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Lightning protection of the 110 kV substation at the wind park Ivan Sedlo against transients caused by direct lightning strikes into connected overhead line

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Abstract—**This paper deals with the lightning protection of 110 kV substation at the wind park Ivan Sedlo against transients caused by direct lightning strikes into connected 110 kV overhead line. Lightning protection level (LPL) I as per standard IEC 62305-1 is selected for this substation to reduce probability of equipment failure to low level. Calculations are done in the EMTP-ATP software. Three critical scenarios are analysed: shielding failure at the connected 110 kV overhead line, lightning strike to the top of first tower in front of the substation and lightning strike to the top of gantry tower at the entrance to the substation. It is presented that LPL I for analysed configuration of substation can be achieved by installing two sets of surge arresters. First set of surge arresters is installed in the transmission line bay, while second set of surge arresters is installed in the transformer bay. Transferred lightning transients through the power transformer are also calculated. It is presented that one additional set of surge arresters is necessary at the 30 kV side of the power transformer, to protected it against transferred lightning transients. Energy duty of all three sets of surge arresters is calculated. At the 110 kV voltage level energy stress of surge arresters is significant and strongly depends on the substation grounding resistance value. Estimated energy stress of set of surge arresters at the 30 kV voltage level is very low.**

Keywords-lightning protection; overhead line; shielding failure; substation; surge arrester; wind park

I. INTRODUCTION

Traditional electric energy sources in power systems are thermal and hydro power plants. These sources of electric power have a negative impact on the environment. Coal thermal power plants significantly pollute the environment due to the burning of enormous amounts of coal, while hydropower plants change the microclimate of a given area due to the existence of large water accumulation. Nuclear power plants, in the case of failures, can have a very negative impact on the environment and they represent potentially very dangerous facilities for a given area. Due to the aforementioned reasons, civilization is turning more and more to alternative sources of electric power. Those alternative sources of electricity are renewable electric energy sources, primarily those based on the wind energy and solar energy.

In recent years, many wind power plants have been built all around the world. The same trend is noticeable in the Republic of Srpska and Bosnia and Herzegovina. According to the transmission system operator in Bosnia and Herzegovina (NOS BIH), many wind parks are planned to be constructed and connected to the transmission system [1]. Their installed power is up to 84 MW per wind park, and it is interesting to note that all of them are planned to be connected to the 110 kV transmission system. Presently, at least five wind parks are finished in Bosnia and Herzegovina: wind park Mesihovina (50.6 MW), wind park Jelovača (36 MW), wind park Podveležje (48 MW), wind park Ivovik (84 MW) and wind park Ivan Sedlo (25 MW). For the construction of large wind parks significant financial resources are needed and the goal of investors is to return invested funds and to earn profit as soon as possible. One of the basic conditions to fulfil this is that wind park has maximum availability, which means that the number of unplanned outages should be minimized. This also means that the number of failures of equipment due to lightning strikes must be as low as possible.

Lightning protection of wind parks is very actual topic [2]-[6]. Proper lightning protection of wind turbine blades as well as of other parts of the wind park is essential for their long-term exploitation without failures [2]-[4]. Lightning protection of connecting overhead lines is also important to provide high availability of the wind park [5]. In general, wind parks represent perhaps the most endangered objects in the electric power system from the lightning strikes. There are several reasons for that. In areas with mountainous terrain, wind parks are built on or near the tops of mountains where the wind energy potential is the highest [6]. In such areas the terrain is very often rocky, so the grounding resistance values of transmission lines, substation and wind power plants can be high [7]. On the tops of mountains or in their vicinity, there is usually an increased density of lightning strikes, so the wind parks built at such locations are more endangered by lightning transients.

To ensure a small number of unplanned outages of wind park, it is essential to design its proper lightning protection. In this paper is analysed lightning protection of 110 kV main substation at the wind park Ivan Sedlo against transients caused by direct lightning strikes into connected double circuit 110 kV overhead transmission line. This wind park consists of 5 wind power plants and have a total installed power of 25 MW. The lightning protection level of the analysed substation is selected to be LPL I, as per IEC 62305-1 [8], to reduce probability of lightning caused failures to minimum value. This means that lightning protection of the substations needs to be implemented for lightning current amplitude equal to 200 kA, and for the waveshape 10/350 μs/μs. That can be an extremely difficult task if substation has non-standard configuration, as those analysed in [9], but in the case of onshore wind parks non-standard configurations of substations are rare. In the mountain regions, due to rocky terrain, grounding resistance values of substations and overhead line towers can be very high and implementation of the proper lightning protection can be challenging task.

The most important results presented in this paper are as follows: 1) configuration of surge arresters in 110 kV part of the substation is presented, including 30 kV side of the power transformer, and it provides LPL I (as per IEC 62305-1) for analysed substation in the case of direct lightning strikes into connected double circuit 110 kV overhead line even in the case of large values of grounding resistance of overhead line towers and substation, 2) efficiency of lightning protection is proved for three critical scenarios: lightning strikes into gantry tower, lightning strikes into first overhead line tower in front of the substation and shielding failure and direct lightning strike into the phase conductor at the overhead line in front of the substation, 3) lightning transients transferred to the 30 kV side of the substations are calculated, 4) energy stress of applied sets of surge arresters is calculated and it is presented that probability of their failures is very low, 5) models of all elements applied in calculations are defined, what enables extension of the presented procedure to other configurations of substations. Presented results are useful and important for other similar substations where highly efficient lightning protection of the equipment in the substation needs to be implemented. Presented analyses do not include lightning protection of the 30 kV switchgear and of the connecting power cables to the wind power plants, since more critical scenario for their protection are lightning strikes to the wind turbine blades.

Paper is structured as follows: in section II are described models of elements applied in calculations, in section III are listed parameters of elements and configuration of the substation analysed in calculations, in section IV are presented results of calculations for three analysed scenarios (shielding failure at the connected overhead line, lightning strikes to the top of gantry tower and lightning strikes to the top of the first overhead line tower in front of the substation), and last section V is conclusion.

II. Models of Elements Applied in Calculations

All calculations in this paper are done in EMTP-ATP software [10]. The models of elements applied in calculations are used from the international technical documents [8],[11]-[15], and from the scientific literature [9],[16]-[18] as follows:

- ✓ Double ramp lightning current waveshape is applied in calculations. In the case of direct lightning strikes to the top of the overhead line tower current wave parameters are 10/350 μs/μs [8] and lightning channel surge impedance is assumed to be 400 Ω [16], while in the case of shielding failures current wave parameters are 5.6/77 μs/μs [17] and lightning channel surge impedance is assumed to be 1000 Ω [16].
- ✓ Overhead line phase conductors and ground wire are modelled as lines with surge impedance equal to 450 Ω and 550 Ω, respectively [16]. Surge propagation velocity is equal to 300000 km/s. The first four overhead line spans in front of the substation have lengths as follows: 75 m, 204 m, 230 m, 238 m. Phase conductors and ground wires are matched with infinite lines.
- ✓ Overhead line towers are modelled as short lines with surge impedance equal to 165 Ω, while the gantry tower surge impedance is equal to 100 Ω. Surge propagation velocity is equal to 255000 km/s [11]. Grounding resistance of overhead line towers is assumed to be 50 Ω, while gantry tower and substation grounding resistance is assumed to be 5 Ω. High values of grounding resistance are assumed because of the rocky terrain and high specific soil resistivity. These values are varied in calculations.
- ✓ Overhead line tower grounding system is modelled by using Cigre ionization model [13].
- ✓ Line insulator flashover is modelled with leader progression model, as described in [17]. Flashover distance of the line insulators is equal to 0.8 m, and corresponding basic lightning insulation level is equal to 550 kV.
- ✓ Station surge arresters are modelled as a non-linear resistor [9],[15]. Non-linear *U-I* characteristics provided by manufacturer and measured with 8/20 μs/μs impulse current are given in Table I. Shaded fields in Table I are calculated by linear extrapolation of measured values. Connecting conductors from the surge arresters to the phase conductors and to the substation grounding system have lengths equal to 5.4 m (surge arrester in overhead line bay), 4 m (surge arrester at the 110 kV terminal of power transformer) and 1.5 m (surge arrester at the 30 kV terminal of power transformer).

TABLE I. NON-LINEAR U-I CURVES OF STATION SURGE ARRESTERS DEFINED BY THE MANUFACTURER FOR 8/20 µS/µS IMPULSE CURRENTS

Current	Surge arrester residual voltage	
	30 kV voltage level	*110 kV voltage level*
0.01 A	60.3 kV	208 kV
1 kA	63.0 kV	-
2.5 kA	67.0 kV	-
5 kA	70.0 kV	219 kV
10 kA	74.0 kV	230 kV
20 kA	84.0 kV	249 kV
40 kA	-	276 kV

- ✓ Power frequency voltage (50 Hz) at the phase conductors is modelled with three phase voltage sources. Critical values which lead to the maximum amplitudes of transient are applied in calculations [17].
- ✓ Inductive voltage instrument transformers are modelled with input surge capacitances assumed to be equal 0.5 nF [9].
- ✓ Two power cables in parallel at the 30 kV voltage level are modelled with equivalent surge impedance equal to 30 Ω, as a line with length equal to 25 m, and with the propagation velocity equal to 150000 km/s [9].
- ✓ Surge capacitances of the two winding 110/30 kV/kV power transformer are assumed to be equal: C_1=2 nF, C_{12}=3 nF, C_2=4 nF. Transformer neutral at the 110 kV voltage level is directly grounded, while at the 30 kV voltage level it is grounded by grounding resistor with resistance of 58 Ω. Transformer rated power is 31.5 MVA. No load loses of transformer are 100 kW, while short circuit impedance is 11%. BCTRAN transformer model is applied in calculations, with included surge capacitances C_1, C_{12} and C_2.

III. PARAMETERS OF ELEMENTS AND CONFIGURATION OF THE SUBSTATION APPLIED IN CALCULATIONS

In Fig. 1 is given tower head geometry of the first overhead line tower in front of the substation. Tower is double circuit and with one ground wire. Heights of the first five towers in front of the substation (to the lowest cross-arm) are as follows: 8 m (gantry tower), 29 m (first overhead line tower in front of the substation) and 20 m, 26 m and 26 m for other towers. Total heights to the top of towers are as follows: 13 m (gantry tower), 42 m (first overhead line tower in front of the substation) and 33 m, 39 m, 39 m for other towers.

In Fig. 2 is presented schematic representation of the substation applied for the equivalent circuit creation in software EMTP-ATP. Lengths of connecting conductors are as follows: d_1=2 m, d_2=2 m, d_3=28, d_4=3 m, d_5=24 m, d_6=3 m. Three critical scenarios are considered in calculations:

- (1) – lightning strike to the top of the first 110 kV overhead line tower in front of the substation.
- (2) – lightning strike to the top of the gantry tower at the entrance to the substation at the 110 kV voltage level.
- (3) – lightning strike to the upper phase conductor of the first 110 kV overhead line tower in front of the substation (shielding failure).

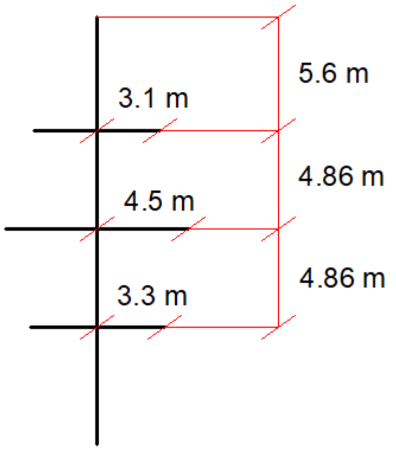


Figure 1. Head geometry of the first overhead line tower in front of the substation

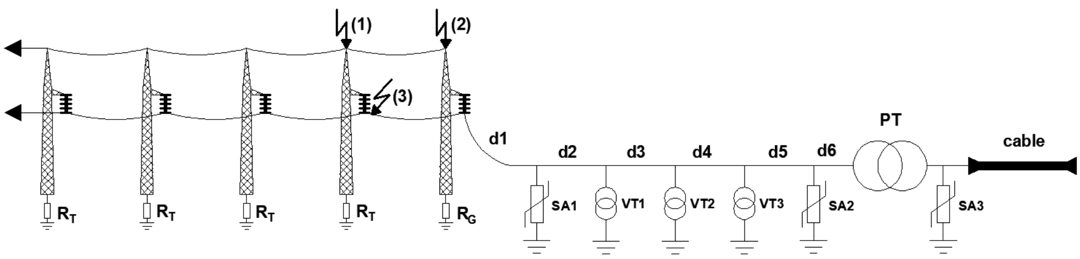


Figure 2. Schematic representation of the substation used for equivalent circuit creation in software EMTP-ATP

IV. Results of Calculations

A. Lightning strike to the upper phase conductor of the first 110 kV overhead line tower in front of the substation (shielding failure)

In this section is analysed scenario (3) from Fig. 2, that is direct lightning strike to the upper phase conductor of the first 110 kV overhead line tower in front of the substation (shielding failure).

Maximum shielding failure current is calculated by using electro-geometric model [19]. Equation (1) is used to calculate striking distances to the phase conductors and ground wires (r_C), and striking distance to the ground (r_G). Both striking distance values are in [m], while lightning current amplitude is in [kA].

$$r_C = 10 \cdot I^{0,65}$$
$$r_G = 0,9 \cdot r_C \qquad (1)$$

By using equation (1) and tower head geometry defined in Fig. 1 maximum shielding failure current amplitude is calculated, as illustrated in Fig. 3. It is equal to 27 kA. It is also calculated that shielding failure current amplitude is lower for middle and bottom phase conductors, as well as for other towers because of their lower heights.

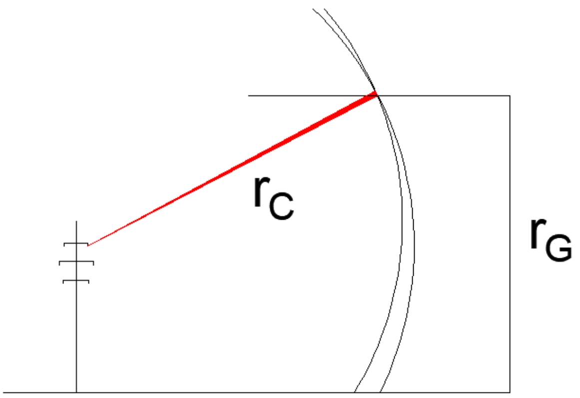


Figure 3. Maximum shielding failure current amplitude is calculated for the upper phase conductor of the first overhead line tower in front of the substation and it is equal to 27 kA

Shielding failures at the gantry tower are not possible because there are two ground wires between the first overhead line tower in front of the substation and gantry tower, as marked with red line in Fig. 4. Two ground wires are used to provide good protection against shielding failures, because geometry of phase conductors in this span is changed from vertical to horizontal.

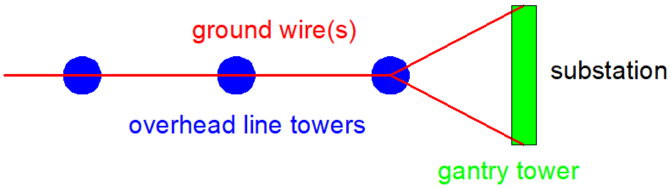
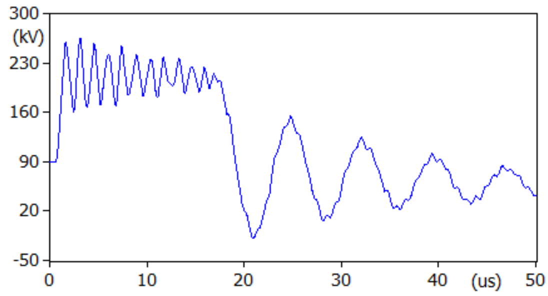


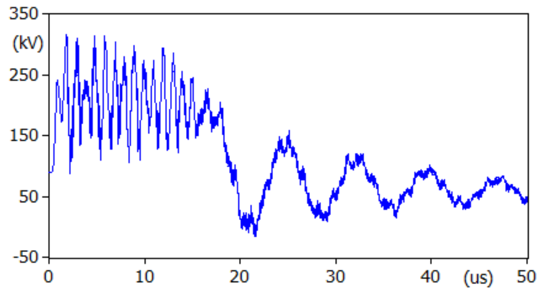
Figure 4. Configuration of ground wires between the first overhead line tower in front of the substation and gantry tower at the entrance to substation

In Fig. 5 are presented the waveshapes of calculated lightning transients in the substation, for the critical phase. In this case, grounding resistance of the transmission line towers has small influence on the amplitude of the transients in the substation, since the current flows through the grounding systems only after the flashover at the line insulators. The calculations were made for the 110 kV side of the power transformer, Fig. 5 a), instrument voltage transformer in the bus coupling bay, Fig. 5 b) and instrument voltage transformer in the transmission line bay, Fig. 5 c). The maximum amplitude of lightning transients appears at the instrument voltage transformer installed in the transmission line bay and its amplitude is about 369 kV, Fig. 5 c). The amplitude of transients is lowest at the power transformer, and it is about 270 kV, Fig. 5 a). The standard lightning impulse withstand voltages of the equipment (BIL) with rated voltage equal to 110 kV can be 450 kV, 550 kV or 650 kV, as per IEC 60071-1 [20]. Therefore, there is a significant safety margin between the maximum calculated amplitude of lightning transients and withstand voltage of equipment, regardless selected BIL value.

The calculations were repeated and lightning transients transferred through the power transformer from the 110 kV to the 30 kV side are calculated. Six single phase power cables, two in parallel per phase and with lengths equal to 25 m each, are connected to the 30 kV side of the power transformer. Critical scenario was assumed in calculations, the switch which connects power cables to 30 kV switchgear is opened and 30 kV power cables are open circuit. The lightning transient waveshapes for this case are presented in Fig. 6, for the critical phase. Lightning transient amplitude at the 30 kV side of the power transformer is about 41 kV, Fig. 6 a), and at the end of 30 kV power cable it is about 48 kV, Fig. 6 b). The lightning impulse withstand voltage of equipment in 30 kV system can be equal to 145 kV or 170 kV [20], so the equipment is adequately protected against transients which are transmitted through the power transformer from the 110 kV side to the 30 kV side.



a)



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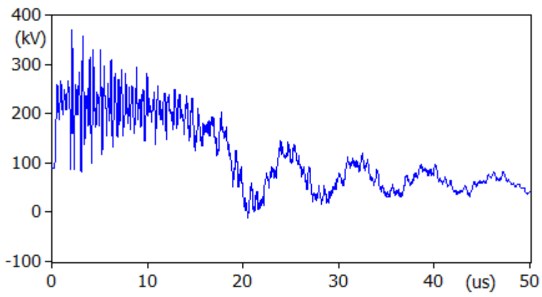
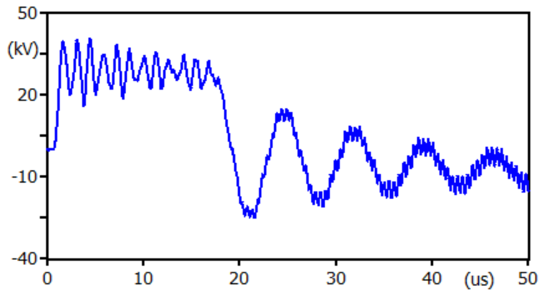


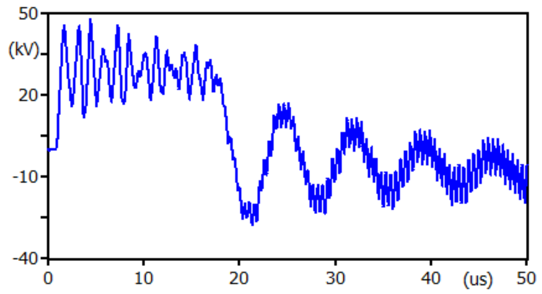
c)

Figure 5. Waveshapes of the lightning transients in critical phase in the 110 kV part of the substation for the case when lightning with current amplitude equal to 27 kA strikes upper phase conductor of the first tower in front of the substation: a) power transformer, b) instrument voltage transformer in the bus coupling bay, c) instrument voltage transformer in the transmission line bay

Currents conducted through the surge arresters installed at the 110 kV side of the substation in the case of shielding failure are presented in Fig. 7. Energy stress of the surge arresters for this case is very low, about 10 kJ and 4 kJ for Fig. 7 a) and Fig. 7 b), respectively. Low energy stress is calculated because of the low lightning current amplitudes and relatively short duration of the current waves in the case of shielding failures.

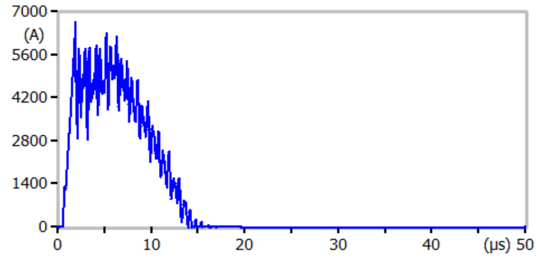


a)

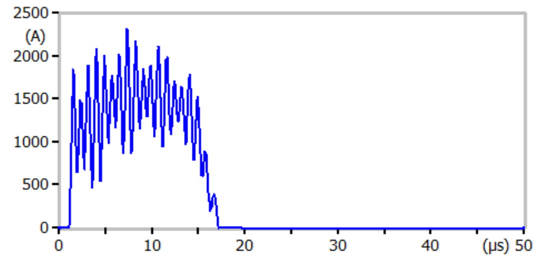


b)

Figure 6. Waveshapes of the lightning transients in critical phase in the 30 kV part of the substation for the case when lightning with current amplitude equal to 27 kA strikes upper phase conductor of the first tower in front of the substation: a) 30 kV side of the power transformer, b) opened end of the 30 kV power cables



a)



b)

Figure 7. Currents conducted through the surge arresters installed in the critical phase in 110 kV part of the substation: a) surge arrester installed in the transmission line bay, b) surge arrester installed in the transformer bay

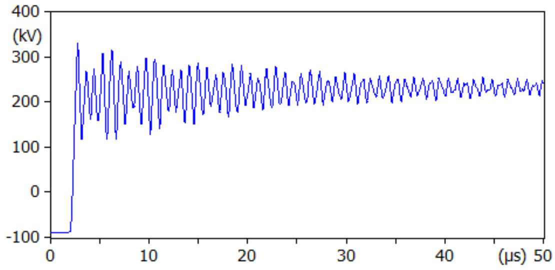
B. Lightning strike to the top of the first 110 kV double circuit overhead line tower in front of the substation

In this section is analysed scenario (1) from Fig. 2, that is direct lightning strike to the top of first double circuit 110 kV overhead line tower in front of the substation. Lightning current waveshape is assumed to be 10/350 µs/µs and with current amplitude equal to 200 kA, as per standard IEC 62305-1 and in accordance with Lightning Protection Level (LPL) I.

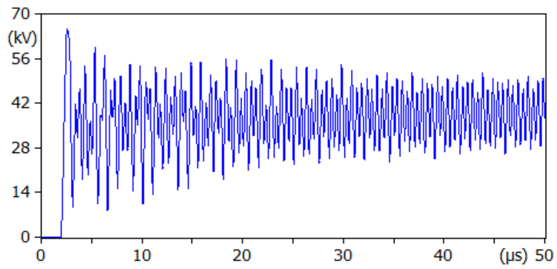
In Fig. 8 are presented the waveshapes of calculated lightning transients in the substation, in critical phase. The calculations were made for the power transformer both at the 110 kV (Fig. 8 a)) and at the 30 kV (Fig. 8 b)) voltage level, for the instrument voltage transformer in the bus coupling bay (Fig. 8 c)) and for the instrument voltage transformer in the transmission line bay (Fig. 8 d)). The BIL of equipment with rated voltage equal to 110 kV can be 450 kV, 550 kV or 650 kV, while at the 30 kV voltage level values can be 145 kV or 170 kV, as per IEC 60071-1. The amplitudes of calculated lightning transients presented in Fig. 8 are significantly lower than the withstand voltages of equipment, regardless the selected BIL value.

The calculations were repeated and lightning transients transferred through the power transformer from the 110 kV to the 30 kV side are calculated. The lightning transients waveshapes for this case in all three phases are presented in Fig. 9. In this case much higher amplitudes of lightning transients are calculated compared to the case from section A, but they are still significantly lower than the BIL of equipment. Amplitude of lightning transients at the end of the power cables are significantly higher in comparison with amplitudes of lightning transients at the beginning of the cables because of the voltage wave reflection at the opened end of power cables.

Energy stress of the station surge arresters at the 110 kV voltage level is significant in this case because of the high lightning current amplitude and long duration of the current front and tail of the wave. Critical case for calculation is that surge arrester grounding is ideal. Maximum energy stress in this case is about 917 kJ for both sets of arresters, in transmission line bay and in the transformer bay. If the grounding resistance of surge arresters is assumed to be 1.5 Ω, what is realistic case, energy stress of both sets of arresters is about 580 kJ. Typical energy class of station surge arresters is medium, and corresponding energy absorption capability of surge arresters is equal to 7.8 kJ/kV$_{Ur}$, what is equal to 749 kJ for arresters with rated voltage equal to 96 kV. It can be concluded that surge arresters' energy stress strongly depends on the substation grounding resistance values. Probability of surge arresters' failures is small even for this critical scenario when overhead line towers have very high grounding resistance value, while substation has small grounding resistance value and lightning current parameters have critical values (amplitude is equal to 200 kA, while current wave parameters are 10/350 µs/µs). Energy stress of surge arresters at the 30 kV side of the power transformer is very low.



a)



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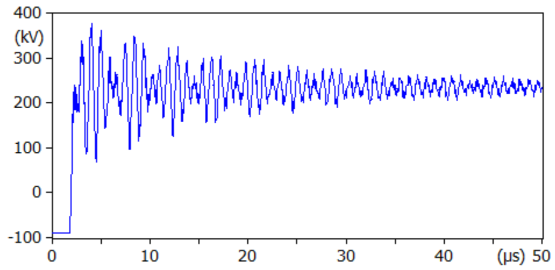

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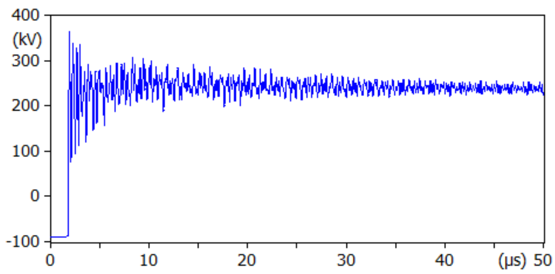
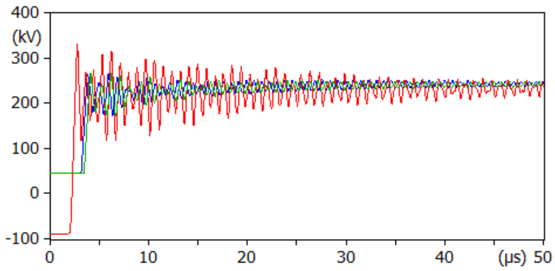
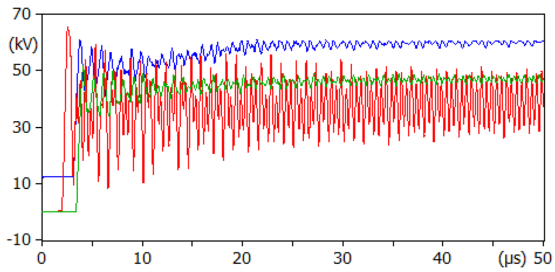


d)

Figure 8. Waveshapes of the lightning transients in the substation in critical phase for the case when lightning with current amplitude equal to 200 kA strikes top of the first tower in front of the substation: a) 110 kV side of the power transformer, b) 30 kV side of the power transformer, c) instrument voltage transformer in the bus coupling bay, d) instrument voltage transformer in the transmission line bay



a)



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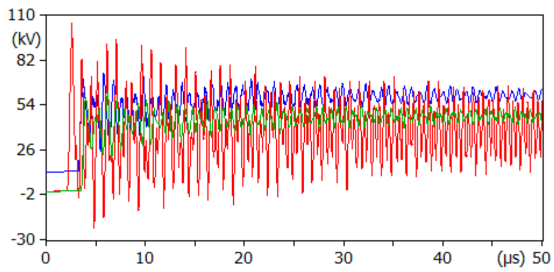


c)

Figure 9. Waveshapes of the lightning transients in the substation in all three phases for the case when lightning with current amplitude equal to 200 kA strikes top of the first tower in front of the substation: a) 110 kV side of the power transformer, b) 30 kV side of the power transformer, c) opened end of the 30 kV power cables

C. Lightning strike to the top of the gantry tower at the 110 kV voltage level

In this section is analysed scenario (2) from Fig. 2, that is direct lightning strike to the top of the gantry tower in front of the substation. Lightning current waveshape is assumed to be 10/350 μs/μs and with current amplitude 200 kA, as per standard IEC 62305-1 and in accordance with LPL I.

In Fig. 10 are presented the waveshapes of calculated lightning transients in the substation, in critical phase. The calculations were made for the power transformer both at the 110 kV (Fig. 10 a)) and at the 30 kV (Fig. 10 b)) voltage level, for the instrument voltage transformer in the bus coupling bay (Fig. 10 c)) and for the instrument voltage transformer in the transmission line bay (Fig. 10 d)). The BIL of equipment with rated voltage equal to 110 kV can be 450 kV, 550 kV or 650 kV, while at the 30 kV voltage level the values can be 145 kV or 170 kV, as per IEC 60071-1. The amplitudes of calculated lightning transients presented in Fig. 10 are high, especially at the instrument transformers placed at the bus coupling bay and in the transmission line bay. This scenario is critical for calculation because higher amplitudes of voltage transients are calculated compared to the results presented in sections A and B. Because of that more detailed calculations are done to investigate impact of the grounding resistance values on the calculated amplitudes of lightning transients.

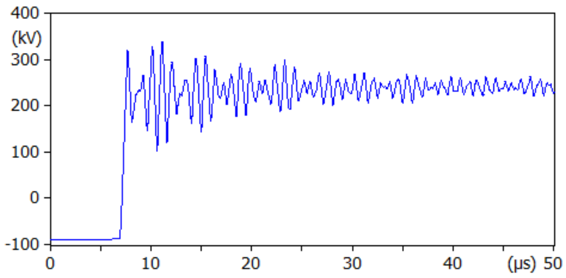
Amplitudes of the lightning transients in critical phase calculated for different values of the grounding resistance of transmission line towers and substation are given in Table II. Increase of the tower and substation grounding resistance values significantly increase amplitudes of lightning transients in the substation. For all values of the grounding resistances insulation of the 110 kV power transformer is properly protected, despite the selected BIL (450 kV, 550 kV or 650 kV at the high voltage side and 145 kV or 170 kV at the low voltage side). This is enabled by the surge arresters installed close to the 110 kV and 30 kV terminals of the power transformer. Instrument transformers installed in the transmission line bay and in the bus coupling bay can be damaged by lightning transients. Possible solution can be selection of the equipment with high BIL value equal to 650 kV. Even in this case, for very high values of the overhead line towers and substation grounding resistance (100 Ω and 8 Ω), there is a probability that lightning strike damage instrument transformers. However, probability of such scenario is very small since critical and low probability parameters and scenarios are applied in calculations.

Calculations of the lightning transients transferred through the power transformer from the 110 kV to the 30 kV side are done, and estimated results for all three phases are presented in Fig. 11. Amplitudes of lightning transients are still significantly lower than the BIL of equipment. Amplitudes of transferred lightning transients at the end of the power cables are significantly higher in comparison with amplitudes of lightning transients at the beginning of the cable (30 kV side of power transformer) because of the voltage wave reflection at the opened end of power cables. In this case, compared to the results from Fig. 9, back-flashovers in the two phases appear with some time delay compared to the back-flashover at the critical phase. That is caused by two reasons: 1) relatively low grounding resistance value of the gantry tower (5 Ω) compared to the value assumed for the overhead line towers (50 Ω), 2) different geometry of gantry tower compared to the geometry of the overhead line towers.

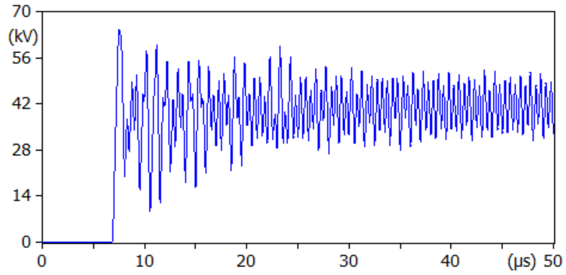
Energy stress of the station surge arresters at the 110 kV voltage level is significant in this case because of the high lightning current amplitude and long duration of the current front and tail of the wave. Same as in section B, in this case energy stress of surge arresters strongly depends on the substation grounding resistance values. Critical case for calculations is that arrester grounding is ideal. Maximum energy stress in this case is about 1182 kJ for surge arresters in the transmission line bay and 873 kJ for surge arresters in the transformer bay. If the grounding resistance of surge arresters is assumed to be 1.5 Ω, what is realistic case, energy stress of surge arresters is reduced to about 628 kJ and 530 kJ, respectively. Typical energy class of station surge arresters is medium, and corresponding energy absorption capability of surge arresters is equal to 7.8 kJ/kV_{Ur}, what is equal to 749 kJ for arresters with rated voltage equal to 96 kV. Probability of failures of surge arresters is small even for this critical scenario when overhead line towers have very high grounding resistance value, while substation has small grounding resistance value and lightning current parameters have critical values (amplitude is equal to 200 kA, and current wave parameters are 10/350 µs/µs). Energy stress of surge arresters at the 30 kV side of the substation is very low.

TABLE II. AMPLITUDES OF LIGHTNING TRANSIENTS IN CRITICAL PHASE FOR DIFFERENT VALUES OF THE GROUNDING RESISTANCE OF SUBSTATION AND OVERHEAD LINE TOWERS IN THE CASE WHEN LIGHTNING WITH CURRENT AMPLITUDE EQUAL TO 200 KA STRIKES TOP OF THE GANTRY TOWER

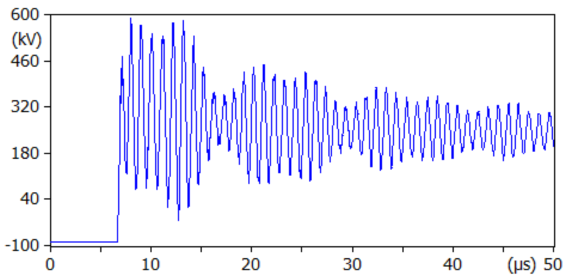
Grounding resistance		*Amplitudes of lightning transients*			
Overhead line towers	Substation	Instrument voltage transformer in the transmission line bay	Instrument voltage transformer in the bus coupling bay	110 kV side of the power transformer	30 kV side of the power transformer
10 Ω	2 Ω	410,4 kV	466,9 kV	278,4 kV	80,5 kV
25 Ω		434,1 kV	485,8 kV	285,0 kV	82,2 kV
50 Ω		442,4 kV	490,8 kV	287,8 kV	82,9 kV
100 Ω		447,7 kV	494,2 kV	289,7 kV	83,4 kV
10 Ω	5 Ω	595,6 kV	594,5 kV	339,3 kV	95,8 kV
25 Ω		602,9 kV	617,0 kV	339,9 kV	96,4 kV
50 Ω		608,0 kV	617,3 kV	338,3 kV	97,1 kV
100 Ω		613,6 kV	600,7 kV	338,1 kV	97,4 kV
10 Ω	8 Ω	635,5 kV	602,2 kV	340,3 kV	98,5 kV
25 Ω		643,4 kV	626,3 kV	343,6 kV	99,3 kV
50 Ω		647,5 kV	610,5 kV	352,2 kV	100,3 kV
100 Ω		653,7 kV	633,1 kV	342,6 kV	100,6 kV



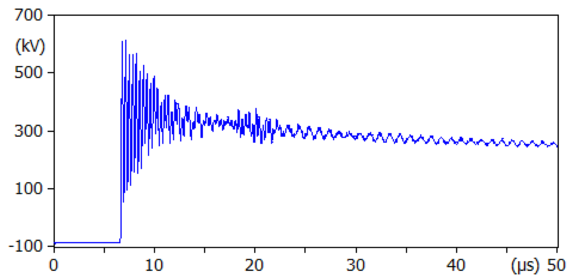
a)



b)



c)



d)

Figure 10. Waveshapes of the lightning transients in the substation in critical phase for the case when lightning with current amplitude equal to 200 kA strikes top of the gantry tower: a) 110 kV side of the power transformer, b) 30 kV side of the power transformer, c) instrument voltage transformer in the bus coupling bay, d) instrument voltage transformer in the transmission line bay

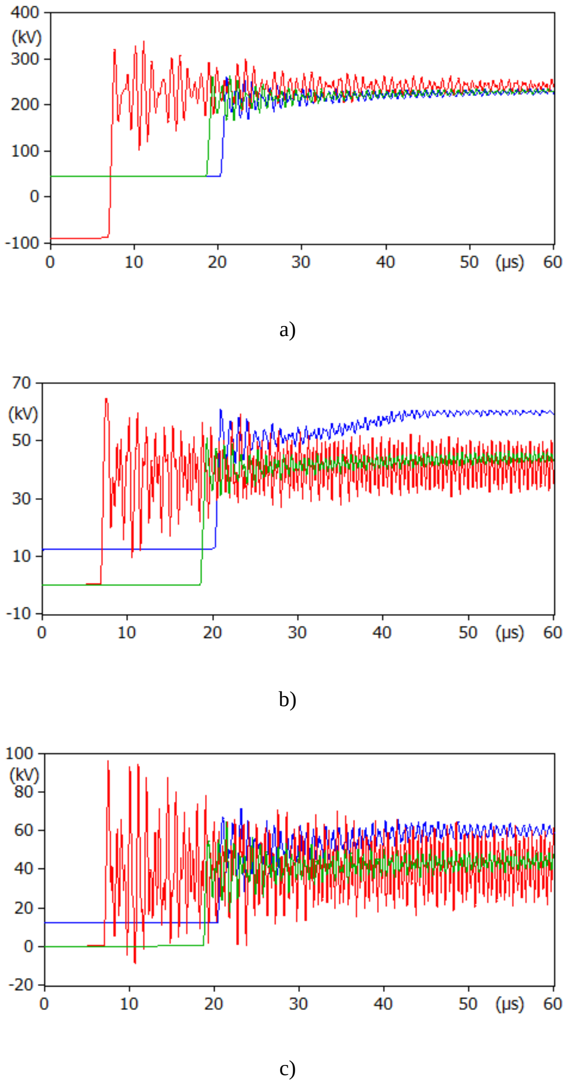


Figure 11. Waveshapes of the lightning transients in the substation in all three phases for the case when lightning with current amplitude equal to 200 kA strikes top of the gantry tower: a) 110 kV side of the power transformer, b) 30 kV side of the power transformer, c) opened end of the 30 kV power cables

V. Conclusions

In this paper is analysed lightning protection of the 110 kV substation at the wind park Ivan Sedlo. Highest level of lightning protection is achieved, LPL I as per standard IEC 62305-1. This means that lightning protection is efficient against direct lightning strikes with current amplitude equal to 200 kA and with the waveshape 10/350 μs/μs which appear to the connected 110 kV overhead line. This is done by installing three sets of station surge arresters: 1) first set of surge arresters is installed in the 110 kV transmission line bay to reduce amplitude of lightning transients which comes through the phase conductors into substation, 2) second set of surge arresters is installed in the 110 kV transformer bay, close to the transformer clamps to protected power transformer against lightning transients, 3) third set of surge arresters is installed at the 30 kV voltage level of power transformer, and protect it against transferred lightning transients from the 110 kV side. Presented analyses do not include lightning protection of the 30 kV switchgear and of the connecting power cables to the wind power plants. If the grounding resistance values of substation and overhead line towers are high, lightning performance of the substation can be improved by selecting equipment with lightning impulse withstand voltage equal to 650 kV. Energy stress of surge arresters is also analysed. In the 110 kV part of the substation energy duty of surge arresters is strongly influenced by the substation grounding resistance value. General conclusion is that the probability of surge arresters' failures is low even for the critical parameters of the lightning current and for the critical lightning strike point. However, several lightning strikes with very high current amplitudes can lead to degradation of surge arresters and necessity for their replacement. Transferred lightning transients from the 110 kV to the 30 kV side of power transformer are also calculated. Their amplitudes are slightly limited by surge arresters installed at the 30 kV side of power transformer and these transients are not danger for insulation of equipment. Energy stress of the surge arresters installed at the 30 kV side of the power transformer is low.

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