparing the NPVs using sensitivity analysis, the conclusion about the protection measure profitability can be made.

4.1 Creating models and NPV calculations

NPV is calculated by the following formula [44]:

$$NPV = \frac{\sum_{t=0}^{T} CF_t}{(1+r)^t} \qquad (55)$$

where CF_t – net cash flow during a single period t,
r – discount rate,
T – project lifetime.

The evaluation of NPVs starts from defining the input parameters.

The lifetime of both variants is supposed equal to 20 years – $T = 20$ *years*. Real discount rate is equal to company WACC. Because an information about firm’s equity and debt is not available the real discount rate is supposed equal to 5 %. In general it can be calculated by the next formula [44]:

$$r_r = WACC = \frac{E}{E+D} \cdot r_e + \frac{D}{E+D} \cdot r_d \cdot (1 - TAX) = 5\% \qquad (56)$$

where r_r – real discount rate,
r_e – cost of equity,
r_d – cost of debt,
E – market value of the firm's equity,
D – market value of the firm's debt,

$E/(E+D)$ – percentage of financing that is equity,
$D/(E+D)$ – percentage of financing that is debt,
TAX – corporate tax rate.

Corporate tax for distribution companies is 20% – $TAX = 20\%$. Escalation is supposed equal to inflation level. Inflation level was equal to 6% for Russia in 2018 [45]. Nominal discount rate can be calculated by the following formula [44]:

$$r_n = (1 + r_r) \cdot (1 + \text{inf}) - 1 = (1 + 5) \cdot (1 + 6) = 11,30\% \qquad (57)$$

where r_n – nominal discount rate.

The degradation ratio is estimated equal to 3 %. This ratio is used to account for the reduction of equipment value over time due to decrease of its reliability and productivity during operation.

It is supposed that in case of maintaining personal injury caused by electric shock the company will pay insurance in the amount of 50000 EUR. Investment in the installation of SPDs is the sum of the market prices of individual devices that were defined in the previous paragraph. Value of the structure is assumed equal to 300 EUR/m^2 – $c_t = 300\ EUR/m^2$ (paragraph 3.3). It is also planned to replace all devices due to the decrease in their reliability in year 10. The annual SPDs maintenance costs are estimated at 50 EUR.

For calculation NPV of total costs of possible losses in the structure without the protection measures the Excel model was created based on defined input parameters (Appendix 5, fig. 1). The model for calculation NPV of total costs for the SPD system is shown in the appendix 5, fig. 2.

As a result of the calculation, the following NPV values were obtained:

- NPV = -3460 EUR for the structure without the protection measures;
- NPV = -2862 EUR for the SPD system.

The NPV of protected structure is higher, it means that in case of dangerous event the costs of losses will be lower.

4.2 Sensitivity analysis

There are five parameters used for analysis:

- Real discount rate – r_r ;
- Inflation – *inf*;

- Maintenance costs;
- Value of the structure – c_t ;
- Degradation ratio – *d*.

Changing this values impacts the NPVs of the projects. These impacts are shown in the fig. 4.1 – 4.5.

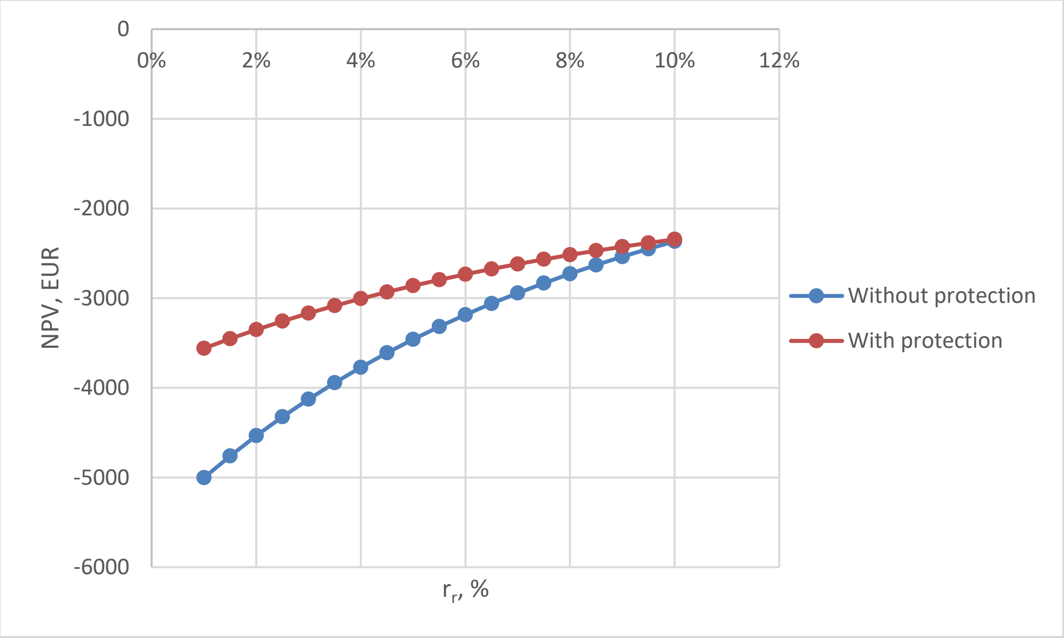


Figure 4.1 Analysis of discount rate influence

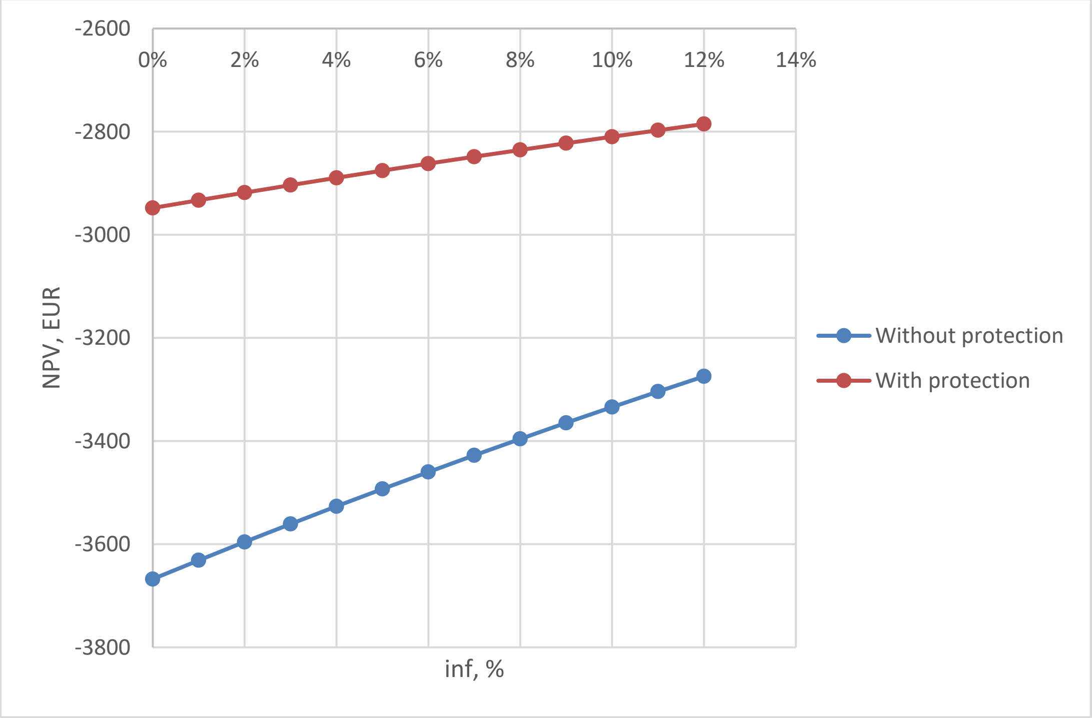


Figure 4.2 Analysis of inflation influence

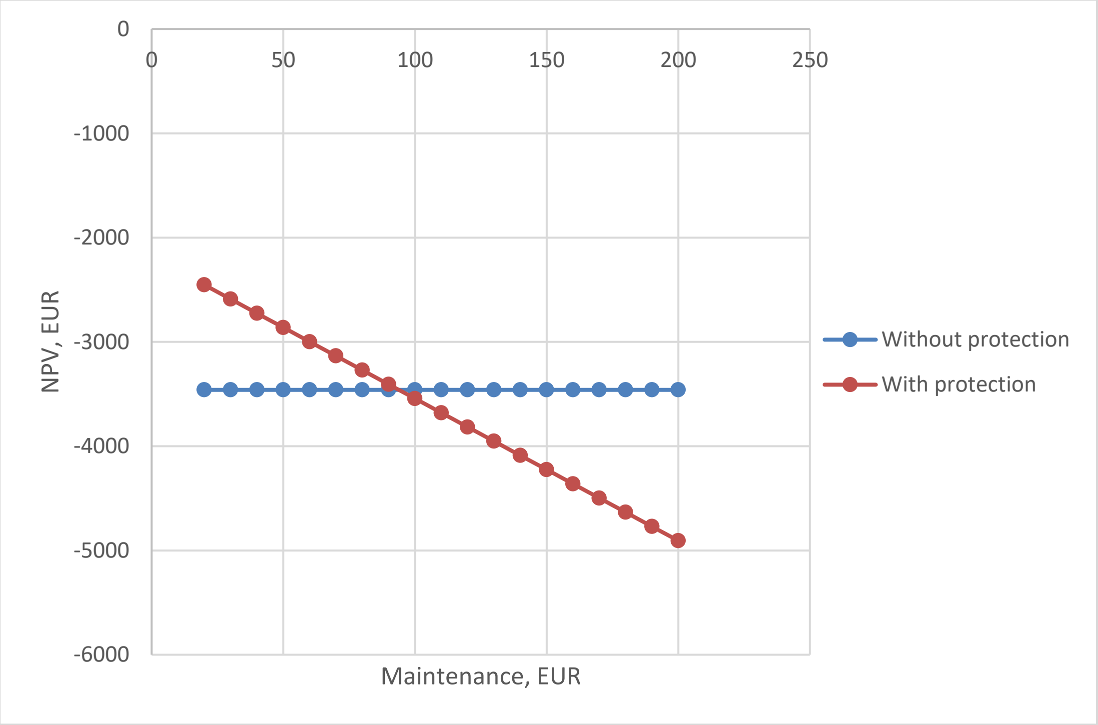


Figure 4.3 Analysis of maintenance costs influence

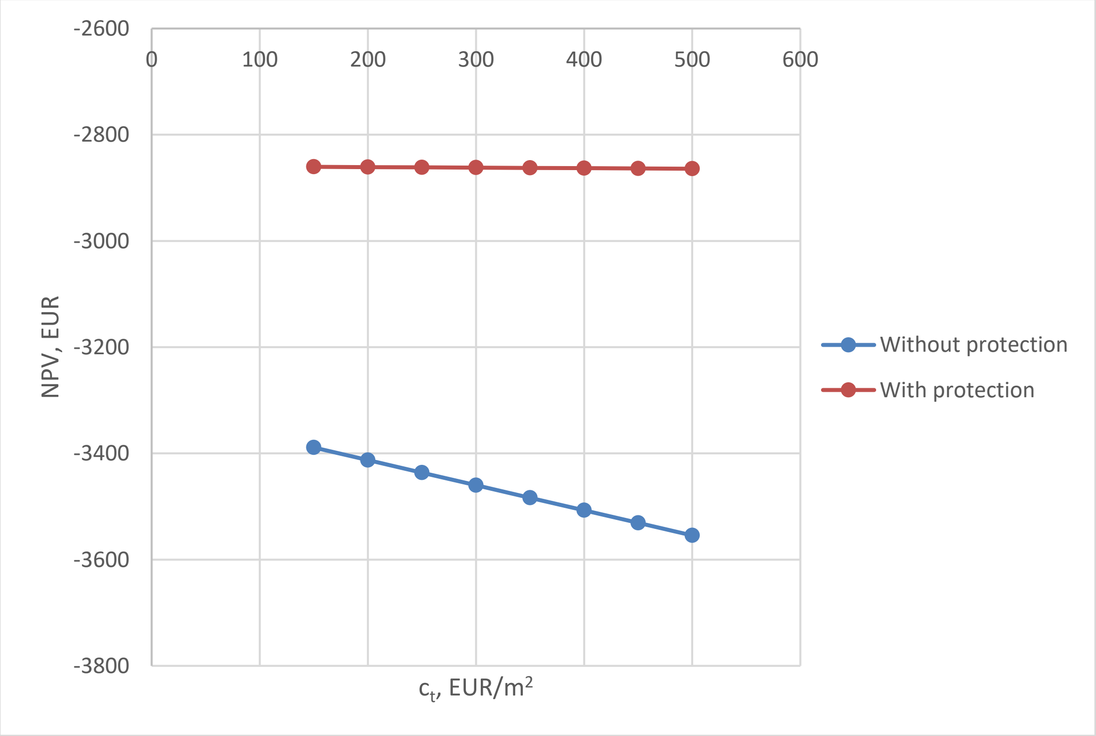


Figure 4.4 Analysis of value of the structure influence

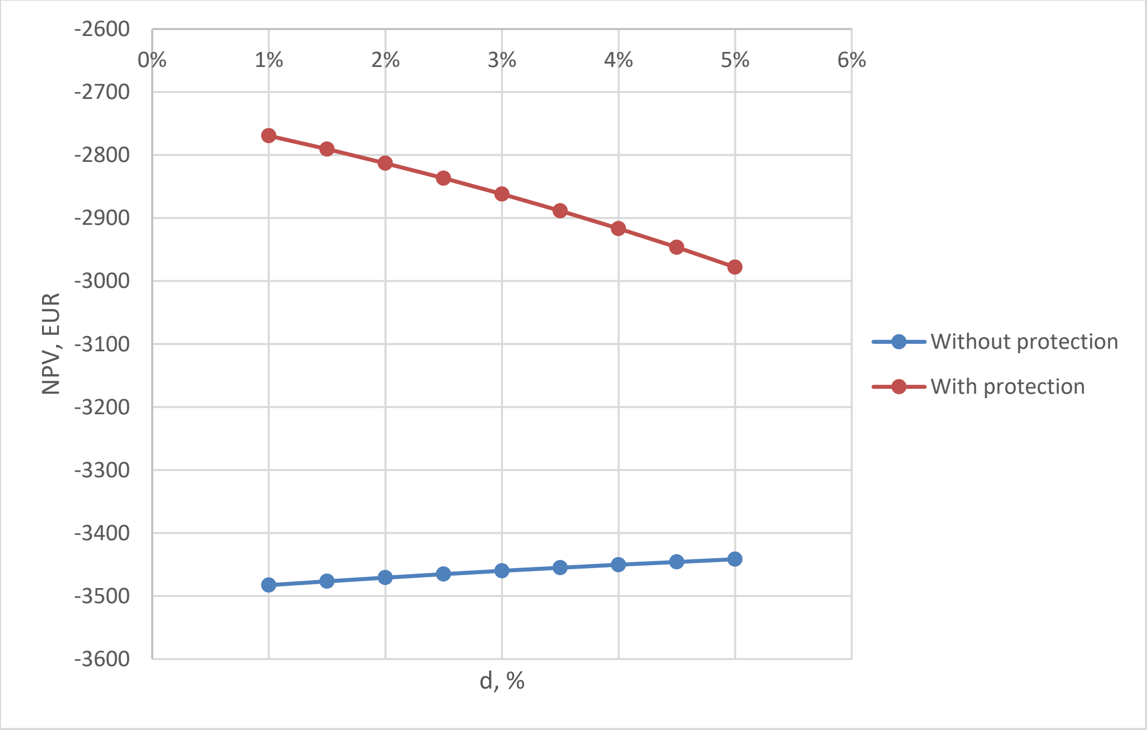


Figure 4.5 Analysis of degradation ratio influence

Looking at the results of sensitivity analysis it can be seen that SPDs installation is more profitable in economic sense. The only switching point is obtained in maintenance costs analysis. In this case the SPDs installation will be not profitable if annual maintenance costs exceed 90 EUR, but it is very unlikely. Thus the final decision is to take protection measures.

Conclusion

The objective of this Master's thesis is designing lightning protection system (LPS) for the indoor transformer substation with implementation of risk and financial management. Whole work is divided into four main paragraphs and each of them contains several subparagraphs.

The first part was assigned to theoretical basis of lightning strike and LPS structure. Consideration of lightning discharge characteristics served the basis for defining of lightning protection levels for researched structure. LPS structure description part allowed to determine the functions of the external and internal LPS elements, standards requirements and their application for the indoor transformer substations. In addition, in the first chapter the possible neutral grounding modes for 10/0,4 kV substations were considered and the recommendations based on standards and advantages were given. The first paragraph defines the important information for creation of overvoltage protection model.

In the second paragraph the steps of overvoltage protection calculation were defined and detailed description of protected structure was given. Then central grounding device (CGD) was designed. At first turn analytical calculation and optimization of grounding device were made. After this, the step and touch voltage tolerable values were computed and program modeling was performed. Program modeling allowed to get graphs of potentials distribution and showed that touch and step voltages do not exceed the safety limits. The calculated grounding device resistance is less than standard value it means that the earth-termination system is reliable for electrical equipment protection.

The third paragraph was dedicated to risk management. The main goal of risk assessment is to determine if protection is required or not. Primarily the risk management steps for researched object were defined and then the calculation model based on this steps was created. The results of risk assessment for considered substation showed that additional protection measures should be taken. In reality, several protection measures can be implemented for reduction of risks, each of them has different impact on risk components. The rational decision maker usually choose the optimal one. The model for protection measures estimation and analysis is introduced in subparagraph 3.5. As the result of estimation the coordinated SPD system was identified as the dominating among the possible protective measures for the researched substation. After this for 10/0,4 kV substation the features of SPDs selection and installation has been considered.

In the fourth paragraph the economical assessment was made. The model for economical assessment was created in Excel program. The results of financial comparison of total cost for the protection measure and costs of possible losses in the structure without the protection measures showed that NPV of protected structure is higher. It means that installation of coordinated SPD system is more profitable, because in case of dangerous event the costs of losses will be lower. To determine how different values of the independent variables affect a particular dependent variables under a given set of assumptions the sensitivity analysis was performed. There are five independent parameters used for analysis. Results of sensitivity analysis proved that SPDs installation is more profitable in economic point of view. The only break-even point is obtained in maintenance costs analysis, but the achievement of this point is very unlikely. Thus the final decision is to take protection measure.

It should be noted, that installation of SPD system is profitable only in case of structure considered in this work. For example, risk management and economic analysis can give completely different results, for the same indoor transformer substation located in the area with different density of thunderstorm discharges per year. At the same time, the methodology of protection measures evaluation, developed in this paper, will be the same.

To sum up, the results of this work can be used for overvoltage protection design of similar structures. Depending on the size and complexity of the structure and the internal systems, different protection measures can be taken. Thus, there are several possibilities to protect the structure. The financial efficiency of protection measures can therefore be further examined, even if the optimal solution has not been found straightforward, conducting the calculations sequence, economic optimal solution can and should be achieved.

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Appendix 1

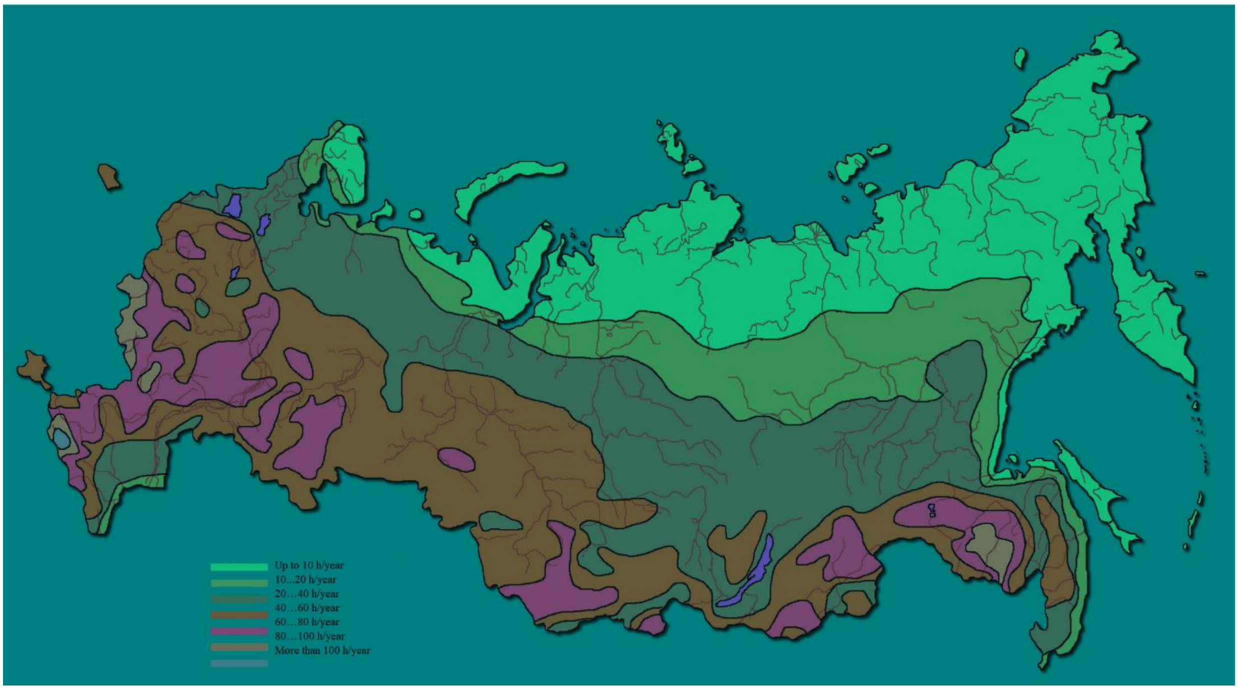


Figure 1 Russia thunderstorm map

Table 1 – Density of lightning strikes in Russia [2]

The average annual duration of thunderstorms, h	The density of lightning strikes in year per 1 km^2
10 — 20	1
21 — 40	2
41 — 60	4
61 — 80	5,5
81 — 100	7
100 and more	8,5

Table 2 – Data for season coefficients [3]

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	

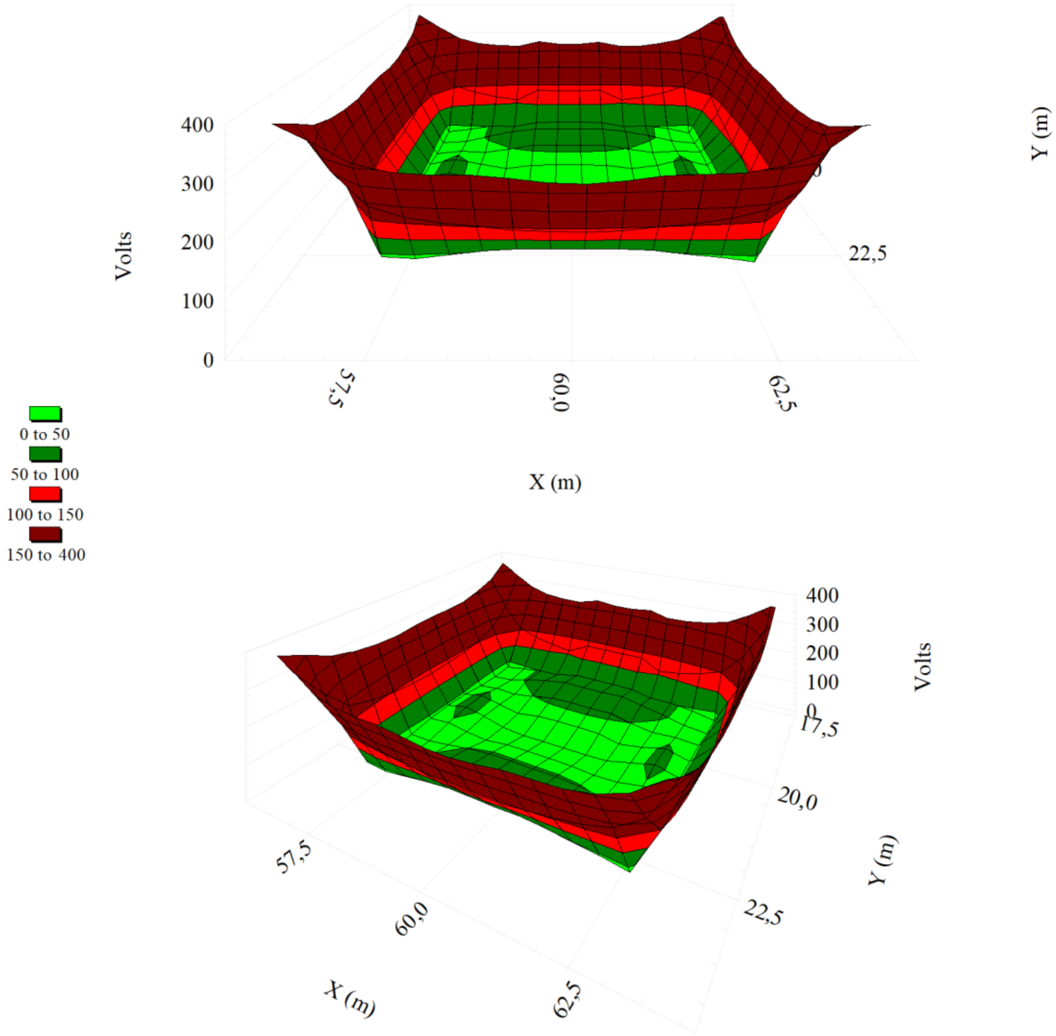


Figure 2 Step voltage distribution graphs obtained in ETAP program

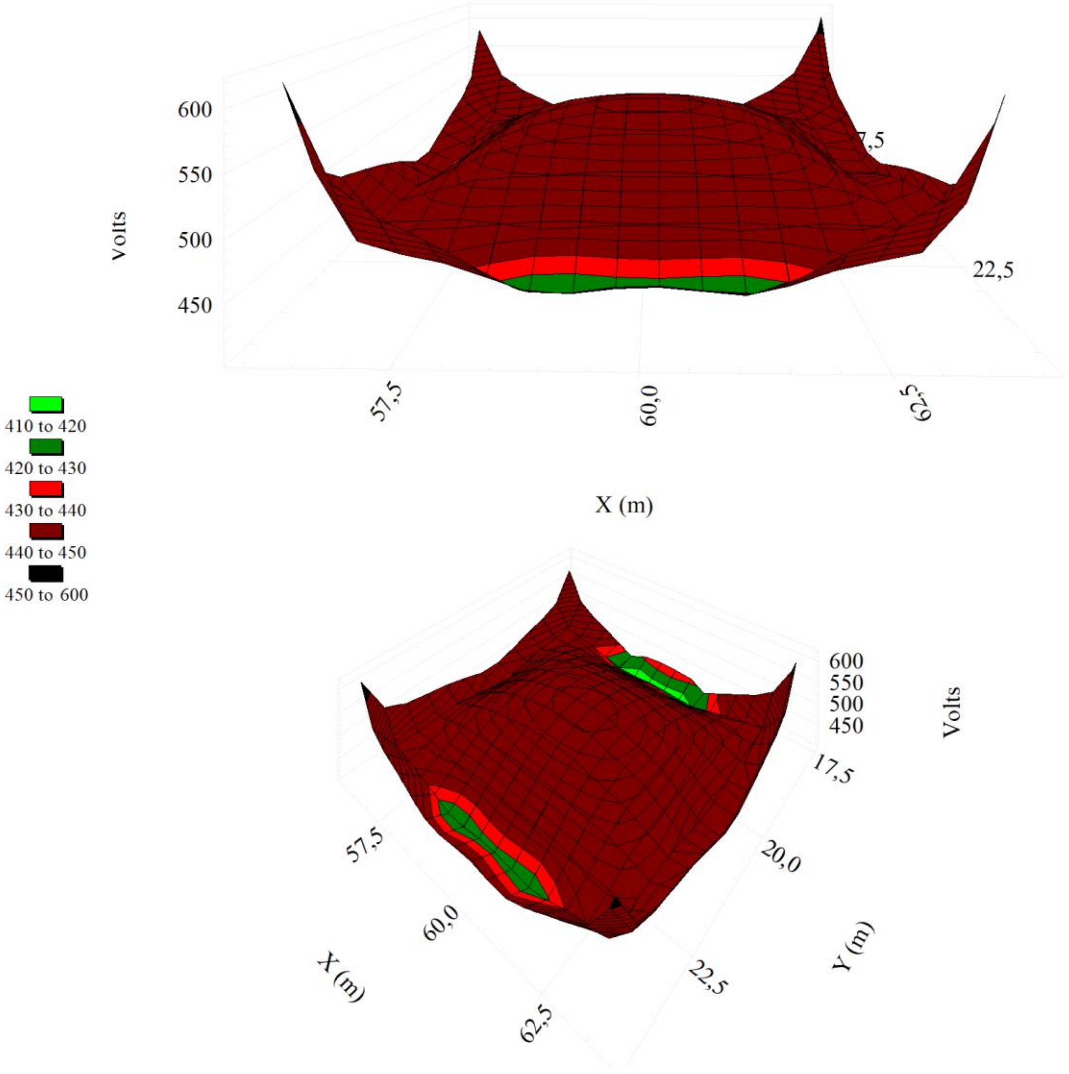


Figure 3 Touch voltage distribution graphs obtained in ETAP program

Appendix 2

Table 1 – Location factor values [6]

Relative location of the structure	C_D
Structure surrounded by higher objects	0,25
Structure surrounded by objects of the same height or smaller	0,5
Isolated structure: no other objects in the vicinity (within a distance of 3H)	1
Isolated structure on a hilltop or a knoll	2

Table 2 – Installation factor of the line values [6]

Routing	C_I
Overhead line	1
Buried cables	0,5

Table 3 – Environmental factor of the line values [6]

Environment	C_E
Rural	1
Suburban	0,5
Urban	0,1
Urban with tall buildings (higher than 20 m)	0,01

Table 4 – Line type factor of the line values [6]

Transformer	C_T
Low-voltage power line	1
High-voltage power line	0,2

Appendix 3

Table 1 – Values of probability P_{TA} [20]

Additional protection measures	P_{TA}
No protection measures	1
Warning notices	10^{-1}
Electrical insulation	10^{-2}
Effective potential control in the ground	10^{-2}
Physical restrictions or building framework used as down conductor	0

Table 2 – Values of probability P_B [20]

Properties of the structure	Class of LPS	P_B
Structure is not protected by an LPS	–	1
Structure is protected by an LPS	IV	0,2
	III	0,1
	II	0,05
	I	0,02
Structure with an air-termination system conforming to class of LPS I and a continuous metal (or reinforced concrete) framework acting as a natural down-conductor system		0,01
Structure with a metal roof and an air-termination system and a continuous metal (or reinforced concrete framework) acting as a natural down-conductor system		0,001

Table 3 – Values of probability P_{SPD} [24]

LPL	P_{SPD}
No coordinated SPD system	1
III-IV	0,05
II	0,02
I	0,01
Surge protective devices with better protection characteristics than required for LPL I	0,005-0,001

Table 4 – Values of C_{LD} and C_{LI} factors [6]

Type of external line	Connection at entrance	C_{LD}	C_{LI}
Unshielded overhead line	Undefined	1	1
Unshielded buried line	Undefined	1	1
Power line with multi-grounded neutral conductor	None	1	0,2
Shielded buried line	Shields not bonded to the same equipotential bonding bar as equipment	1	0,3

Continuation of table 4

Shielded overhead line	Shields not bonded to the same equipotential bonding bar as equipment	1	0,1
Shields bonded to the same equipotential	Shields bonded to the same equipotential bonding bar as equipment	1	0
bonding bar as equipment	Shields bonded to the same equipotential bonding bar as equipment	1	0
Lightning protection cable or wiring in lightning protection cable ducts, metallic conduit or metallic tubes	Shields bonded to the same equipotential bonding bar as equipment	0	0

Table 5 – Values of K_{S3} factors [6]

Type of internal wiring	K_{S3}
Unshielded cable – no routing precaution in order to avoid loops (meaning a loop surface of about 50 m2)	1
Unshielded cable – routing precaution in order to avoid large loops (loops formed by conductors with different installation paths in small buildings, meaning a loop surface of about 10 m2)	0,2
Unshielded cable – routing precaution in order to avoid loops (meaning a loop surface of about 0.5 m2)	0,01
Shielded cables and cables running in metal conduits	0,0001

Table 6 – Values of probability P_{TU} [6]

Protection measure	P_{TU}
No protection measure	1
Warning notices	10^{-1}
Electrical insulation	10^{-2}
Physical restrictions	0

Table 7 – Values of probability P_{EB} [20]

LPL	P_{EB}
No SPD	1
III-IV	0,05
II	0,02
I	0,01
Surge protective devices with better protection characteristics than required for LPL I	0,005-0,001

Table 8 – Values of probability P_{LD} dependent on U_W and Rs (shield resistance) [20]

Type of line	Routing, shielding and bonding		Maximum born Impulse voltage U_W , kV				
			1	1,5	2,5	4	6
	Overhead or buried line, unshielded or shielded (shield is not bonded to the same equipotential bonding bar as the equipment)		1	1	1	1	1
Power or telecommunication lines	Shielded overhead or buried line (shield is bonded to the same equipotential bonding bar as the equipment)	5 Ohm/km < Rs ≤ 20 Ohm/km	1	1	0,95	0,9	0,8
		1 Ohm/km < Rs ≤ 5 Ohm/km	0,9	0,8	0,6	0,3	0,1
		Rs ≤ 1 Ohm/km	0,6	0,4	0,2	0,04	0,02

Table 9 – Values of probability P_{LI} [6]

Line type	Impulse withstand voltage U_W , kV				
	1	1,5	2,5	4	6
Power lines	1	0,6	0,3	0,16	0,1
Telecommunication lines	1	0,5	0,2	0,08	0,04

Appendix 4

Table 1 – Typical mean values for L_T , L_F and L_0 for loss type L1 [6]

Type of damage	Typical loss value		Type of structure
D1	L_T	10^{-2}	All types
D2	L_F	10^{-1}	Risk of explosion
		10^{-1}	Hospital, hotel, school, public building
		$5\cdot10^{-2}$	Building with entertainment facility, church, museum
		$2\cdot10^{-2}$	Industrial structure, economically used plant
		10^{-2}	Others
D3	L_0	10^{-1}	Risk of explosion
		10^{-2}	Intensive care unit and operating section of a hospital
		10^{-3}	Other areas of a hospital

Table 2 – Values of the reduction factor r_t [6]

Type of surface	Contact resistance, Ohm	r_t
Agricultural, concrete	≤ 1	10^{-2}
Marble, ceramic	1 – 10	10^{-3}
Gravel, moquette, carpets	10 – 100	10^{-4}
Asphalt, linoleum, wood	≥ 100	10^{-5}

Table 3 – Values of the reduction factor r_p [6]

Measures	r_p
No measures	1
One of the following measures: fire extinguishers, fixed manually operated fire extinguishing installations, manual alarm installations, hydrants, fire compartments, escape routes	0,5
One of the following measures: fixed automatically operated fire extinguishing installations, automatic alarm installations	0,2

Table 4 – Values of the reduction factor r_f [6]

Risk	Type of risk	r_f
Explosion	Zone 0, 20 and solid explosives	1
	Zone 1, 21	10^{-1}
	Zone 2, 22	10^{-3}

Continuation of table 4

Fire	High	10^{-1}
	Middle	10^{-2}
	Low	0
Explosion or fire	None	0

Table 5 – Values of the increase factor h_Z [6]

Type of special risk	h_Z
No special risk	1
Low risk of panic	2
Average level of panic	5
Difficulty of evacuation	5
High risk of panic	10

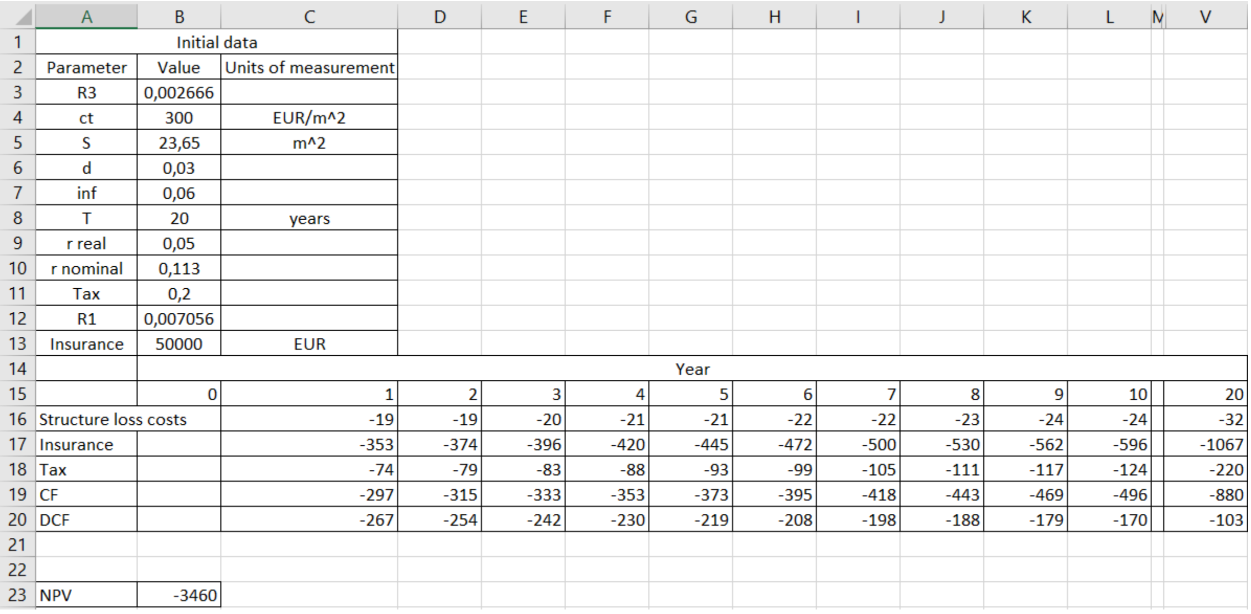
Table 6 – Typical mean values for L_F and L_0 for loss type L2 [6]

Type of damage	Typical loss value		Type of structure
D2	L_F	10^{-2}	Gas, water, power supply
		10^{-1}	TV, telecommunication
D3	L_0	10^{-2}	Gas, water, power supply
		10^{-3}	TV, telecommunication

Table 7 – Typical mean values for L_T , L_F and L_0 for loss type L3 [6]

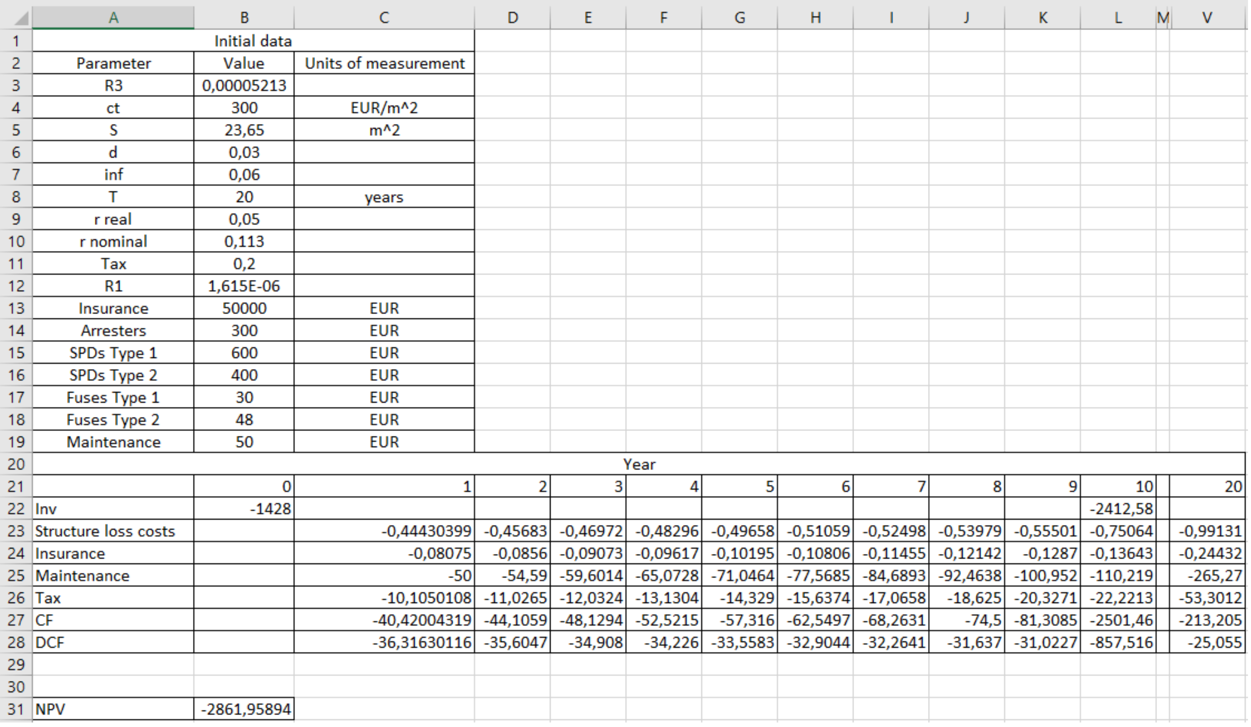
Type of damage	Typical loss value		Type of structure
D1	L_T	10^{-2}	All types
D2	L_F	1	Risk of explosion
		0,5	Hospital, industrial structure, museum, agriculturally used plant
		0,2	Hotel, school, office building, church, building with entertainment facility, economically used plant
		0,1	Others
D3	L_0	10^{-1}	Risk of explosion
		10^{-2}	Hospital, industrial structure, office building, hotel, economically used plant
		10^{-3}	Museum, economically used plant, school, church, building with entertainment facility
		10^{-4}	Others

Appendix 5



	A	B	C	D	E	F	G	H	I	J	K	L	M	V
1	Initial data													
2	Parameter	Value	Units of measurement											
3	R3	0,002666												
4	ct	300	EUR/m^2											
5	S	23,65	m^2											
6	d	0,03												
7	inf	0,06												
8	T	20	years											
9	r real	0,05												
10	r nominal	0,113												
11	Tax	0,2												
12	R1	0,007056												
13	Insurance	50000	EUR											
14		Year												
15		0	1	2	3	4	5	6	7	8	9	10		20
16	Structure loss costs		-19	-19	-20	-21	-21	-22	-22	-23	-24	-24		-32
17	Insurance		-353	-374	-396	-420	-445	-472	-500	-530	-562	-596		-1067
18	Tax		-74	-79	-83	-88	-93	-99	-105	-111	-117	-124		-220
19	CF		-297	-315	-333	-353	-373	-395	-418	-443	-469	-496		-880
20	DCF		-267	-254	-242	-230	-219	-208	-198	-188	-179	-170		-103
21														
22														
23	NPV	-3460												

Figure 1 Excel model for NPV calculation of total costs of possible losses in the structure without the protection measures



	A	B	C	D	E	F	G	H	I	J	K	L	M	V
1	Initial data													
2	Parameter	Value	Units of measurement											
3	R3	0,00005213												
4	ct	300	EUR/m^2											
5	S	23,65	m^2											
6	d	0,03												
7	inf	0,06												
8	T	20	years											
9	r real	0,05												
10	r nominal	0,113												
11	Tax	0,2												
12	R1	1,615E-06												
13	Insurance	50000	EUR											
14	Arresters	300	EUR											
15	SPDs Type 1	600	EUR											
16	SPDs Type 2	400	EUR											
17	Fuses Type 1	30	EUR											
18	Fuses Type 2	48	EUR											
19	Maintenance	50	EUR											
20	Year													
21		0	1	2	3	4	5	6	7	8	9	10		20
22	Inv	-1428										-2412,58		
23	Structure loss costs		-0,44430399	-0,45683	-0,46972	-0,48296	-0,49658	-0,51059	-0,52498	-0,53979	-0,55501	-0,75064		-0,99131
24	Insurance		-0,08075	-0,0856	-0,09073	-0,09617	-0,10195	-0,10806	-0,11455	-0,12142	-0,1287	-0,13643		-0,24432
25	Maintenance		-50	-54,59	-59,6014	-65,0728	-71,0464	-77,5685	-84,6893	-92,4638	-100,952	-110,219		-265,27
26	Tax		-10,1050108	-11,0265	-12,0324	-13,1304	-14,329	-15,6374	-17,0658	-18,625	-20,3271	-22,2213		-53,3012
27	CF		-40,42004319	-44,1059	-48,1294	-52,5215	-57,316	-62,5497	-68,2631	-74,5	-81,3085	-2501,46		-213,205
28	DCF		-36,31630116	-35,6047	-34,908	-34,226	-33,5583	-32,9044	-32,2641	-31,637	-31,0227	-857,516		-25,055
29														
30														
31	NPV	-2861,95894												

Figure 2 Excel model for calculation NPV of total costs in case of SPD system installation