RESEARCH ARTICLE



# Lightning Protection of the Underground Cable Line Connecting an Overhead Line to a 110 kV Substation

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## Abstract

**This paper analyzes the lightning protection of a 110 kV underground cable line connecting two overhead transmission lines with a 110 kV substation. The transition from two overhead lines to two underground cable lines is implemented at a special double-circuit overhead line tower located approximately 2.4 km from the 110 kV substation. Lightning transients are calculated at: (i) both cable terminations, first at the transition tower and second at the substation, (ii) at the first (more critical) cable joint, (iii) at the cable sheath to the surrounding soil and objects. The latter analysis is performed to assess the risk of outer cable insulation breakdown between the sheath and the transition tower or its grounding system, as well as between the cable sheath and the substation grounding system at the opposite end of the cable. The applied surge arrester configuration is presented, and it can provide a high level of lightning protection for the analyzed system. In addition, the energy stress of the surge arresters is calculated to verify that they are not overstressed during the mitigation of lightning transients.**

**Keywords**: cable line, insulation breakdown, lightning protection, overhead line, surge arrester, transition tower.

## 1 Introduction

The necessity to implement a mixed power line consisting of an overhead line (OHL) and an underground cable line (UCL) sometimes appears in power systems. Typical applications include the entry of OHLs into urban areas, the connection of OHLs to substations located in urban environments, and crossings of OHLs over highways, railways, rivers, or lakes. In such situations, the construction of an OHL is often not feasible. Therefore, a transition from an OHL to a UCL is adopted, since UCLs are generally acceptable in most situations, particularly in urban areas. The transition from an OHL to a UCL can be realized in several ways; however, the most applied solution is the use of a special transition tower [1]. Two characteristic configurations can be identified:

- The OHL-UCL-OHL transition [2–5], applied in cases where it is not possible to construct a standard OHL along a certain section of the route.
- The OHL-UCL-substation transition, most used when a substation is constructed in an urban area and a standard OHL connection to the substation is not feasible [6].

Mixed lines are mostly applied in AC transmission lines, but they can also be used in DC transmission lines [7].

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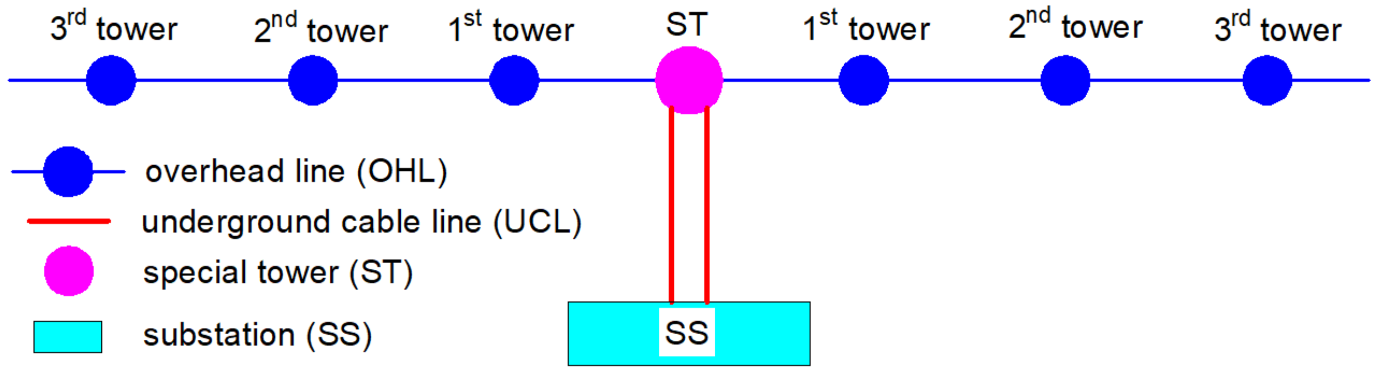


**Figure 1.** Simplified schematic representation of the analyzed system.

Proper lightning protection of mixed lines is essential for their safe and reliable operation. In such systems, lightning protection of the equipment in the case of a strike to the OHL section is typically analyzed [2–6]. Both lightning strikes to the ground wire [5] and shielding failures at the OHL are considered [4]. The protection system must be designed to limit lightning transients at the transition tower, between phase conductors and the tower, between phase conductors and the cable sheath, and between the cable sheath and the tower or tower grounding electrodes. In the latter case, the outer cable insulation is of particular concern, and the probability of its breakdown is evaluated. Although the breakdown of the outer cable insulation does not cause an immediate fault in the UCL, such damage allows moisture and water to enter the cable system, which can lead to breakdown of the main cable insulation over an extended period.

This paper analyzes the lightning protection of a mixed 110 kV OHL-UCL-substation system consisting of two OHLs, two UCLs, and a substation. The transition tower is located approximately 2.4 km from the 110 kV substation, enabling the connection of two overhead lines to a new substation constructed in an urban area. The analyses presented are more comprehensive than those reported in existing literature, which mostly consider either lightning strikes to the ground wire [2, 3, 5] or shielding failures at the OHL [4]. Furthermore, previous studies typically calculate only lightning transients in the system [2–5], without evaluating the energy stress of surge arresters. In addition, reference [6] considers a case where the cable sheath is grounded at only one end. In contrast, this paper analyzes a configuration in which the cable sheath is grounded at both ends.

The comprehensive analyses presented in this paper include:

- Consideration of four different lightning strike points along the OHL section of the system.
- Analysis of both lightning strikes to the ground wire and shielding failures at the OHL.
- Variation of the power-frequency (50 Hz) voltage phase angle and the grounding resistance values of the OHL towers.
- Calculation of the energy stress of surge arresters.

In this manner, the effectiveness and robustness of the proposed surge arrester configuration are verified under a wide range of calculation scenarios.

## 2 Applied models and parameters of elements in calculations

Numerical calculations of lightning transients and graphical presentation of calculated results are done using EMTP-ATP [8, 9] and MATLAB [10], as described in [11]. Models of elements applied in calculations are described in [11–23].

A simplified schematic representation of the analyzed system is presented in Figure 1. The existing single-circuit 110 kV OHL is divided into two sections to connect to the newly built 110 kV substation (SS). Two 110 kV UCLs are constructed to connect the special tower (ST) of the OHL and SS.

The geometries of the OHL towers, including the special tower (ST), are given in [12]. The length of OHL spans is 350 m. The lightning impulse withstand voltage (BIL) of equipment in the system is equal to 550 kV, while the BIL of the outer cable insulation is assumed to be 37.5 kV [24]. Power cables are of the type A2XS(FL)2Y (Al/XLPE/Cu Wire/Al Tape/PE) 1x1000RM/95 mm². The length of the UCL is 2400 m. Two sets of cable joints are applied, and direct bonding of the sheath is applied. The flashover distance of polymer line insulators is equal to 0.86 m.

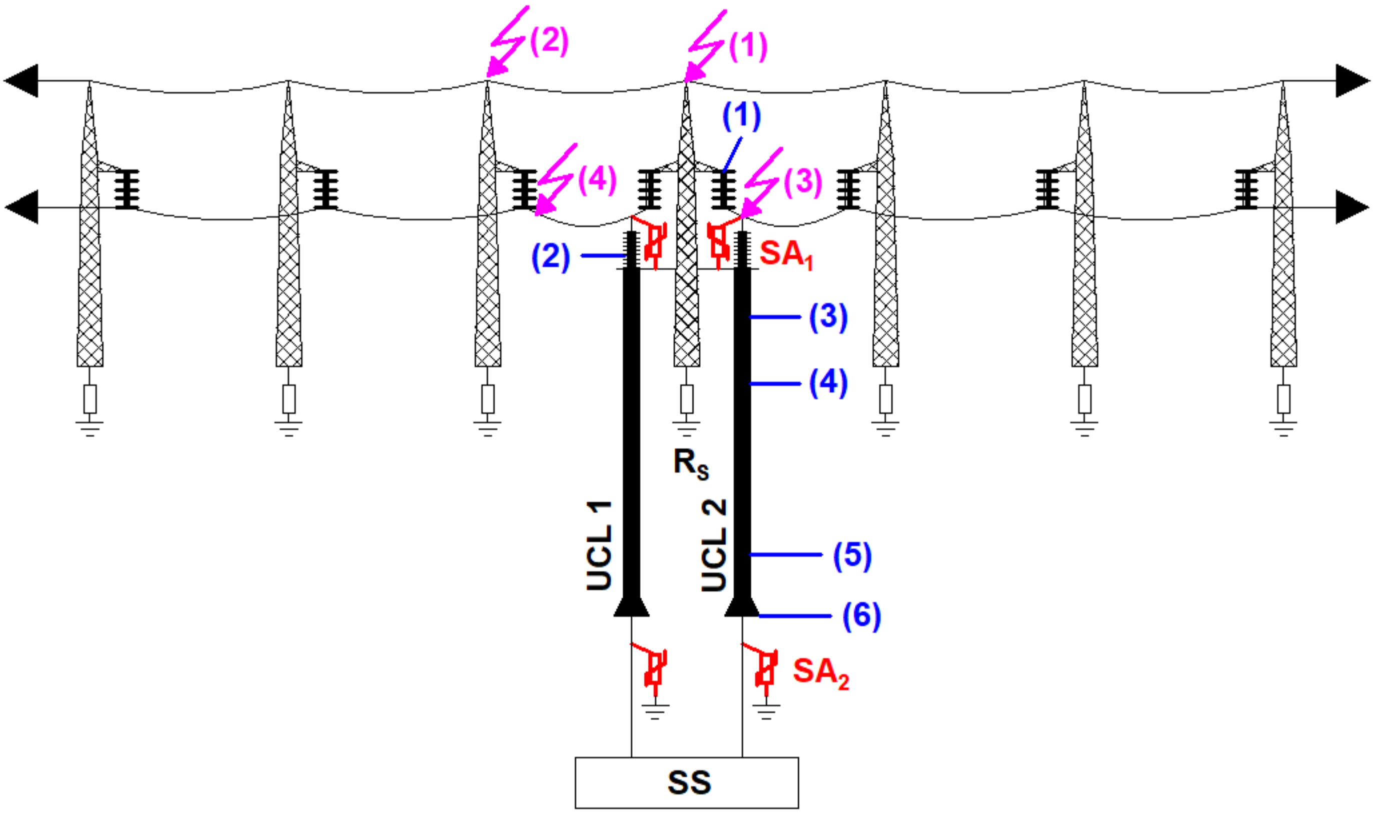


**Figure 2.** Schematic representation of the configuration of the analyzed system.

The non-linear $U - I$ protection curve of surge arresters applied in lightning transients' calculations is defined in [12]. Values of other important parameters of elements applied in calculations can be found in [12].

In the case of a lightning strike to the ground wire, the lightning current amplitude is assumed to be 200 kA, with a waveform of 10/350 $\mu$s [18]. In the case of a shielding failure, the lightning current amplitude is calculated using the electro-geometric model, and the current waveform was 5.6/77 $\mu$s [23]. The default values of the grounding resistance of the OHL towers were assumed to be 15 $\Omega$, while the grounding resistance of the special tower was assumed to be 10 $\Omega$.

A schematic representation of the configuration of the analyzed system and of the special tower is given in Figures 2 and 3, respectively. Four lightning strike points are considered, as marked in Figure 2:

1. Lightning strike to the ground wire at the special tower.
2. Lightning strike to the ground wire at the tower near the special tower.
3. Shielding failure at the special tower.
4. Shielding failure at the tower near the special tower.

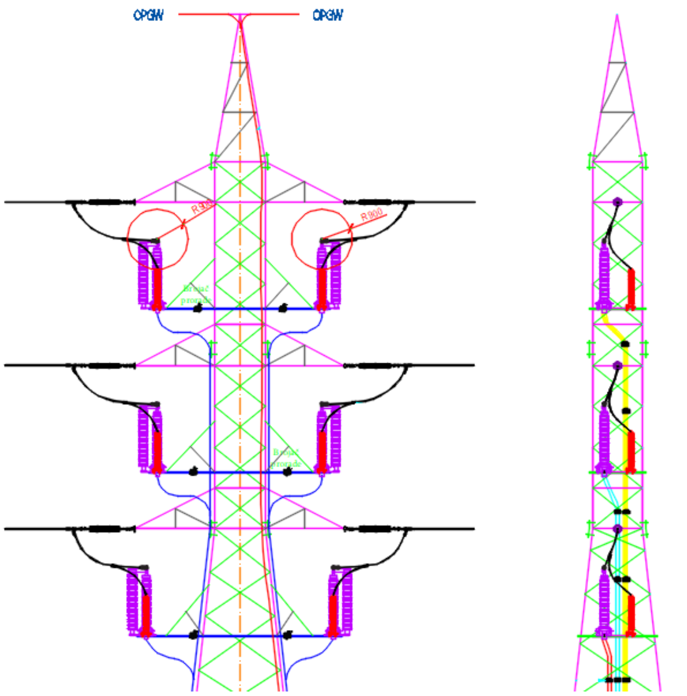


**Figure 3.** Schematic representation of the configuration of the special tower (ST).

Lightning transients are calculated at six points:

1. At the line insulators installed on the special tower.

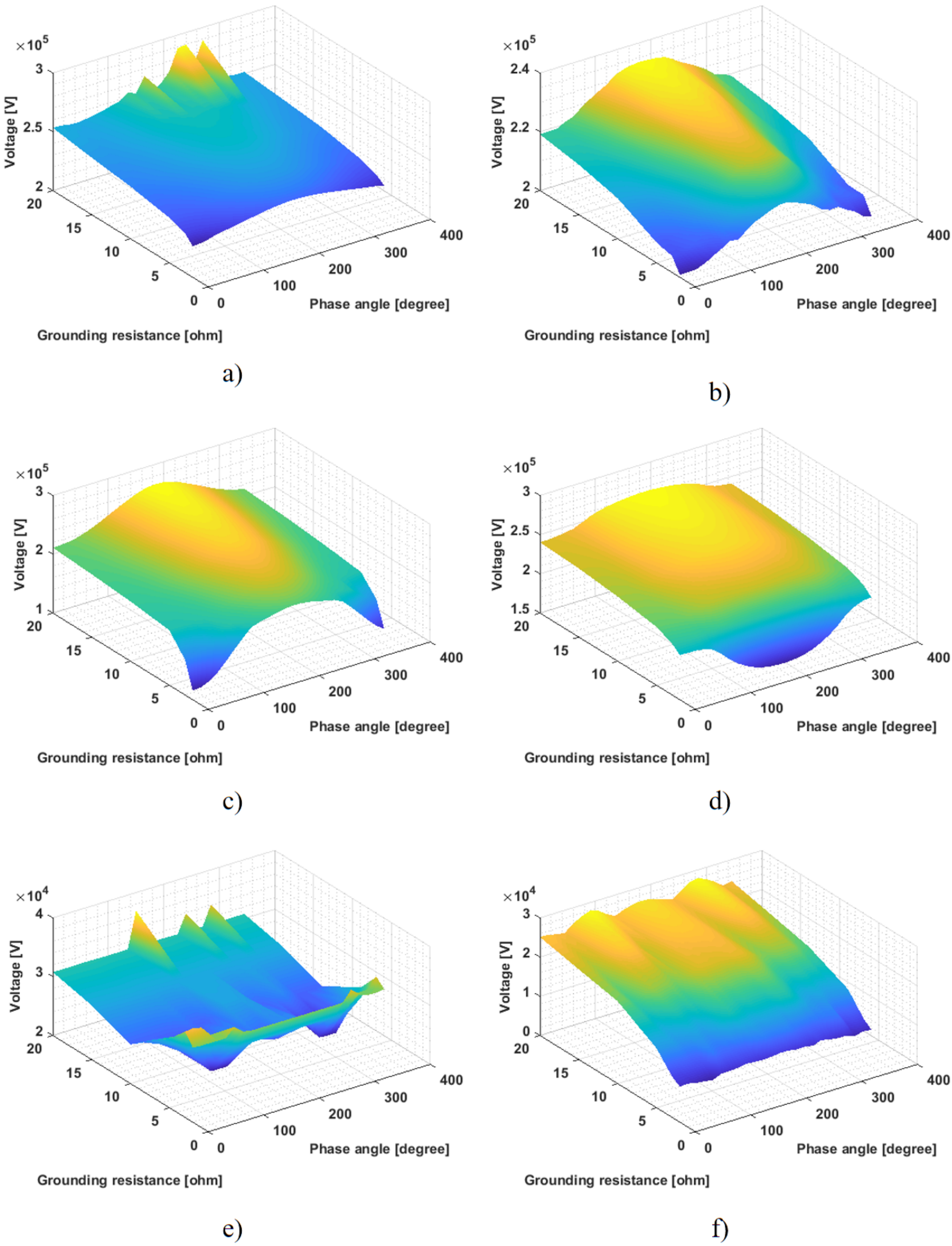


**Figure 4.** Calculated amplitudes of lightning transients: a) line insulators at the special tower (ST), b) cable termination at the ST, c) first cable joint, d) cable termination in the substation (SS), e) cable outer insulation at the ST, f) cable outer insulation in the SS.

2. At the cable terminations on the special tower.
3. Between the cable sheath and the grounding system of the special tower.
4. At the first cable joint (it is more critical compared to the second joint).
5. Between the cable sheath and the substation grounding system.
6. At the cable terminations in the substation.

## 3 Results of calculations

### 3.1 Lightning strike point (1) from Figure 2

The calculated amplitudes of lightning transients for different values of the tower grounding resistance and for different phase angles of the operating voltage are given in Figure 4. The waveforms of lightning transients for OHL towers with grounding resistance value equal to 15 Ω and a special tower grounding resistance value equal to 10 Ω are presented in Figure 5.

From Figures 4 and 5, it can be observed that the amplitudes of the lightning transients are significantly lower than the equipment's BIL of 550 kV. Additionally, lightning transients are lower than the withstand voltage of the outer cable insulation, between the cable sheath and surrounding soil and objects, which is assumed to be 37.5 kV.

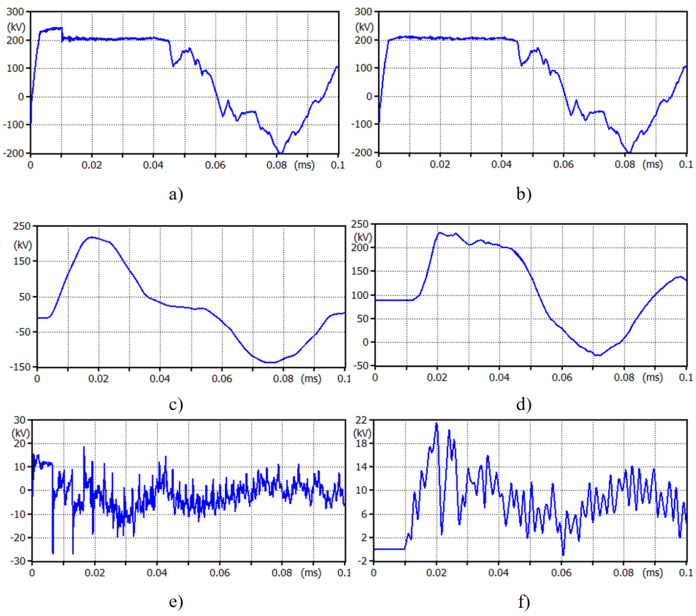

Figure 5. Calculated waveforms of lightning transients: a) line insulators at the special tower (ST), b) cable termination at the ST, c) first cable joint, d) cable termination in the substation (SS), e) cable outer insulation at the ST, f) cable outer insulation in the SS.

The calculation of the lightning transients between the cable sheath and the tower grounding electrodes in Figures 4 and 5 was performed for the most critical cable, that is, the one connected to the highest crossarm of the tower (blue line in Figure 6). For the cables connected to the two lower crossarms of the tower, the voltages are lower (red and green lines in Figure 6).

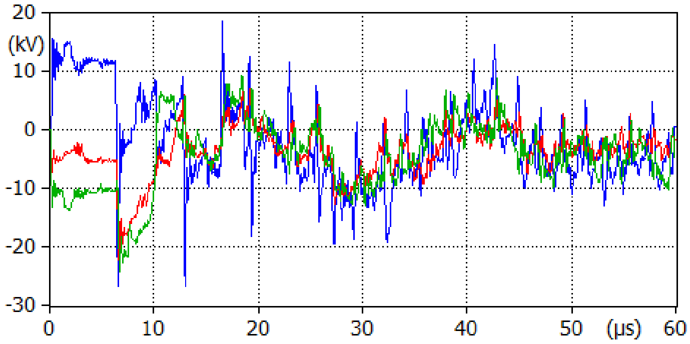


Figure 6. Calculated waveforms of lightning transients in all three phases at the outer cable insulation between the cable sheath and grounding electrodes of the special tower (ST).

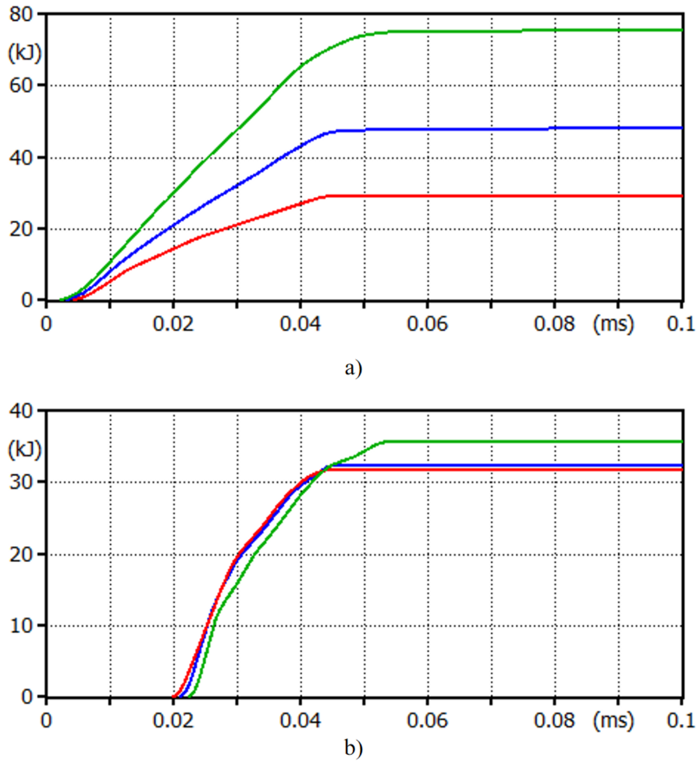


Figure 7. Calculated absorbed energy of surge arresters: a) surge arresters at the special tower (ST), b) surge arresters in the substation (SS).

The energy absorbed by the surge arresters was calculated, and the calculation results are shown in Figure 7. For lower values of the OHL tower grounding resistance, lower energy stresses of the surge arresters are obtained, since a larger portion of the lightning current is dissipated into the soil through the OHL towers' grounding systems, thereby reducing the energy stress of the surge arresters. The energy absorption capability of the applied surge arresters is equal to 8 kJ/kVUr, which corresponds to 768 kJ for a surge arrester with a rated voltage of 96 kV. The calculated energy stresses of surge arresters are significantly below this value; therefore, there is no risk of thermal destruction.

### 3.2 Lightning strike point (2) from Figure 2

The calculation results in this case are shown in Figure 8.

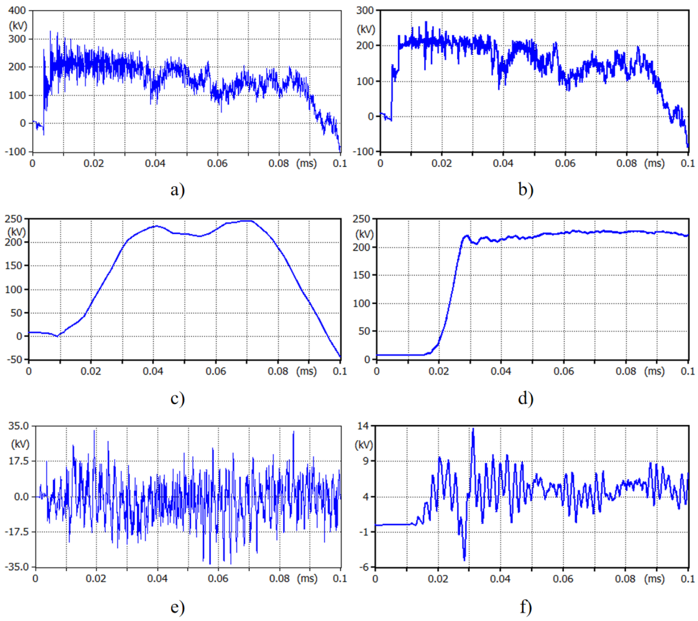


**Figure 8.** Calculated waveforms of lightning transients: a) line insulators at the special tower (ST), b) cable termination at the ST, c) first cable joint, d) cable termination in the substation (SS), e) cable outer insulation at the ST, f) cable outer insulation in the SS.

It can be observed that the amplitudes of lightning transients are significantly lower than the BIL of the equipment (550 kV). The amplitude of lightning transients at the outer cable insulation is equal to 33.7 kV, which is close to the withstand voltage of 37.5 kV. The calculations were performed for the most critical cable, namely the one connected to the highest crossarm of the tower, as explained in subsection 3.1. The energy absorbed by the surge arresters was calculated, and the results are shown in Figure 9. The calculated energy stresses of the surge arresters are significantly below 768 kJ; therefore, there is no risk of thermal destruction.

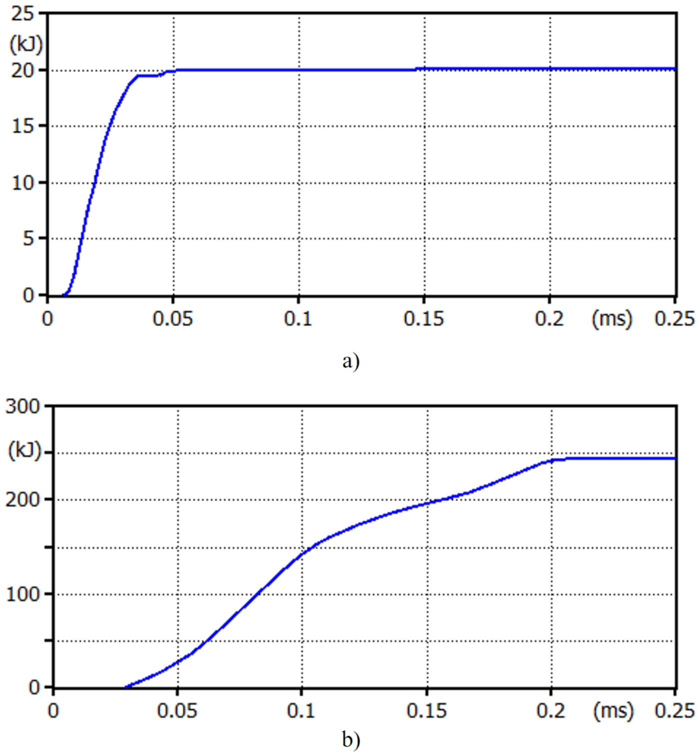


**Figure 9.** Calculated absorbed energy of surge arresters: a) surge arresters at the special tower (ST), b) surge arresters in the substation (SS).

### 3.3 Lightning strike point (3) from Figure 2

The maximum amplitude of the shielding failure current at the special tower is calculated using the electro-geometric model, as suggested in [15, 20]:

$$r_c = 10 \cdot I^{0.65} \tag{1}$$

$$r_g = 0.9 \cdot r_c \tag{2}$$

where $r_c$ and $r_g$ are the striking distances to the phase conductors and to the ground, respectively, [m], and $I$ is the lightning current amplitude [kA].

Ground wires and phase conductors at the special tower are aligned in the vertical axis, and the maximum calculated amplitude of the shielding failure current is equal to 7 kA, as shown in Figure 10. The calculations of lightning transients were performed for a discharge current of 10 kA, due to a safety margin, and the fact that in the adjacent spans to the special tower, the arrangement of conductors changes; consequently, the shielding effect of the ground wire within these two spans is not constant.

The calculated waveforms of lightning transients in this case are shown in Figure 11. It can be observed that the amplitudes of lightning transients are significantly lower than the BIL of the equipment (550 kV), while

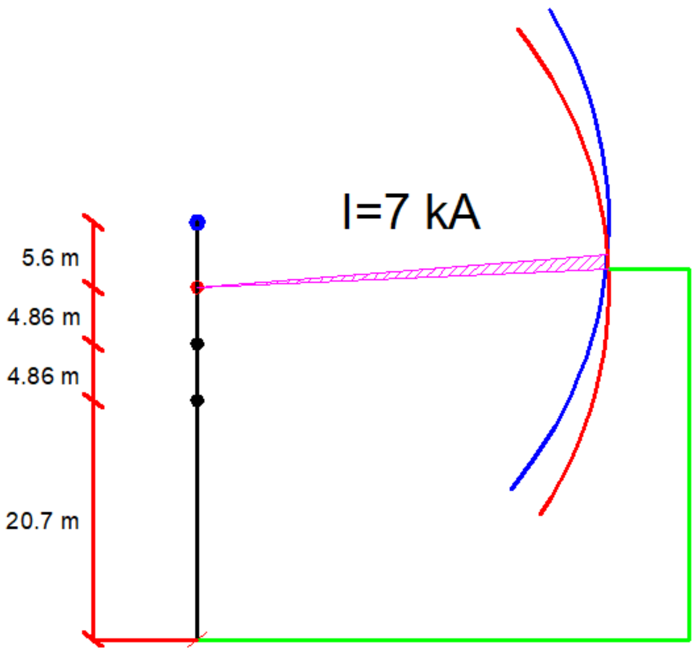


**Figure 10.** The maximum amplitude of the shielding failure current at the special tower is calculated to be 7 kA.

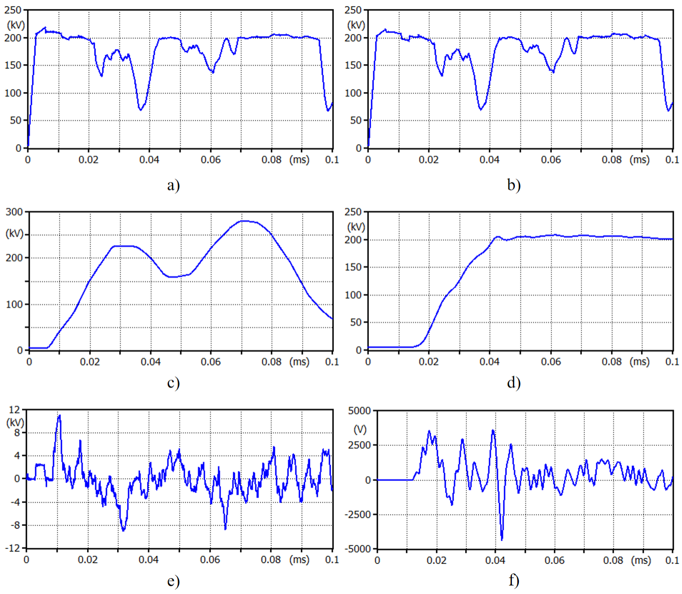


**Figure 11.** Calculated waveforms of lightning transients: a) line insulators at the special tower (ST), b) cable termination at the ST, c) first cable joint, d) cable termination in the substation (SS), e) cable outer insulation at the ST, f) cable outer insulation in the SS.

at the outer cable insulation, they are noticeably below the withstand voltage of 37.5 kV. The energy absorbed by the surge arresters in this case is shown in Figure 12. A low level of energy stress of the surge arresters can be observed, which is expected regarding the low amplitude of the discharge current.

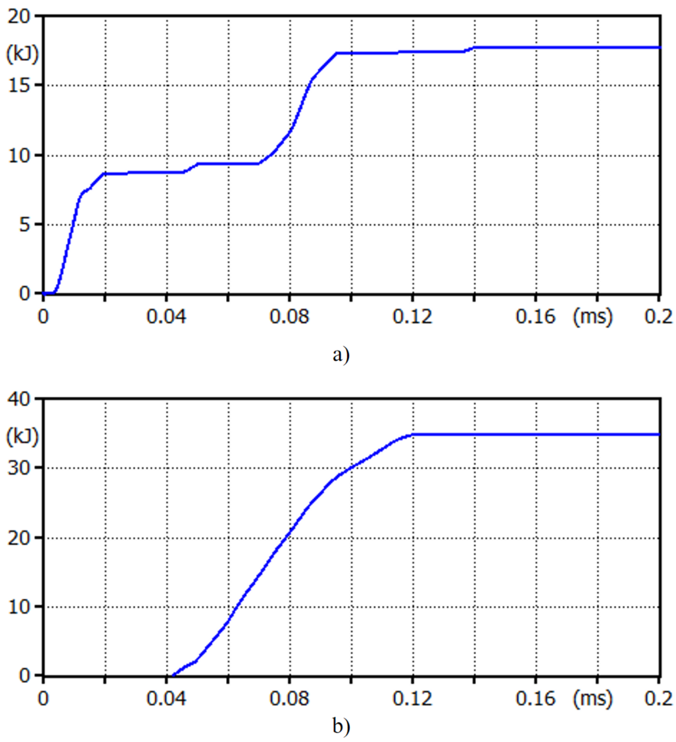


**Figure 12.** Calculated absorbed energy of surge arresters: a) surge arresters at the special tower (ST), b) surge arresters in the substation (SS).

### 3.4 Lightning strike point (4) from Figure 2

The maximum amplitude of the shielding failure current in this case is calculated to be 27 kA, considering tower head geometry from [12]. The calculations are performed with the current amplitude equal to 30 kA, to include a safety margin in the calculated results. Calculated waveforms of lightning transients are presented in Figure 13, and they are significantly below the BIL of the equipment (550 kV). Also, the amplitude of lightning transients at the cable outer insulation is up to 28.4 kV, which is lower than the withstand voltage (37.5 kV). High frequency oscillations can be observed in Figure 13(e)), and this increases the dielectric stress of the outer insulation.

Absorbed energy of surge arresters is presented in Figure 14. Low energy stress is calculated due to the low amplitude of the lightning current.

## 4 Conclusion

Based on the results presented, it can be concluded that two sets of surge arresters, first at the special tower and second in the substation, can provide a high level of lightning protection of analyzed system. Surge arresters can be installed as close as possible to the cable terminations. High level of lightning protection is achieved both in the case of

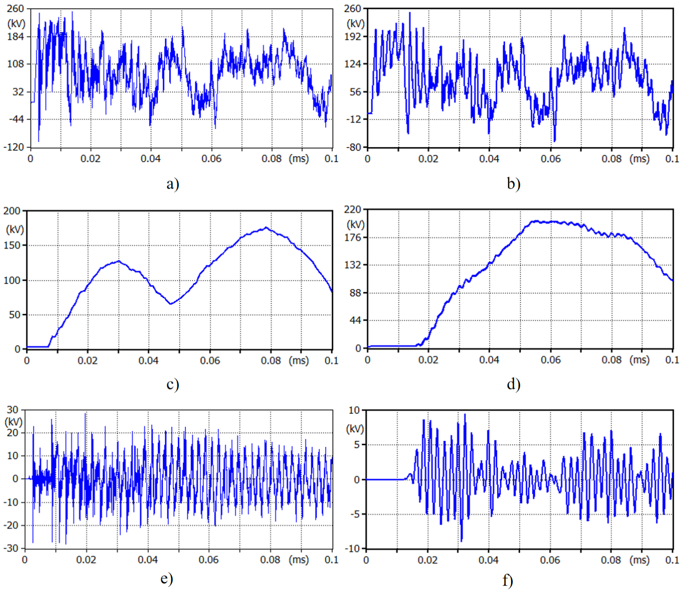


**Figure 13.** Calculated waveforms of lightning transients: a) line insulators at the special tower (ST), b) cable termination at the ST, c) first cable joint, d) cable termination in the substation (SS), e) cable outer insulation at the ST, f) cable outer insulation in the SS.

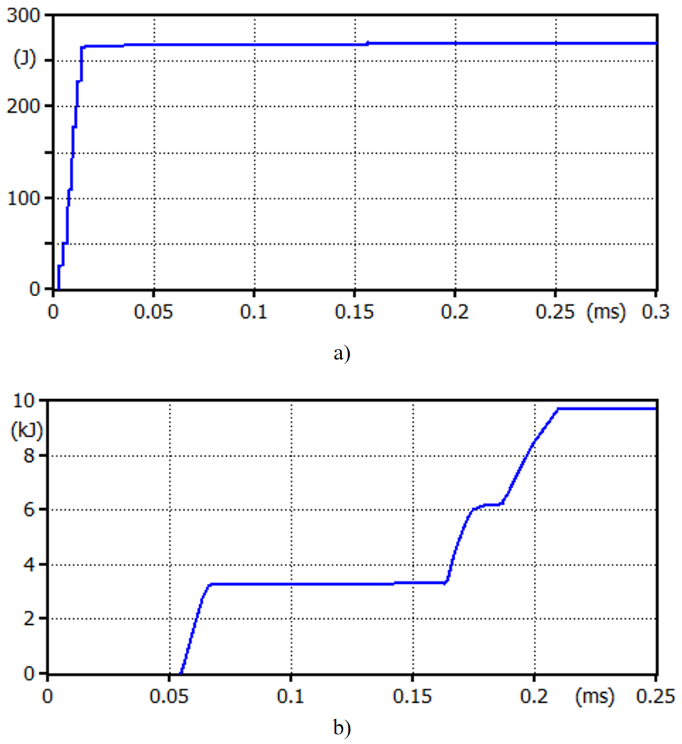


**Figure 14.** Calculated absorbed energy of surge arresters: a) surge arresters at the special tower (ST), b) surge arresters in the substation (SS).

shielding failures as well as in the case of lightning strikes to the ground wire. In the analyzed case, the cable sheath at both ends is directly grounded. This reduces dielectric stress on the outer cable insulation, causing it to be properly protected against lightning transients. However, one must keep in mind that the BIL of the outer cable insulation is not defined by the manufacturers, especially in the case of lightning transients whose waveform contains significant high-frequency oscillations. The calculated energy stress of the surge arresters is well below their energy absorption capability; therefore, the probability of thermal damage is low.

## Data Availability Statement

Data will be made available on request.

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## Conflicts of Interest

The authors declare no conflicts of interest.

## AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

## Ethical Approval and Consent to Participate

Not applicable.

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