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ENHANCING THE RELIABILITY OF POWER SYSTEMS BY OPTIMIZING
LIGHTNING PROTECTION OF OVERHEAD TRANSMISSION LINES

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Abstract

This paper addresses the reliability issues of power systems caused by lightning-induced overvoltages resulting from lightning strikes to components of overhead transmission lines (OHL). It is demonstrated that lightning discharges are one of the key causes of transmission line outages and significant economic losses. A method is proposed to improve the efficiency of lightning protection by upgrading the design of lightning protection cables using V-shaped metallic elements to increase the protection zone. Calculations were carried out to assess the expansion of the protection zone depending on the geometrical parameters of the design. A mathematical model was developed and implemented in the MATLAB Simulink environment to analyze the behavior of OHL under direct lightning strikes to the shield wire and phase conductors. The model takes into account lightning current parameters, structural characteristics of supports, grounding device properties, and insulation parameters. Simulation results showed a significant influence of grounding resistance on the level of resulting overvoltages and the effectiveness of lightning protection. The proposed technical solutions can be used to enhance the lightning resistance and operational reliability of overhead transmission lines, especially in regions with high lightning activity.

Keywords: power system reliability, lightning protection, overhead transmission lines, grounding wire, MATLAB modeling

I. Introduction

Power systems play a fundamental role in the functioning of modern society by ensuring a stable electricity supply to industrial, residential, and commercial facilities. However, their reliability is continuously challenged by atmospheric overvoltages, particularly those caused by lightning discharges, including direct lightning strikes.

Lightning is one of the primary causes of transmission line malfunctions, significantly reducing the reliability of power supply systems. According to statistics from a provincial power grid in China, more than 45% of all transmission line outages between 2005 and 2014 were caused by lightning discharges [1].

An analysis of historical data provided by a UK-based service indicates that between 2010 and 2019, lightning strikes were the direct cause of more than 20,000 power outage incidents [2, 3]. As research shows, these outages can lead to substantial economic losses, including the costs of repair and restoration work, reduced technical reliability of power systems, and negative impacts on consumers and the business environment as a whole [4-6]. In many cases, under normal operating conditions, lightning-related outages can account for 30% to 50% of all automatic

disconnections. For instance, according to data from the power utility company of Paraná State (Brazil), approximately 35% of all recorded power outages are directly linked to lightning activity.

As seen from the above, the reliability of power systems is largely determined by the effectiveness of lightning protection for overhead transmission lines (OHL) against overvoltages caused by lightning discharges. These overvoltages result from complex physical processes associated with atmospheric phenomena, including direct and secondary lightning strikes on the structural elements of OHLs. Traditional approaches to assessing lightning protection, which are based on semi-empirical relationships and electro-geometrical models, often fail to adequately evaluate the vulnerability of a particular object and consider factors such as topography, soil characteristics, support structure design, and climatic conditions [7, 8].

To objectively determine the lightning susceptibility of a transmission line and develop effective measures to enhance its lightning resistance, it is necessary to transition to new calculation models based on a physically substantiated description of the processes involved in the formation and development of lightning near ground-based objects. Modern research confirms that detailed modeling of lightning interaction with infrastructure elements can significantly improve the accuracy of accident forecasts and, consequently, enhance the justification of design decisions [9].

II. Problem Statement

Modern power systems play a key role in ensuring the reliable electricity supply to various facilities, including industrial, residential, and commercial buildings. However, one of the main threats to the reliability of such systems is atmospheric discharges, particularly lightning, which can cause significant equipment damage and lead to prolonged outages. These phenomena create lightning-induced overvoltages that can damage insulation, cause short circuits, and lead to serious disruptions in power grid operations.

As a result, improving the reliability of OHL and reducing the consequences of lightning strikes have become critical tasks for ensuring the stability of power systems [10-12]. Existing protection methods, such as lightning rods, grounding wires, and line surge arresters, although effective, do not always provide the required level of safety, especially in areas with high lightning activity. For example, lightning strikes on phase conductors lead to the formation of powerful overvoltages, necessitating a more comprehensive approach to protection.

One promising direction for addressing this issue is the modernization of lightning protection cable designs, which can significantly improve the efficiency of protection against lightning strikes [13]. Furthermore, an important aspect is the assessment of the reliability of power systems, particularly overhead transmission lines, using computer modeling methods.

Therefore, the task is to develop and optimize a lightning protection system for overhead transmission lines, considering modern reliability requirements and operational characteristics. This will require not only improvements in design solutions but also the integration of intelligent technologies for assessing the condition of power systems.

III. Solution to the Problem

Application of Effective Grounding Wires

Grounding wires-lightning protection cables and grounding systems play an essential role in protecting overhead transmission lines (OHL) by absorbing lightning strikes. Although damage to such cables is possible [14, 15], it generally results in less destructive consequences compared to strikes on phase conductors, which can lead to prolonged outages. The reliability of lightning

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protection systems requires consideration of both electrical and mechanical aspects of line operation under complex weather conditions.

An analysis of existing protection methods has shown that the most straightforward and reliable way to mitigate the consequences of lightning discharges is the use of grounding wires. However, the effectiveness of these systems depends on their placement relative to the phase conductors. To increase the protection zone, we propose partially modifying the grounding wire design by adding metallic elements along its length, positioned in a "V" shape at a 45° angle to the ground (Figure 1). These elements increase the heterogeneity of the electric field, improving the protective properties of the grounding cables [16].

To calculate the additional protection zone between the "V"-shaped elements, several factors need to be considered, such as the length of the rods and the distance between them, as well as the protection radius, which depends on these parameters. In this case, Table 1 provides information on the rod length, the distance between the rods, the protection radius, and the percentage of the additional protection zone for various rod lengths.
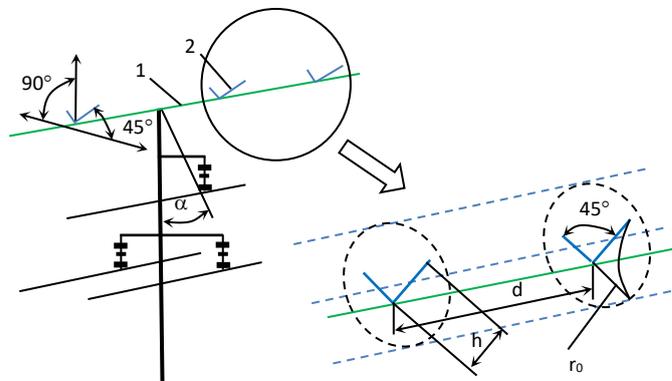

Figure 1: *Placement of "V"-shaped elements on the surface of the lightning protection cable.*

Table 1: *Protection Zone Between "V"-Shaped Rods*

Length of Rod (h, cm)	Distance Between Rods (a, cm)	Protection Zone Radius (r_0, cm)	Additional Zone (%)
10	100	15	30
20	100	30	60
30	100	45	90
40	100	60	120

As seen in the table, as the rod length increases, the protection radius also increases, which directly impacts the additional protection zone of the grounding wire. The additional protection zone represents the percentage increase compared to the base protection radius for the minimum rod length (10 cm).

The graph shown in Figure 2 illustrates how the additional protection zone increases as the rod length increases.

The additional protection zone between the "V"-shaped rods plays a crucial role in ensuring the safety and efficiency of the lightning protection cable for OHL. As the rod length increases, there is a consistent expansion of the protection radius, which leads to a larger overall protected area. The graph, constructed from the data in the table, clearly demonstrates this relationship, showing how the additional protection zone increases as the rod length changes.

The graph indicates that the additional protection zone grows proportionally to the rod length. This suggests a linear relationship, allowing for high accuracy in predicting the system's

behavior when its parameters are modified. For example, when the rod length is 10 cm, the additional zone is 30%. When the rod length is increased to 20 cm, this value increases to 60%, and at 40 cm, it reaches 120%. This growth shows that the protection expands with the increasing size of the design, creating a larger safe zone [17].

While increasing the rod length extends the protected area, this process has its limits. Excessive elongation of the rods can lead to reduced mechanical stability of the structure, increased loads, and installation complications. Therefore, it is important to find a balance between the effectiveness of protection and the practical feasibility of the system.
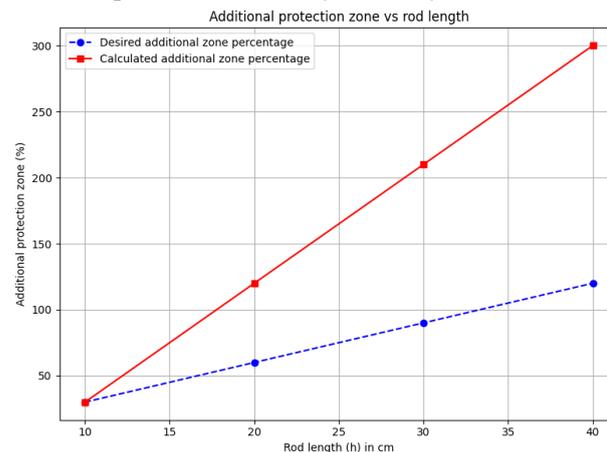

Figure 2: *Additional protection zone vs rod length*

The graph confirms that increasing the rod length leads to a proportional increase in the protection zone, making the system predictable and reliable. However, to ensure maximum efficiency, it is necessary to consider both the calculated data and the actual operating conditions, thereby ensuring stable and long-lasting performance of the protection system.

As seen from the above, the result of the calculation — that is, the reliability indicator of the lightning protection system, expressed as the number of lightning-induced outages of the overhead transmission line (OHL) per year — is significantly influenced not only by the condition of the lightning protection cable and the choice of support structure model but also by the condition of its grounding. This is because the most common occurrence of linear insulation breakdown, which is the most probable cause of line outages, typically happens at the support.

To determine the level of lightning resistance of the OHL, a computational model was developed in MATLAB, and a comprehensive analysis was carried out, including the evaluation of the lightning protection cable parameters, the support structure design, and the characteristics of the grounding systems. The obtained data allowed for a quantitative assessment of the reliability of the OHL.

III. Simulation Based on MATLAB Simulink

Model Description

The model presented in Figure 3 was developed using the MATLAB Simulink software environment. This platform offers a wide range of tools for modeling high-voltage overhead transmission lines, including the ability to analyze lightning-induced overvoltages and electromagnetic effects caused by lightning strikes. This allows for the investigation of line behavior and the development of effective protection methods. The simulation model was adapted based on typical studies conducted by several authors, as outlined in works [18–21], which explored the processes of lightning-induced overvoltage occurrence on high-voltage transmission lines.

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Two scenarios were considered:

– Direct lightning strike on the lightning protection cable;
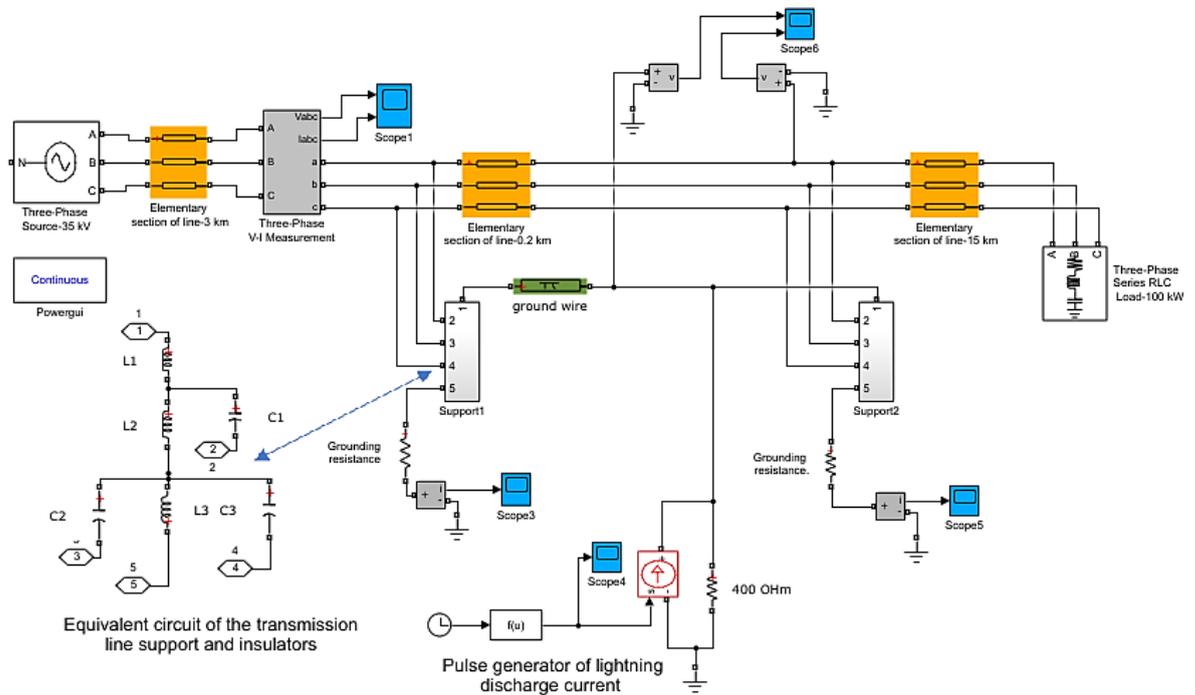
– Direct lightning strike on the phase conductor.

Figure 3. *Simulation of Lightning Strike on OHL Elements in MATLAB*

Description of the Lightning Discharge

For the calculation of the lightning current impact on electrical equipment, it was necessary to create a lightning discharge model. The Bruce and Gold lightning current model is widely used to describe the time-dependent characteristics of lightning impulse current. This model provides high accuracy in reproducing the front and decay of the impulse, which is crucial when analyzing lightning overvoltages and their impact on power supply systems. The model is represented as follows [22-24]**:**

$$i(t) = \frac{I_m}{\eta}\left[e^{-\alpha t} - e^{-\beta t}\right]$$

where: $i(t)$ — Instantaneous value of the current at time t, μs ; I_m — Amplitude of the lightning impulse current, kA ; η – Amplitude wave correction factor; α and β — Time constants characterizing the rise and decay rates of the impulse, $\alpha > \beta$ (α= 0.014 ÷ 0.05 μs⁻¹ determines the steepness of the decline; β= 0.002 ÷ 0.01 μs⁻¹ — pulse front); t — time, μs.

To describes the current impulse waveform, a biexponential function (3) is used, which, considering the calculated decrements and parameters of the current impulse 1.2/50 μs, has the following implementation in the Simulink environment: $100000/e^{-0.017*}(e^{(-14300*u)}-e^{(-6*u)})$.

The current impulse generator model is shown in Figure 3, and the graph corresponding to the obtained curve of the model is shown in Figure 4. The parameters of this curve comply with the IEC 62305 standard for lightning protection of electrical power systems from direct lightning strikes [25].
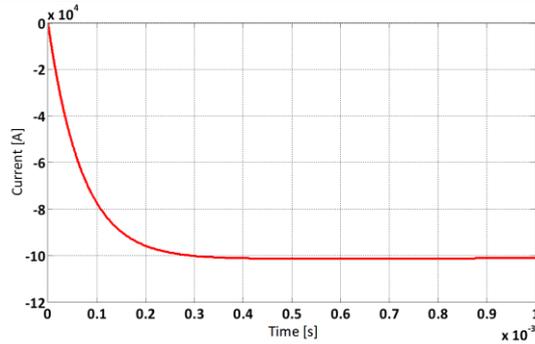
Figure 4. *Lightning current curve shape: current pulse parameters 50/1.2, 100 kA.*

The main parameters of the 35 kV overhead lines and the intermediate steel support are shown in Table 2 and in Figure 5
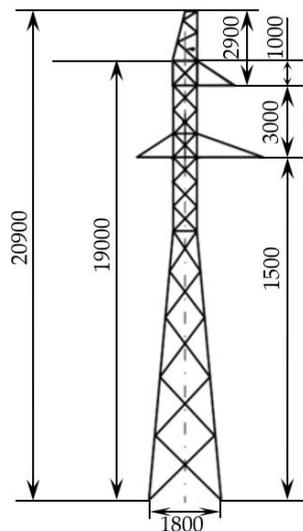

Figure 5. *Dimensions of the metal single-chain intermediate support for 35 kV*

Table 2. *Parameters of the 35 kV overhead line*

No	Transmission Line Parameter	Values
1	Nominal frequency	50 Hz
2	Number of conductors per phase	1
3	Nominal cross-section of steel-aluminum (AC) conductors	120/19 mm²
4	Per unit resistance (positive sequence)	0.333 Ohm/km
5	Per unit resistance (zero sequence)	0.333 Ohm/km
6	Per unit inductance (positive sequence)	1.317×10^{-3} Hen/km
7	Per unit inductance (zero sequence)	1.438×10^{-3} Hen/km
8	Per unit capacitance (positive sequence)	1.97×10^{-12} F/m
9	Per unit capacitance (zero sequence)	2.24×10^{-12} F/m
10	Diameter of lightning protection cable	12.1 mm
11	Resistance of lightning protection cable	2.1 Ohm/km
12	Inductive resistance of lightning protection cable	$(2.77 - 3.41) \times 10^{-3}$ H/km
13	Capacitance of lightning protection cable	8.28×10^{-6} F/km

The electrical equivalent circuit of the support was chosen in the form of a set of inductances and capacitances, as shown in Figure 3. To calculate the values of inductance, the known value of

the line inductance for this type of supports was used, which is Lp= 0.6-0.8 μH/m (L=Lp * h), where h is the height of the support, and for our case, we adopted Lp = 0.65 μH/m [26].

In the equivalent circuit, the insulator string was modeled as an equivalent capacitance, in parallel with which a resistor was included to simulate leakage currents. Due to the relatively small inductance of the insulator string and crossarms, it was not considered in the calculations.

To determine the capacitance value, an equivalent circuit of a string consisting of 3 U70B (PS-70E) insulators was used, for which the equivalent capacitance was 7.1 pF. This value was adopted for the support model when simulating the insulator string. The expected 50% impulse breakdown voltage of the insulator string consisting of three U70B insulators is approximately 270 kV [27-29].

To calculate the transient process during a lightning strike to the transmission line, a model consisting of two supports was used, which is sufficient for studying the lightning strike in the above-mentioned cases (Figure4).

Each section of the transmission line was modeled as an equivalent six-port network, including three phase conductors represented by a Distributed Parameters Line element. The lightning protection wire, provided in the line as a single unit, was modeled using the Pi Section Line element.

IV. Simulation Results

Lightning Strike to the Grounding Shield Cable

This line is single-circuit. To determine the overvoltage that occurs when lightning strikes the ground wire and the phase conductors, the model considers two supports, with a distance of 200 meters between them. The grounding wire is installed on both supports. The main focus is on the maximum overvoltage values occurring at the supports for different values of the grounding resistance of the supports and the grounding shield cable during a direct lightning strike. As a result of the strike, overvoltages are generated on the line (Figure 6), and Table 3 presents the maximum current values flowing through the support and the maximum voltage values occurring between the phases and the ground for different grounding resistance values of the supports [31].

Table 3. *Lightning strike on the ground wire*

Lightning impulse current amplitude, kA,	Tower footing resistance, [Ohm]	Maximum value of current flowing through the support, A	Maximum value of voltage occurring between phases and ground, V
100	5	$5.0 \cdot 10^4$	$2.2 \cdot 10^5$
	6	**$5.0 \cdot 10^4$**	**$2.7 \cdot 10^5$**
	10	$5.0 \cdot 10^4$	$4.2 \cdot 10^5$
	20	$4.95 \cdot 10^4$	$7.8 \cdot 10^5$
	30	$4.9 \cdot 10^4$	$11.2 \cdot 10^5$
	40	$4.8 \cdot 10^4$	$14 \cdot 10^5$

As seen in Table 3, with an increase in the grounding resistance of the support, the dissipation of lightning current is hindered, and the overvoltage between the phases of a ground wire increases. When the resistance value reaches 6 Ω, this becomes a critical value for the considered line-supports, as it causes a breakdown (Fig. 7) between a ground wire and the support, which results in the line's impulse strength reaching 270 kV.
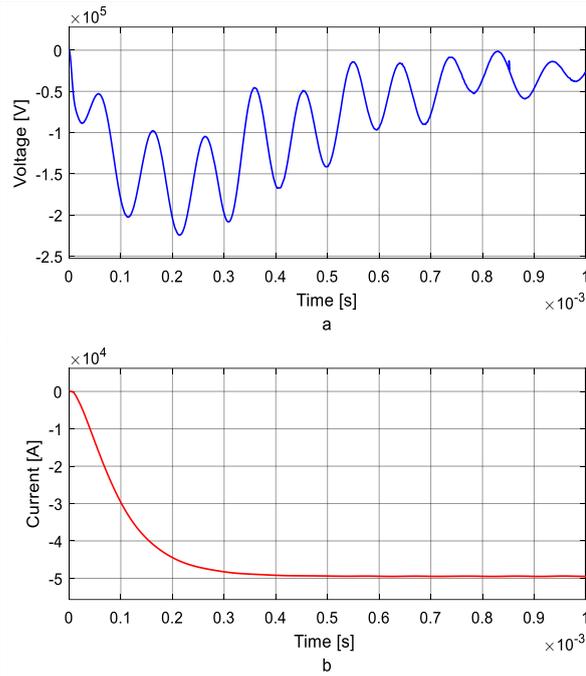
Figure 6. *Lightning strike on the shield cable with a grounding resistance of the supports of 5 Ohms:*
a - inductive overvoltage - phase voltage; b - current flowing through the grounding of the supports.
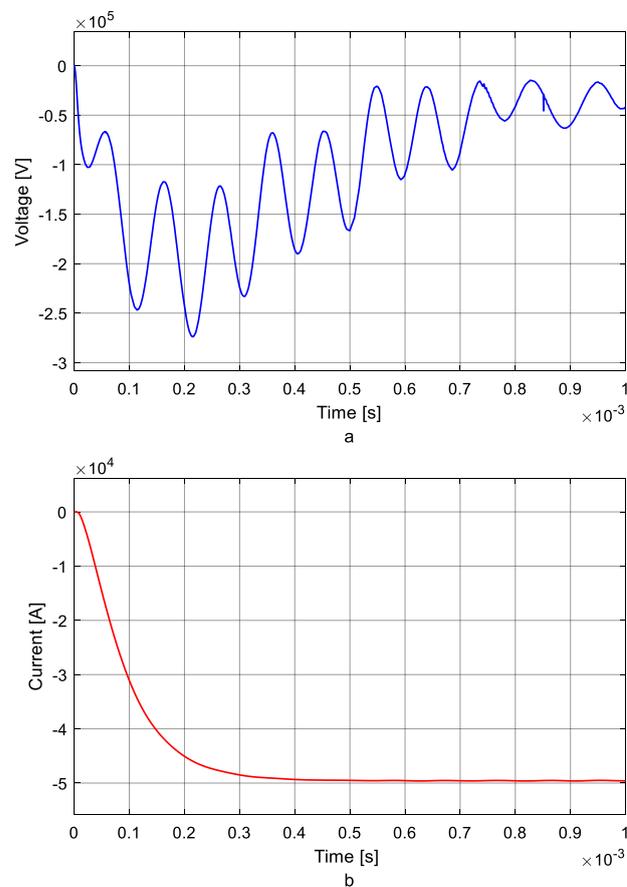

Figure 7. *Flashover when lightning strikes a ground wire:*
a - induction overvoltage—phase voltage; b - current flowing through the support ground electrode.

Modeling a lightning strike on a phase conductor.

To assess the lightning resilience of electrical equipment under external overvoltages, a scenario of a direct lightning strike to the phase conductor of a transmission line was simulated. A simulation was conducted with a grounding resistance of 5 Ω. As a result, the maximum phase overvoltage reached a value of 3.5×10^7 V. In this case, the overvoltage in phase A was several times higher compared to the results obtained from the lightning strike to the lightning protection cable (Fig. 8). This is due to the fact that when lightning strikes the cable, insulation breakdown occurs, which consumes part of the electrical potential [32-35]. In the case of a direct lightning strike to the phase conductor, potential losses are significantly lower, leading to higher levels of impact.

To determine the maximum lightning current at which insulation breakdown has not yet occurred, a series of experiments were conducted. However, it was established that practically any lightning strike, even with a current of 1-2 kA, leads to insulation breakdown of the line [36-39].

Thus, the proposed method for evaluating the effectiveness of the lightning protection system allows for a more accurate reflection of real operating conditions and identification of the limiting capabilities of protective measures.
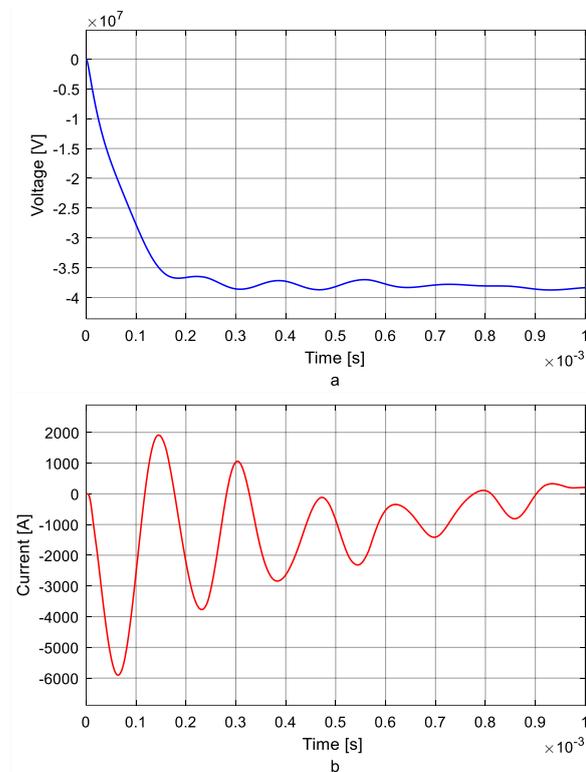

Figure 8. *Direct lightning strike on the phase conductor of the line:*
a-curve of currents occurring in phase A; b-current flowing through the support ground electrode

V. Conclusions

The study established that the reliability of transmission line operation under lightning activity is largely determined by the effectiveness of the lightning protection systems in place. Traditional methods, such as lightning ground wire, lightning rods, and line arresters, remain key elements of protection. However, their efficiency can be significantly improved through the use of innovative design solutions and modern approaches to grounding system design. One such solution is the modification of ground wire with the use of V-shaped elements, which increases the protection radius and reduces the risk of direct lightning strikes on the phase conductor. The

model of a power system section with an overhead transmission line, developed in the MATLAB Simulink environment, allowed for the assessment of overvoltages caused by lightning strikes to both the lightning protection cable and the phase conductors. The simulation results showed that an increase in the grounding resistance of the supports leads to higher levels of overvoltage in the line. In particular, at a grounding resistance of 6 Ω, a critical voltage level is reached that can cause insulation breakdown and equipment damage. This highlights the need for constant monitoring and optimization of grounding parameters, especially in areas with high lightning activity. The results obtained and the proposed methodologies can be used for further improvement of protection systems, ultimately contributing to the increased reliability and safety of electrical power systems as a whole.

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