ICCK Transactions on Electric Power Networks and Systems
http://dx.doi.org/10.62762/TEPNS.2025.439655

RESEARCH ARTICLE

Lightning Protection of the 110 kV Substation at the Wind Park – Surge Arresters in the Line Bay or at the Gantry Tower

Mladen Banjanin[1,*]

[1] Faculty of Electrical Engineering, University of East Sarajevo, 71123 East Sarajevo, Bosnia and Herzegovina

Abstract

This paper analyzes the lightning protection of a 110 kV substation in a wind park, focusing on transients caused by lightning strikes to the connected 110 kV overhead line. Two configurations of surge arresters are compared: 1) application of the standard surge arresters installed in the line bay between the grounding system and phase conductors, 2) application of the surge arresters at the gantry tower. Both solutions are compared from the aspect of maximum amplitudes of lightning transients in the substation, as well as from the aspect of the energy stress of two sets of surge arresters at the 110 kV voltage level. Regarding the maximum amplitudes of lightning transients in the substation, it is presented that in the analyzed case, both solutions have some advantages and disadvantages, and neither solution is better in all aspects. However, standard installation of surge arresters in the line bay is significantly efficient from the aspect of sharing energy stress between the sets of surge arresters.

Submitted: 13 August 2025
Accepted: 15 September 2025
Published: 22 October 2025

Vol. 1, **No.** 1, 2025.
10.62762/TEPNS.2025.439655

***Corresponding author:**
✉ Mladen Banjanin
mladen.banjanin@etf.ues.rs.ba

Keywords: gantry tower, substation lightning protection, surge arrester, transmission line bay.

1 Introduction

Implementation of the proper lightning protection system is essential for reliable exploitation of high voltage substations. Lightning protection of a high voltage substation is mainly implemented for two reasons: 1) protection against direct lightning strikes into the elements of the high voltage substation [1, 2], 2) protection against lightning transients caused by lightning strikes into the connected overhead line [3–5]. In the second case, lightning protection of the substation is mainly implemented using two sets of surge arresters [4, 5]. The first set is installed in the transmission line bay, while the second set is installed in the transformer bay. Both sets are, in most cases, installed in a standard way, between the phase conductors and the grounding system of the substation. This solution, in most cases, leads to a very high lightning protection level of the elements in the substation [4, 5]. However, there is also the possibility of installing line arresters at the first overhead line towers in front of the substation to improve the lightning protection of the equipment in the substation [6–8]. This solution can be applied in cases when: 1) There is a long cable line or gas-insulated line between the power transformer

Citation
Banjanin, M. (2025). Lightning Protection of the 110 kV Substation at the Wind Park – Surge Arresters in the Line Bay or at the Gantry Tower. *ICCK Transactions on Electric Power Networks and Systems*, 1(1), 26–37.

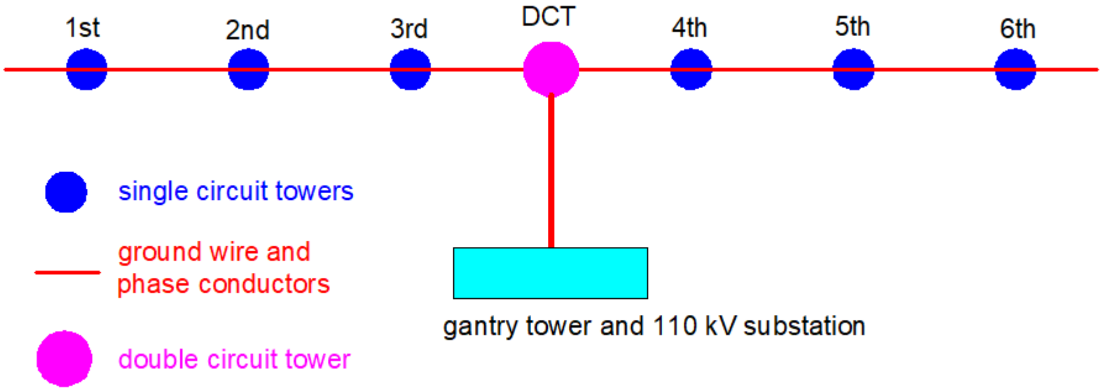


Figure 1. The schematic representation of the configuration of the connected 110 kV overhead line in front of the substation.

and switchgear with direct connection to the power transformer (without bushings). In this case, surge arresters cannot be installed near the terminals of a power transformer [6]. 2) To additionally reduce amplitudes of lightning transients in the substation, to reduce energy stress of station surge arresters and avoid back-flashover and short circuits in front of the substation [7, 8]. Novelty of this paper is the analysis of the possibility of replacing standard station surge arresters in the line bay with surge arresters installed at the gantry tower. In this way, more compact substations can be implemented. In the case of large substations with non-standard configurations, there is also the possibility to install additional sets of station surge arresters, but that increases investment costs and reduces the reliability of the substation [9].

In this paper, the lightning protection of the real 110 kV substation against transients caused by lightning strikes into the connected overhead transmission line is analyzed. Two solutions are compared:

1. Application of the standard station surge arresters installed in the transmission line bay between the grounding system and phase conductors. This solution is common all over the world.

2. Application of surge arresters at the gantry tower. This solution is not standard but can be useful in cases when there is a limited space to build the substation, or in cases when surge arresters in the line bay are not applied during the construction phase and need to be installed during exploitation of the substation.

Comparisons of two solutions are made from the aspect of maximum amplitudes of lightning transients in different points of the substations, and from the aspect of the energy stress of two sets of surge arresters at the 110 kV voltage level. It is presented that in the analyzed case, both solutions have some advantages and disadvantages from the aspect of the maximum amplitudes of lightning transients that can appear in the substation. However, installation of both sets of surge arresters in the standard way between the phase conductors, with the grounding system, leads to much better sharing of energy stress between the sets of surge arresters.

2 Applied models and parameters of elements in calculations

Numerical calculations of lightning transients in the substation are done in the EMTP-ATP software [10, 11]. Analyses and graphical presentation of the calculated results are done using the MATLAB software [12]. The interaction between two software is described in [5]. The models of elements applied during the creation of the equivalent circuit are the same as in [4, 5]. Calculations and modeling are done in accordance with relevant international standards and technical documents [13–20]. Some parameters of elements are used from the project documentation of the real high voltage substations.

The schematic representation of the configuration of the connected 110 kV overhead line in front of the substation is presented in Figure 1. The existing single circuit 110 kV overhead line is cut into two parts, and both parts are connected to the new double circuit tower (DCT). DCT is further connected to the 110 kV substation of the wind park.

The parameters of the connected overhead transmission line are presented in Table 1. The geometry of the DCT and of the single circuit towers is shown in Figure 2.

Schematic representation of the configuration of the

Table 1. Parameters of the connected 110 kV overhead line.

Span lengths [m]						
1st to 2nd	2nd to 3rd	3rd to DCT*	DCT* to gantry	DCT* to 4th	4th to 5th	5th to 6th
243	187	73	73	185	190	210

Tower heights to lower console [m]							
Gantry	DCT*	1st	2nd	3rd	4th	5th	6th
10.0	14.7	16.2	15.2	16.2	20.2	15.2	14.2

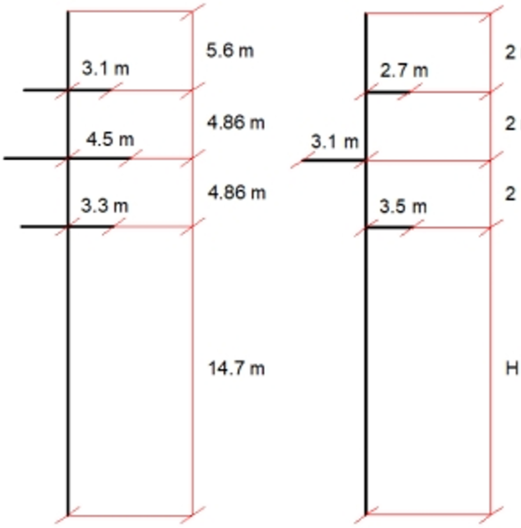
Note: DCT - 110 kV double circuit overhead line tower.*

analyzed substation is given in Figure 3. Two configurations of the surge arresters (SA1) in the line bay are analyzed:

- **SA1-LA** – surge arresters installed at the gantry tower.
- **SA1** – surge arresters installed in the standard way, between the phase conductors and the grounding system.

The lightning impulse withstand voltage (BIL) of equipment in the substation is as follows:

- All equipment in the 110 kV part of the substation: 550 kV.
- Power transformer, 33 kV voltage level: 125 kV.
- Other equipment in the 33 kV part of the substation: 170 kV.



(a) (b)

Figure 2. Geometry of the: (a) double circuit 110 kV tower in front of the substation, (b) other single circuit 110 kV overhead line towers.

Non-linear U-I characteristics of the surge arresters with rated voltages equal to 36.6 kV and 96 kV installed at 33 kV and 110 kV voltage levels of the substation, respectively, are given in Table 2.

The photos of the surge arresters at the gantry tower and of the double circuit tower (DCT) are given in Figure 4.

Other important parameters of elements are used from the technical documentation of typical substations with similar configurations, or typical data for these types of calculations are applied, as follows:

- **Transmission line.** Tower surge impedance is 170 Ω. Gantry tower surge impedance is 120 Ω. Surge velocity is 255000 km/s. Span lengths of the transmission line are given in Table 1. Gantry tower grounding resistance is assumed to be 10 times lower than the grounding resistance of the overhead line towers.
- **Phase conductor and ground wire.** Surge impedances are 450 Ω and 550 Ω, respectively. Surge velocity is 300000 km/s.
- **Lightning current.** The waveshape is represented by a double ramp function. Current amplitude, front and tail of the wave durations, and lightning channel surge impedance are: 200 kA, 10/350 μs/μs, 400 Ω.
- **Instrument voltage transformer** surge capacitance is 0.5 μF.
- **Surge arresters** are modeled as non-linear resistors. U-I characteristics are given in Table 2. Lengths of connecting conductors to the phase conductor and to the grounding system for SA1, SA2, and SA3 are 9 m, 4.3 m, and 5 m, respectively.
- **The power transformer** turn ratio is 115/33 kV/kV. Surge capacitances are $C_1 = 3\ \mu$F, $C_{12} = 3\ \mu$F, $C_2 = 4\ \mu$F. Other data are as follows: YNd5, 63 MVA

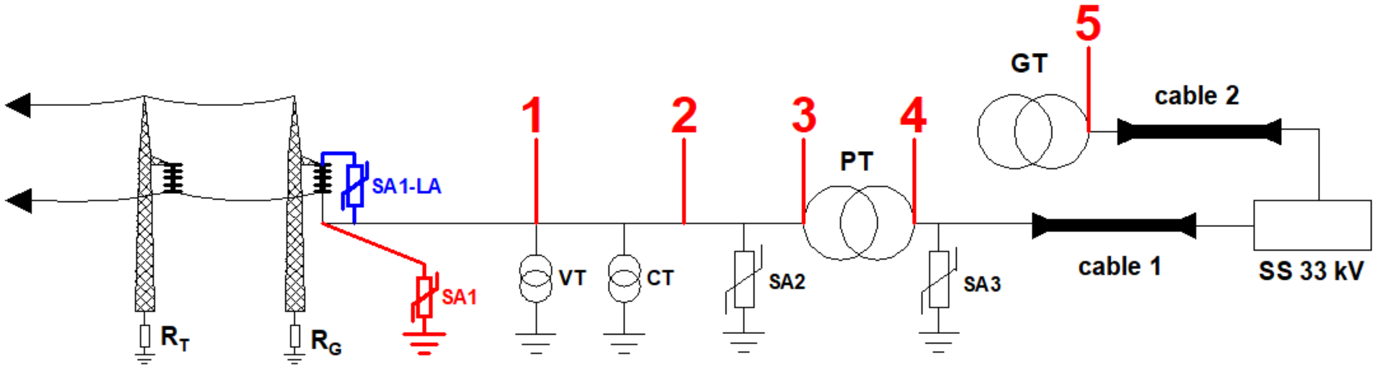


Figure 3. Schematic representation of the configuration of the analyzed substation.

Table 2. Non-linear U-I characteristics of the surge arresters at the 110 kV and 33 kV voltage levels of the substation.

Voltage level	33 kV		110 kV	
	Current	Voltage	Current	Voltage
U-I non-linear curve defined by the manufacturer for the impulse current wave 8/20 µs/µs	1 kA	75.8 kV	5 kA	212 kV
	2.5 kA	80.2 kV	10 kA	226 kV
	5 kA	84.2 kV	20 kA	244 kV
	10 kA	89.1 kV	40 kA	268 kV
	20 kA	101.6 kV	-	-

(a) (b)

Figure 4. Photos of the surge arresters in 110 kV substations of wind parks: (a) at the gantry tower (SA1-LA), (b) in the line bay (SA1).

(ONAF), $P_0 = 40$ kW, $P_k = 140$ kW, $I_0 = 0.08\%$, $Uk = 11\%$.

- **The grounding transformer** surge capacitance is 2.5 μF.

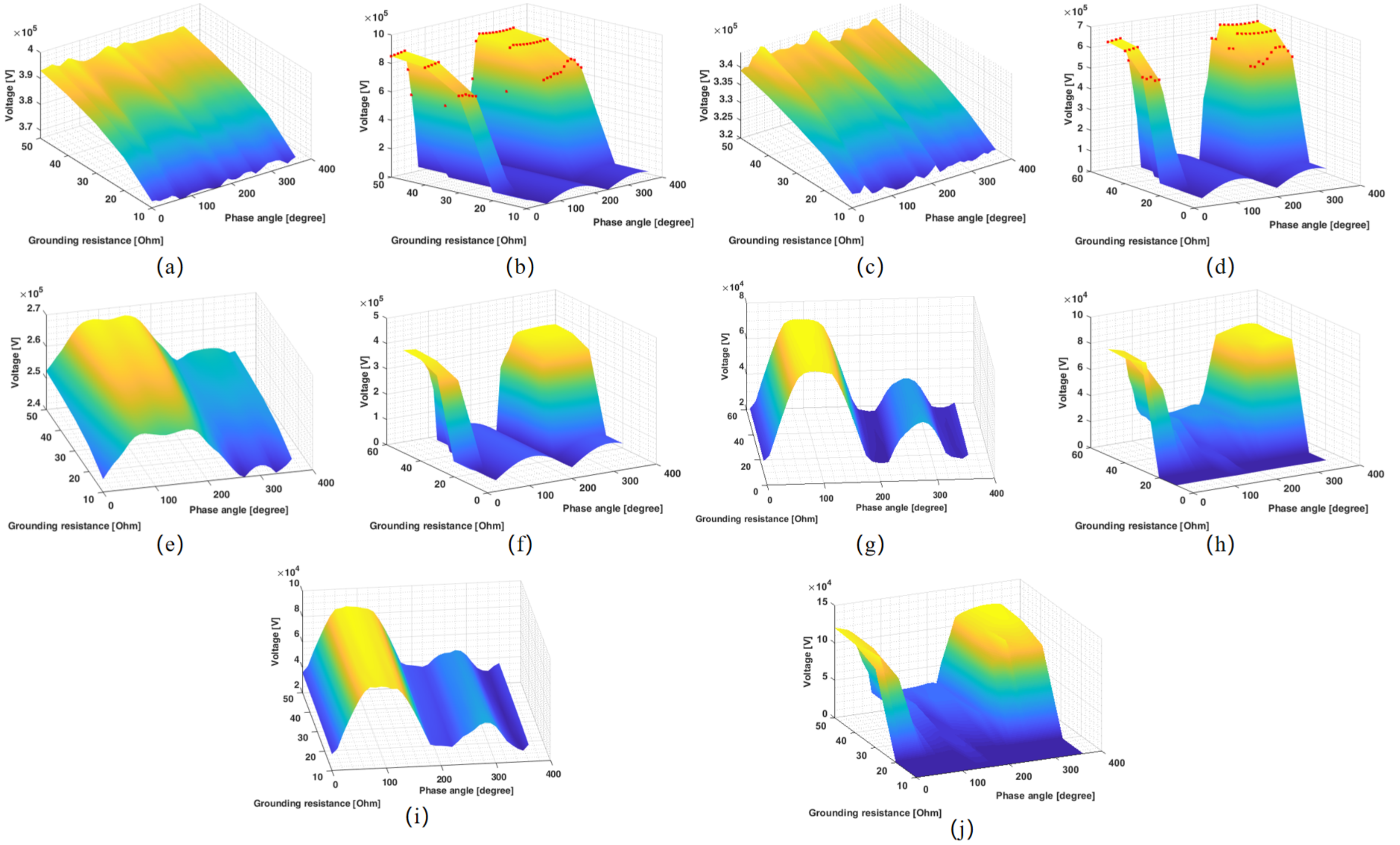


Figure 5. Calculated amplitudes of lightning transients in the substation in the case of the lightning strike to the top of the gantry tower: (a) Point 1, SA1-LA, (b) Point 1, SA1, (c) Point 2, SA1-LA, (d) Point 2, SA1, (e) Point 3, SA1-LA, (f) Point 3, SA1, (g) Point 4, SA1-LA, (h) Point 4, SA1, (i) Point 5, SA1-LA, (j) Point 5, SA1.

- **Lengths of conductors in the substation** are as follows: The gantry tower to the voltage transformer (VT) in the line bay is 5.5 m. The VT to the current transformer (CT) in the line bay is 7 m. The CT to the 110 kV busbars is 11 m. The 110 kV busbars to the surge arrester (SA2) in the transformer bay are 15.5 m. The SA2 to the power transformer is 4 m.
- **Power cables.** Lengths of power cables at the 33 kV voltage level are: Cable 1 length is 63 m, Cable 2 length is 55 m. Surge impedance of cables is 60 Ω, and surge velocity is 150000 km/s.
- The flashover distance of line insulators is 0.83 m.
- The grounding resistance and power frequency voltage phase angle values are varied in calculations.

3 Calculation of the amplitudes of lightning transients in the substation

Amplitudes of lightning transients in the substation are calculated at five points, marked in Figure 3:

- Point 1 – voltage transformer in the line bay.
- Point 2 – 110 kV busbars.
- Point 3 – power transformer, 110 kV side.
- Point 4 – power transformer, 33 kV side.
- Point 5 – grounding transformer at the 33 kV voltage level.

All amplitudes of the lightning transients in the following figures higher than 500 kV are marked with red circles, since those values can be considered as dangerous for the insulation of equipment, with nearly 10% safety margin included. Amplitudes of lightning transients at the 33 kV voltage level are not dangerous for the insulation of equipment, since their values are below 90% of the BIL of the equipment.

3.1 Lightning strikes the top of the gantry tower

Calculated amplitudes of lightning transients for this case are presented in Figure 5. It can be observed that in the case of installation of set of surge arresters SA1-LA all amplitudes of lightning transients are well below BIL of equipment, Figure 5(a), Figure 5(c), Figure 5(e), Figure 5(g), Figure 5(i). In the case when standard surge arresters SA1 are installed back-flashovers do not appear at the line insulators of gantry tower if its grounding resistance is <3 Ω,

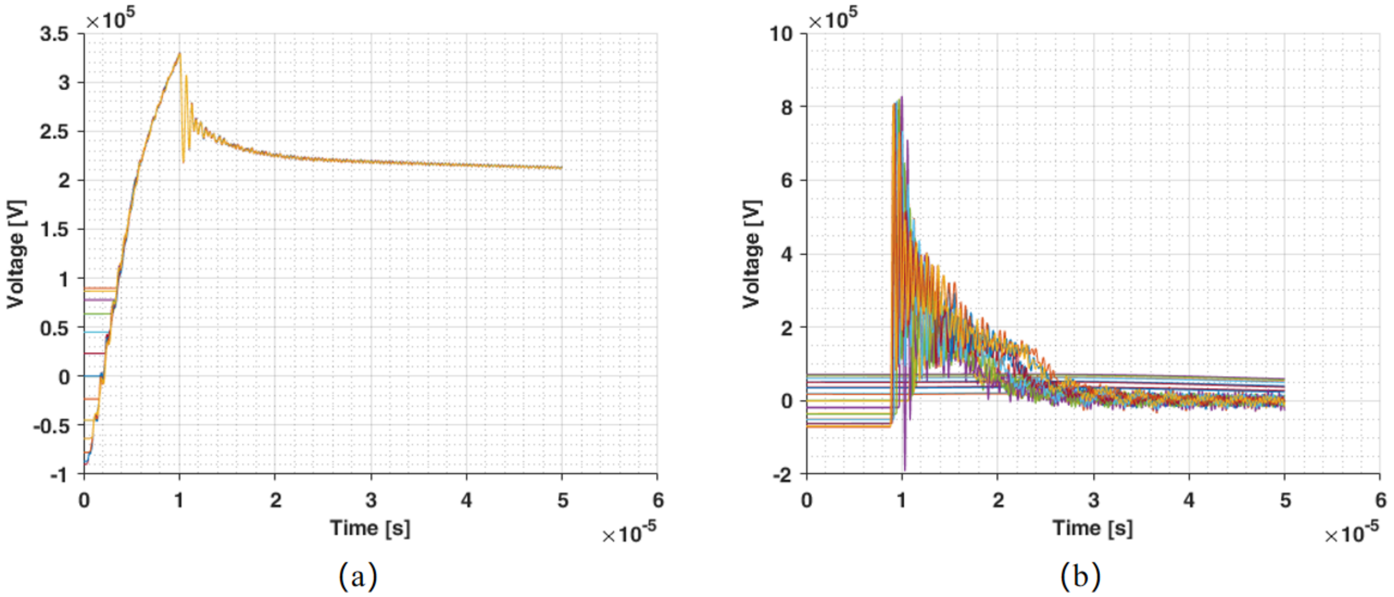


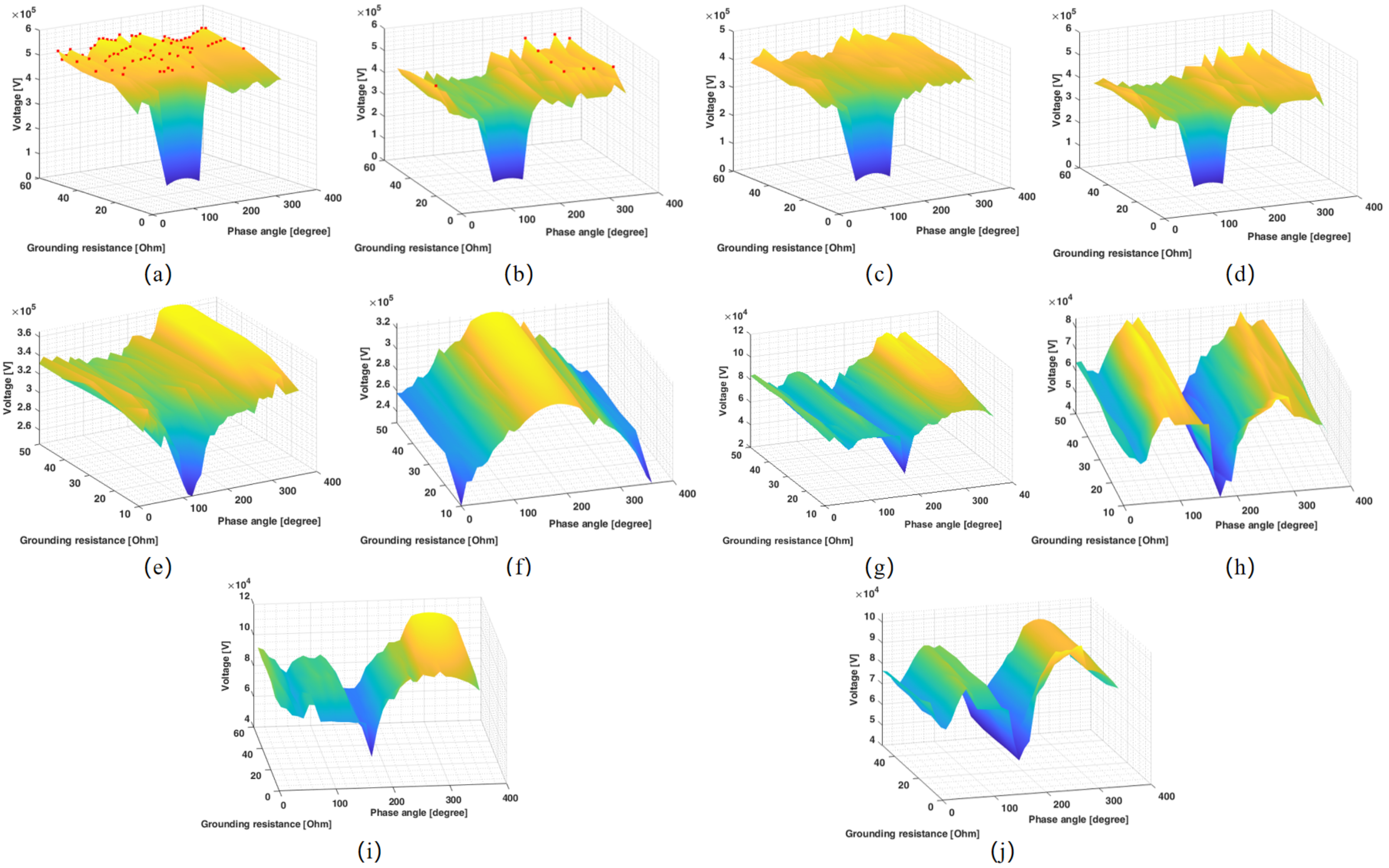
Figure 6. Calculated waveshapes of lightning transients at the voltage transformer in the line bay in the case of the lightning strike to the gantry tower for different values of the phase angle of power frequency voltage: (a) SA1-LA, (b) SA1.

and equipment in the substation is well protected, Figure 5(b), Figure 5(d), Figure 5(f), Figure 5(h), Figure 5(j). However, if the substation (gantry tower) resistance is ≥3 Ω, back-flashovers appear at the line insulators at the gantry tower and very high lightning transients appear at the voltage transformer in the line bay and at the 110 kV busbars, Figures 5(b) and 5(d), up to 865 kV. Consequently, voltage and current instrument transformers in the line bay and equipment at the 110 kV busbars will be damaged by lightning transients. Due to the set of surge arresters SA2 and SA3 installed close to the power transformer, its insulation is properly protected in both cases and at both voltage levels, 110 kV and 33 kV. Even the insulation of the grounding transformer at the 33 kV voltage level is well protected in both cases against transferred lightning transients through the power transformer, although the set of surge arresters SA3 is installed near the power transformer and is far away from grounding transformer.

Calculations are repeated to compare two solutions of installing surge arresters in the line bay, assuming that the grounding resistance values of overhead line towers and of the gantry tower are 35 Ω and 3.5 Ω, respectively. Critical point in the substation is considered, that is, the instrument voltage transformer in the line bay. Calculated waveshapes of lightning transients for different values of the phase angle of power frequency voltage are presented in Figure 6. It can be observed that the SA1-LA solution is much more efficient in reducing amplitudes of lightning transients compared to the SA1 solution in the case when lightning strikes the top of the gantry tower, especially if back-flashovers appear at the line insulators of gantry tower. In Figure 6(b), it can be observed that for some values of the phase angle of power frequency voltage, the back-flashover does not appear in the observed phase, but it appears in another one or two phases. Because of that, the voltage waveshape is flat, since there are no lightning transients in the observed phase but only the power frequency voltage.

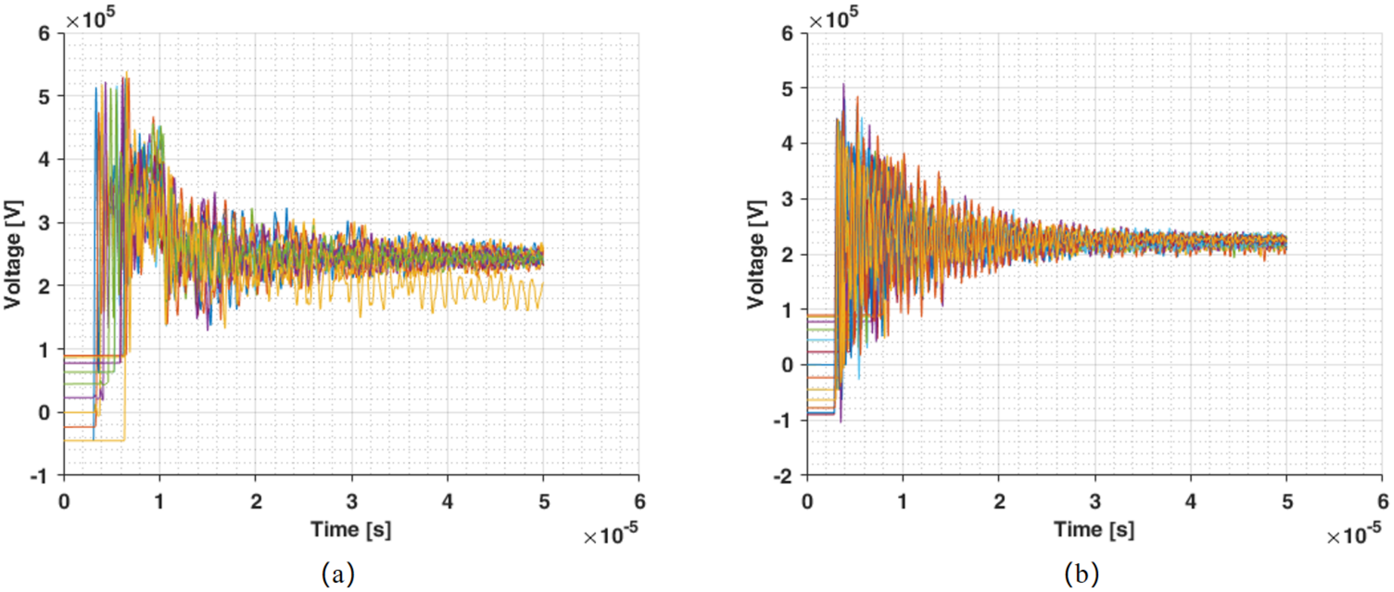
3.2 Lightning strikes to the top of the DCT

Calculated amplitudes of lightning transients for this case are presented in Figure 7. It can be observed that in the case of the installation of a set of surge arresters, SA1-LA voltage transformers in the line bay are not properly protected. Amplitudes of lightning transients are up to 571 kV, which is more than the BIL of the equipment (550 kV), Figure 7(a). Other equipment, including the 110 kV busbars, is properly protected. In the case that a set of surge arresters SA1 is installed in the standard way, the maximum amplitude of the lightning transient is 537 kV, Figure 7(b). This is lower than the BIL of the equipment at the 110 kV voltage level (550 kV), but a 10% safety margin is not satisfied. This is also lower compared to 571 kV, which is calculated in the case when the set of surge arresters SA1-LA is applied, showing that in this case, the SA1 solution is more efficient compared to the SA1-LA.



(a) (b) (c) (d) (e) (f) (g) (h) (i) (j)

Figure 7. Calculated amplitudes of lightning transients in the substation in the case of the lightning strike to the top of the DCT: (a) Point 1, SA1-LA, (b) Point 1, SA1, (c) Point 2, SA1-LA, (d) Point 2, SA1, (e) Point 3, SA1-LA, (f) Point 3, SA1, (g) Point 4, SA1-LA, (h) Point 4, SA1, (i) Point 5, SA1-LA, (j) Point 5, SA1.



(a) (b)

Figure 8. Calculated waveshapes of lightning transients at the voltage transformer in the line bay in the case of the lightning strike to the DCT for different values of the phase angle of power frequency voltage: (a) SA1-LA, (b) SA1.

Calculations are repeated to compare two solutions, assuming that the grounding resistance values of overhead line towers and of the gantry tower are 35 Ω and 3.5 Ω, respectively. Critical point in the substation is considered, that is, the instrument voltage transformer in the line bay. Calculated waveshapes of lightning transients for different values of the phase angle of power frequency voltage are presented in

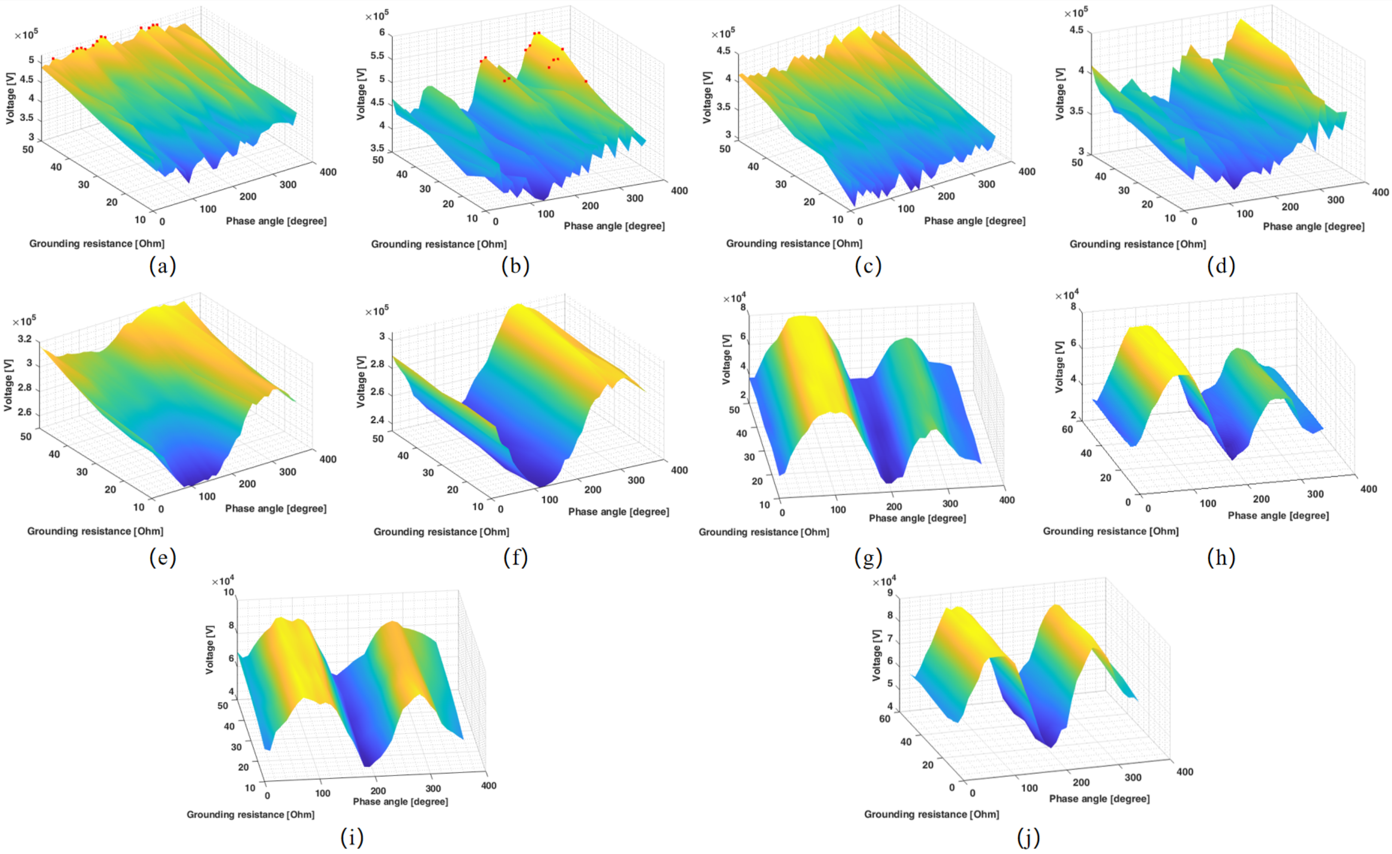


Figure 9. Calculated amplitudes of lightning transients in the substation in the case of the lightning strike to the top of the 3rd tower: (a) Point 1, SA1-LA, (b) Point 1, SA1, (c) Point 2, SA1-LA, (d) Point 2, SA1, (e) Point 3, SA1-LA, (f) Point 3, SA1, (g) Point 4, SA1-LA, (h) Point 4, SA1, (i) Point 5, SA1-LA, (j) Point 5, SA1.

Figure 8. It can be observed that the SA1-LA solution is in this case slightly less efficient compared to the SA1 solution.

3.3 Lightning strikes the top of the 3rd tower

Calculated amplitudes of lightning transients for this case are presented in Figure 9.

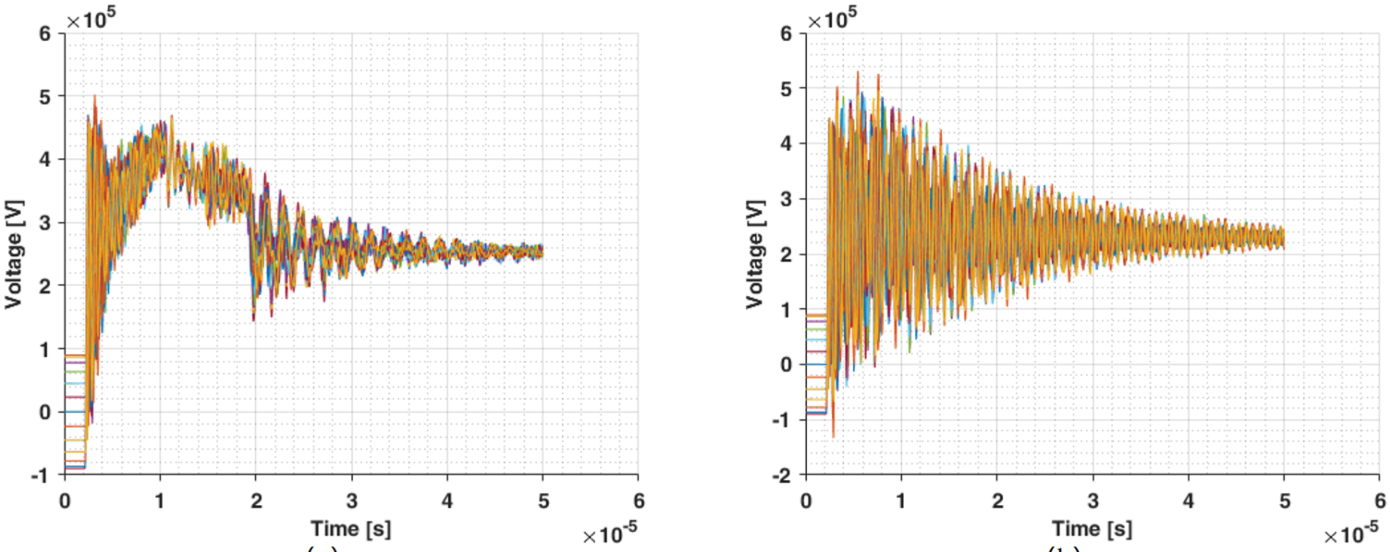
It can be observed that voltage transformers in the line bay, in the case of SA1-LA surge arrester application, are properly protected, except if the tower grounding resistance is 50 Ω when the amplitude of the lightning transient reaches 520 kV. In that case, the 10% safety margin is not satisfied. Other equipment, including the 110 kV busbars, is properly protected. In the case when the SA1 set of surge arresters is applied, the maximum amplitude of the lightning transient at the voltage transformer is 552 kV, which is higher than the BIL of the equipment (550 kV). Critical amplitudes of lightning transients in this case are reached in more calculation scenarios and for lower values of the tower grounding resistance compared to the SA1-LA solution. This means that in this case, protection is slightly more efficient when the SA1-LA set of surge arresters is applied, as in section 3.1.

Calculations are repeated to compare two solutions, assuming that the grounding resistance values of overhead line towers and of the gantry tower are 35 Ω and 3.5 Ω, respectively. Critical point in the substation is considered, that is, the instrument voltage transformer in the line bay. Calculated waveshapes of lightning transients for different values of the phase angle of power frequency voltage are presented in Figure 10. It is concluded that the SA1-LA solution is in this case slightly more efficient compared to the SA1 solution.

4 Calculated absorbed energy of the sets of surge arresters at the 110 kV voltage level

4.1 Lightning strikes the top of the gantry tower

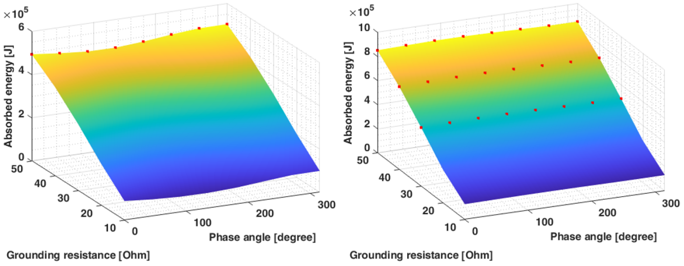
Calculated energy stress of surge arresters at the 110 kV voltage level of the substation in the case of a lightning strike to the top of the gantry tower when a set of surge arresters SA1-LA is applied is presented in Figure 11. The Maximum calculated energy stress in Figure 11 is up to 860 kJ (9 kJ/kV$_{Ur}$), which means that the energy class of selected surge arresters must be at least station



(a) (b)

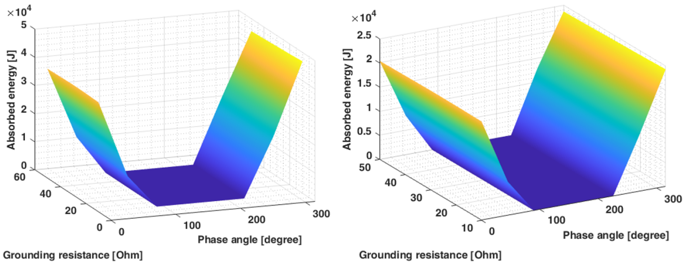
Figure 10. Calculated waveshapes of lightning transients at the voltage transformer in the line bay in the case of the lightning strike to the DCT for different values of the phase angle of power frequency voltage: (a) SA1-LA, (b) SA1.

medium, or station high [21].



(a) (b)

Figure 11. Calculated absorbed energy of surge arresters at the 110 kV voltage level of the substation in the case of a lightning strike to the gantry tower when the SA1-LA set of surge arresters is applied: (a) SA1-LA, (b) SA2.



(a) (b)

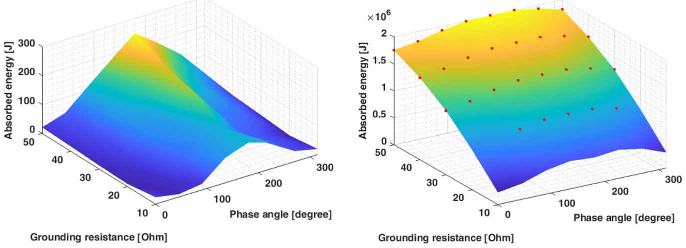
Figure 12. Calculated absorbed energy of surge arresters at the 110 kV voltage level of the substation in the case of a lightning strike to the gantry tower when the SA1 set of surge arresters is applied: (a) SA1, (b) SA2.

Calculated energy stress of surge arresters at the 110 kV voltage level of the substation in the case of a lightning strike to the top of the gantry tower when a set of surge arresters SA1 is applied are presented in Figure 12. In this case, surge arresters absorb very low energy and are not endangered by lightning strikes.

4.2 Lightning strikes to the top of the DCT

Calculated energy stress of surge arresters at the 110 kV voltage level of the substation in the case of a lightning strike to the top of the DCT when a set of surge arresters SA1-LA is applied is presented in Figure 13. Maximum calculated energy stress in Figure 13 is about 2000 kJ (20.8 kJ/kV$_{Ur}$), and this value is calculated for surge arresters installed in the transformer bay. This is extremely high energy stress, and it is difficult to find surge arresters that can absorb this amount of energy. At the same time, line arresters at the gantry tower absorb very low energy, about 300 J, which means that almost all energy is absorbed by the set of surge arresters installed near the power transformer. The reason for that is that standard station surge arresters are directly grounded to the substation grounding system and conduct large currents, while line arresters are grounded to the gantry tower, whose surge impedance limits the current conducted and energy stress. Also, since lightning transients come both at phase conductors and at the ground wires, the potential difference at the set of surge arresters installed at the gantry tower can be significantly lower compared to the surge arresters installed in the transformer bay.

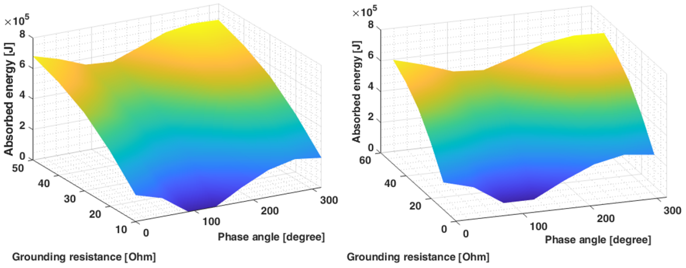
Calculated energy stress of surge arresters at the 110 kV voltage level of the substation in the case of a lightning strike to the top of the DCT when a set of surge arresters, SA1 is applied is presented in Figure 14. In this case, surge arresters absorb almost the same



(a) (b)

Figure 13. Calculated absorbed energy of surge arresters at the 110 kV voltage level of the substation in the case of a lightning strike to the DCT when SA1-LA set of surge arresters is applied: (a) SA1-LA, (b) SA2.

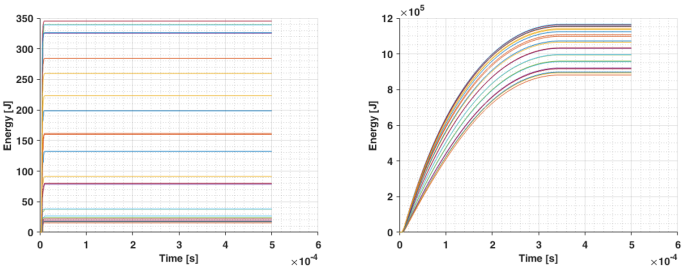
energy, up to 700 kJ $(7.3\ \text{kJkV}_{Ur})$, which means that the energy class of selected surge arresters must be at least station medium [21]. This means that two sets of standard station surge arresters installed between the phase conductors and the grounding system of the substation share well total energy stress, which leads to uniform energy dissipation.



(a) (b)

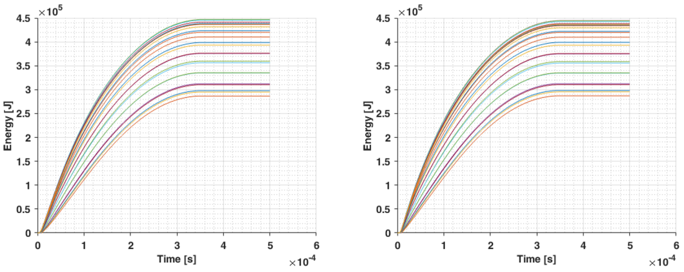
Figure 14. Calculated absorbed energy of surge arresters at the 110 kV voltage level of the substation in the case of a lightning strike to the DCT when the SA1 set of surge arresters is applied: (a) SA1, (b) SA2.

The calculations are repeated for the case when the grounding resistance values of overhead line towers and of the gantry tower are 35 Ω and 3.5 Ω, respectively, and for different values of the power frequency voltage phase angles. Calculated results are presented in Figure 15, in the case when the set of surge arresters SA1-LA is applied, and in Figure 16, in the case when the set of surge arresters SA1 is applied. Non-uniform energy stress of sets of surge arresters SA1-LA and SA2 can also be observed in this case, Figure 15. The maximum absorbed energy of surge arresters SA2 is in this case up to 1170 kJ $(12.2\ \text{kJ/kV}_{Ur})$, which means that the energy class of selected surge arresters must be station high [21]. In the case when the sets of surge arresters SA1 and SA2 are applied, Figure 16, energy stress is uniform and up to 450 kJ $(4.7\ \text{kJ/kV}_{Ur})$, which means that even the surge arresters with the energy class station low can fulfill requirements [21].



(a) (b)

Figure 15. Calculated absorbed energy of surge arresters at the 110 kV voltage level of the substation for different values of the power frequency voltage phase angle in the case of a lightning strike to the DCT when the SA1-LA set of surge arresters is applied: (a) SA1-LA, (b) SA2.



(a) (b)

Figure 16. Calculated absorbed energy of surge arresters at the 110 kV voltage level of the substation for different values of the power frequency voltage phase angle in the case of a lightning strike to the DCT when the SA1 set of surge arresters is applied: (a) SA1, (b) SA2

5 Conclusion

Based on the results presented, the following conclusions can be given:

- Surge arresters installed at the gantry tower are more efficient in reducing amplitudes of lightning transients in the substation in the case when lightning strikes the gantry tower. This solution is also slightly more efficient in the case when lightning strikes at the 3rd tower.
- Surge arresters installed in the line bay, between the phase conductor and substation grounding system, are slightly more efficient in reducing amplitudes of lightning transients in the substation in the case when lightning strikes a double circuit tower (DCT) in front of the substation.
- In the case when surge arresters are installed at the gantry tower, two sets of surge arresters at the 110 kV voltage level absorb almost the same energy when lightning strikes the gantry tower. In other cases, the sharing of energy stress between two sets of surge arresters is strongly non-uniform,

and the set of surge arresters installed in the transformer bay absorbs most of the energy. Consequently, these surge arresters must be selected with high energy absorption capability. In cases when the expected grounding resistance values of overhead line towers in front of the substation are high, this solution can be avoided because of the very high energy stress of surge arresters installed near the power transformer and the possibility of their thermal failures.

- In the case when surge arresters are installed in the standard way, between the phase conductors and the grounding system, two sets of surge arresters at the 110 kV voltage level have relatively uniform energy stress, and both sets of surge arresters can be selected with the same energy absorption capability. The probability of thermal failures of surge arresters installed in the transformer bay is significantly lower in this case, even for high values of grounding resistance of overhead line towers.
- In analyzed configuration, installation of the surge arresters in the line bay at the gantry tower is slightly better solution from the aspect of reduction of the amplitudes of lightning transients in the substation, while installation of the surge arresters in the line bay in standard way between the phase conductors and grounding system in significantly better from the aspect of energy stress sharing between the two sets of surge arresters at the 110 kV voltage level of the substation. Both solutions have some advantages and disadvantages, and neither solution is better in all cases.
- Optimum solution of installation of surge arresters in the transmission line bay must be found for every specific case separately, since calculated results are strongly influenced by the parameters of elements and configuration of the analyzed substation and connected lines.
- Standard surge arresters in the line bay can be a preferable solution because there is uniform energy stress sharing between the surge arresters installed in the line bay and transformer bay, and because it is easier to perform diagnostic tests of surge arresters during exploitation. Surge arresters at gantry tower can be applied in cases when compact substations need to be designed, or in cases when surge arresters must be retrofitted because they are not planned in the project documentation or are not installed in existing substations. However, in that case, it is more difficult to perform diagnostic tests of surge arresters during exploitation. Also, if possible, this solution can be avoided in cases where the grounding resistance of overhead line towers is very high.

Data Availability Statement

Data will be made available on request.

Funding

This work was supported without any funding.

Conflicts of Interest

The author declares no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

References

[1] Ioannidis, A. I., & Tsovilis, T. E. (2023). Evaluation of the Direct-Stroke Shielding Performance of Substations Through Stochastic Modeling of Lightning Attachment. *IEEE Transactions on Electromagnetic Compatibility*, *66*(2), 532-544. [CrossRef]

[2] Ioannidis, A. I., & Tsovilis, T. E. (2021). Shielding failure of high-voltage substations: A fractal-based approach for negative and positive lightning. *IEEE Transactions on Industry Applications*, *57*(3), 2317-2325. [CrossRef]

[3] Savic, M. S., & Savic, A. M. (2015). Substation lightning performance estimation due to strikes into connected overhead lines. *IEEE Transactions on Power Delivery*, *30*(4), 1752-1760. [CrossRef]

[4] Banjanin, M., Crnovčić, V., & Tomšič, M. (2024). Lightning protection of the 110 kV substation at the wind park Ivan Sedlo against transients caused by direct lightning strikes into connected overhead line. *International Journal of Electrical Engineering and Computing*, *8*(2), 43-52. [CrossRef]

[5] Banjanin, M., Taljan, U., Kanduč, P., Lavtar, M., & Radović, B. (2025). EMTP-ATP and MATLAB-Based Parameter Variation Calculations – Case Study of Lightning Protection of 110 kV Substation at the Wind Park. *B&H Electrical Engineering*, *19*(1), 45-51.

[6] Banjanin, M. S. (2017). Line Arresters Application in Lightning Protection of High Voltage Substations with Non-standard Configuration. *Electric Power Components and Systems*, *45*(11), 1173–1181. [CrossRef]

[7] Uglešić, I., Milardić, V., Filipović-Grčić, B., & Tokić, A. (2008). Preventing flashover near a substation by installing surge arresters. In *29th International Conference on Lightning Protection* (pp. 6-33).

[8] Franc, B., Filipović-Grčić, B., & Milardić, V. (2016). Lightning overvoltage performance of 110 kV air-insulated substation. *Electric Power Systems Research, 138*, 78-84. [CrossRef]

[9] Hosseini, S. A., Mirzaie, M., & Barforoshi, T. (2015). Impact of surge arrester number and placement on reliability and lightning overvoltage level in high voltage substations. *International Journal of Electrical Power & Energy Systems, 65*, 146-158. [CrossRef]

[10] Canadian-American EMTP User Group. (2011). ATP Rule Book. European EMTP–ATP Users Group Association. Retrieved from http://www.ee.mtu.edu/atp

[11] ATPDraw. (n.d.). ATPDraw (Version 7.6) [Computer software]. Retrieved from https://www.atpdraw.net/

[12] The MathWorks Inc. (2023). MATLAB (Version R2023b) [Computer software]. Retrieved from https://www.mathworks.com

[13] Grant, I. S. (1985). A simplified method for estimating lightning performance of transmission lines a report prepared by the working group on lightning performance of transmission lines. *IEEE Power Engineering Review*, (4), 48-48. [CrossRef]

[14] Whitehead, J. T., Chisholm, W. A., Anderson, J. G., Clayton, R., Elahi, H., Eriksson, A. J., ... & Renowden, J. R. (1993). Estimating lightning performance of transmission line 2–Updates to analytical models. *IEEE Transactions on Power Delivery (Institute of Electrical and Electronics Engineers);(United States)*, 8(3). [CrossRef]

[15] CIGRE Working Group 33.01. (1991). *Guide to Procedures for Estimating the Lightning Performance of Transmission Lines* (Technical Brochure No. 63). CIGRE.

[16] Imece, A. F., Durbak, D. W., & Elahi, H. (1996). Modeling guidelines for fast front transients. *IEEE Transactions on Power Delivery, 11*(CONF-950103-). [CrossRef]

[17] International Electrotechnical Commission. (2010). *Protection against lightning – Part 1: General principles* (IEC 62305-1, 2nd ed.). Geneva, Switzerland: IEC.

[18] International Electrotechnical Commission. (2004). *Insulation co-ordination - Part 4: Computational guide to insulation co-ordination and modeling of electrical networks* (IEC 60071-4, 1st ed.). Geneva, Switzerland: IEC.

[19] Mcdaniel, J., Chisholm, W. A., Abidin Ab Kadir, M. Z., Alba, J., Aguado, M., Ainscough, J., ... & Zessin, W. N. (2010). IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines (IEEE Std 1410™-2010). [CrossRef]

[20] International Electrotechnical Commission. (2010). *Insulation co-ordination—Part 1: Definitions, principles and rules* (IEC 60071-1:2006/AMD1:2010; 9th ed.) Retrieved from https://webstore.iec.ch/en/publication/577

[21] International Electrotechnical Commission. (2014). *Surge arresters—Part 4: Metal-oxide surge arresters without gaps for a.c. systems* (IEC 60099-4; 3rd ed.). Retrieved from https://webstore.iec.ch/en/publication/59657

Mladen Banjanin was born in Sarajevo, Yugoslavia, in 1988. He received his BSc degree in 2011 from the Faculty of Electrical Engineering, University of East Sarajevo, Bosnia and Herzegovina, and MSc and PhD degrees in 2012 and 2017, respectively, from the School of Electrical Engineering, University of Belgrade, Serbia. He is an associate professor at the Faculty of Electrical Engineering, University of East Sarajevo, and a visiting professor at the Faculty of Electrical Engineering, University of Banja Luka. His main areas of interest cover lighting protection, high voltage engineering, and power quality. (Email: mladen.banjanin@etf.ues.rs.ba)