G Model
EPSR-4515; No. of Pages 7
ARTICLE IN PRESS
Electric Power Systems Research xxx (2015) xxx–xxx
Contents lists available at ScienceDirect
Electric Power Systems Research
journal homepage: www.elsevier.com/locate/epsr

Lightning overvoltage performance of 110 kV air-insulated substation

Bojan Franc, Božidar Filipović-Grčić*, Viktor Milardić

Faculty of Electrical Engineering and Computing, Department of Energy and Power Systems, University of Zagreb, Unska 3, 10000 Zagreb, Croatia

ARTICLE INFO

Article history:
Available online xxx

Keywords:
Lightning overvoltages
Overvoltage protection
110 kV air-insulated substation
EMTP simulations
Insulation coordination
Lightning location system

ABSTRACT

This paper presents an analysis of lightning overvoltage performance of 110 kV air-insulated substation connecting hydro power plant with the rest of the power system. The demonstrated procedure includes the application of a three-dimensional electro-geometric model of transmission line entering the substation, description of modeling process and EMTP simulations. Different overvoltage protection schemes were discussed including station surge arresters with different rated voltages and energy classes. The installation of line surge arresters on the first towers of the transmission line entering the substation for the improvement of the lightning performance of substation was analyzed.

Lightning parameters derived from lightning location system observations around 110 kV substation were analyzed and compared to ones used in literature and calculations. For this purpose an algorithm for the assessment of the lightning flash multiplicity was developed in order to determine the current amplitude probability distribution of the first and subsequent cloud to ground strokes. Energy absorbed by surge arresters due to multiple strokes was determined and an optimal overvoltage protection scheme was proposed.

1. Introduction

The magnitude and rate of rise of overvoltages due to lightning strikes on transmission lines is an important consideration for substation insulation and the strategy adopted for limiting these overvoltages. The transmission line faults caused by lightning can be classified into backflashovers and flashovers due to shielding failures. Both events cause overvoltages which travel toward the substation from the struck point. Attenuation due to high frequency nature of lightning overvoltages is caused by corona loss and skin effect. Therefore, usually lightning strokes that are close to the substation are considered when assessing overvoltage protection requirements and the associated risk of failure of the substation equipment. Insulation faults on a transmission line in front of substation can provoke short circuit currents with high magnitudes. The consequence of insulator flashover is the forming of a surge with a very steep front that enters the substation and causes insulation stress especially on windings of power transformers [1]. The procedure presented in this paper includes the application of a three dimensional electro-geometrical model (EGM) of 110 kV transmission line entering the substation, transient simulations in EMTP/ATP software and the evaluation of the lightning performance of substation equipment.

2. Electro-geometric model of 110 kV transmission line entering the substation

The goal of the EGM simulation is to determine the distribution of lightning current amplitudes which strike shield wire or phase conductor of the transmission line. The basic parameter needed for EGM simulation is the statistical distribution of lightning current amplitude. The distribution for negative lightning current amplitudes of the first stroke, suggested by Anderson [2] and adopted by IEC [3] is described by following expression:

$$P = \frac{1}{1 + \left(I/31\right)^{2.6}} \tag{1}$$

where P is a probability of occurrence of lightning current amplitude higher than I. The general expression for the striking distance R is represented by the following equation:

$$R = a \cdot I^{b} \tag{2}$$

The striking distance can vary significantly and therefore different values of constants and modifications of the above equation are proposed by various investigators [4]. The expression for the striking distance recommended by IEEE WG with constants $a = 8$, $b = 0.65$ was used in simulations.

* Corresponding author. Tel.: +385 1 6129 714; fax: +385 1 6129 890.
E-mail addresses: bojan.franc@fer.hr (B. Franc), bozidar.filipovic-grcic@fer.hr (B. Filipović-Grčić), viktor.milardic@fer.hr (V. Milardić).

http://dx.doi.org/10.1016/j.epsr.2015.12.002

Please cite this article in press as: B. Franc, et al., Lightning overvoltage performance of 110 kV air-insulated substation, Electr. Power Syst. Res. (2015), http://dx.doi.org/10.1016/j.epsr.2015.12.002

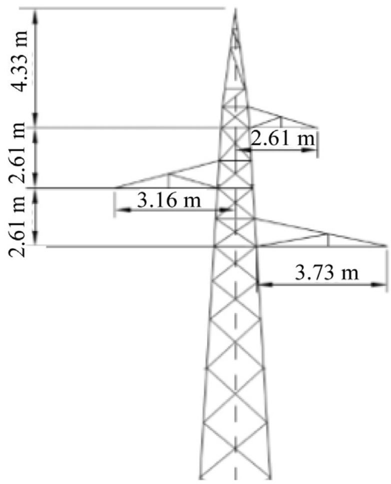

Fig. 1. 110 kV transmission line tower.

A first few spans of a single-circuit 110 kV transmission line with single shield wire entering the substation were considered in EGM (Fig. 1).

In order to collect enough data for the statistical calculation, the Monte Carlo simulations were conducted for a large number of generated lightning current amplitudes. The simulations were carried out until 1000 lightning strokes ended at phase conductors and 72,059 ended at towers and shield wire. The highest amplitude of lightning current impacting phase conductors was 14.2 kA. Fig. 2 shows the probability distribution of lightning current amplitudes impacting phase conductors.

54.3% of strokes impacting phase conductors finished in the upper phase which is most exposed to direct lightning strokes, while 36.1% and 9.6% strokes finished in the middle and lower phase, respectively. Fig. 3 shows the probability distribution of lightning current amplitudes impacting shield wire and towers.

3. Modeling of 110 kV transmission line and air-insulated substation

Single-circuit 110 kV transmission line with one shield wire entering the air-insulated substation was modeled in EMTP/ATP software. The model shown in Fig. 4 represents the most unfavorable operating switching configuration of the substation with respect to lightning overvoltages: single transmission line bay, transformer bay and measuring bay in operation. Overvoltages were calculated on the substation equipment marked in Fig. 4: (1)

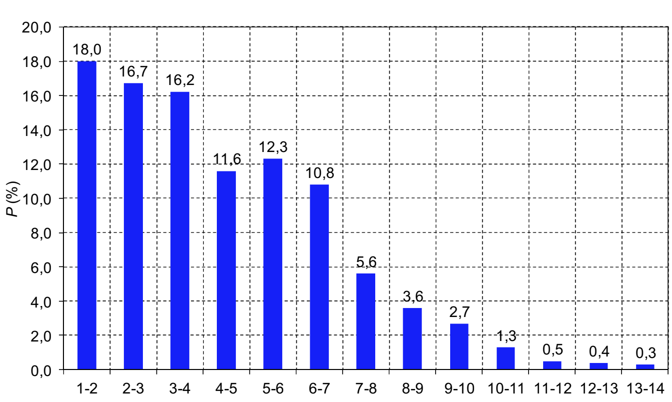

Fig. 2. Probability distribution of lightning current amplitudes impacting phase conductors.

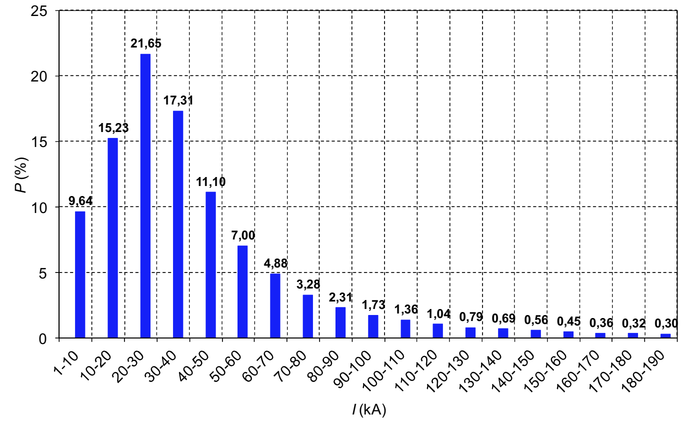

Fig. 3. Probability distribution of lightning current amplitudes impacting shield wire and towers.

voltage transformers in line bay; (2) current transformers in line bay; (3) circuit breakers in line bay; (4) circuit breakers in transformer bay; (5) current transformers in transformer bay; (6) power transformer; (7) voltage transformers in measuring bay.

The calculations of lightning overvoltages were carried out in case when lightning strikes upper phase conductor and shield wire at the first tower close to substation.

Three different overvoltage protection schemes were analyzed:

(A) Surge arresters (SAs) with U_r = 96 kV in transformer bay and SAs with U_r = 144 kV in line bay.
(B) SAs with U_r = 102 kV installed in line bay and in transformer bay.
(C) SAs with U_r = 102 kV installed in line bay, transformer bay and in all phases of the first three towers entering the substation.

The first protection scheme (A) represents the situation where SAs in line bay and transformer bay have different rated voltages. This protection scheme was analyzed in order to determine the influence of SA's rated voltage on overvoltage protection and energy sharing between arresters.

The second protection scheme (B) represents the situation where SAs in line bay and transformer bay have the same rated voltage selected according to [5].

The third protection scheme (C) represents the situation where SAs with the same rated voltage are installed in line bay, transformer bay and in all phases of the first three towers entering the substation. This protection scheme was analyzed in order to determine the influence of line surge arresters (LSAs) on overvoltage protection inside the substation. Energy sharing between LSAs and substation SAs was analyzed in case of multiple lightning strokes.

The transmission line conductors and shield wire were represented by frequency-dependent model in EMTP and five spans close to substation were taken into account. To avoid reflections of traveling waves, the line was terminated with multiphase matching resistance on one end.

Surge impedances of the transmission line towers [3] were determined by using the following equation:

$$Z = 60 \cdot \left\{ \ln\left(\frac{H}{R}\right) - 1 \right\} \quad (3)$$

where H represents tower height and R equivalent radius of a tower base. Each tower was divided in four parts: the first part from tower top to upper arm, the second one from upper arm to middle arm, the third part from middle arm to lower arm and the last part from lower arm to the ground. This way it was possible to calculate transient voltages of tower arms.

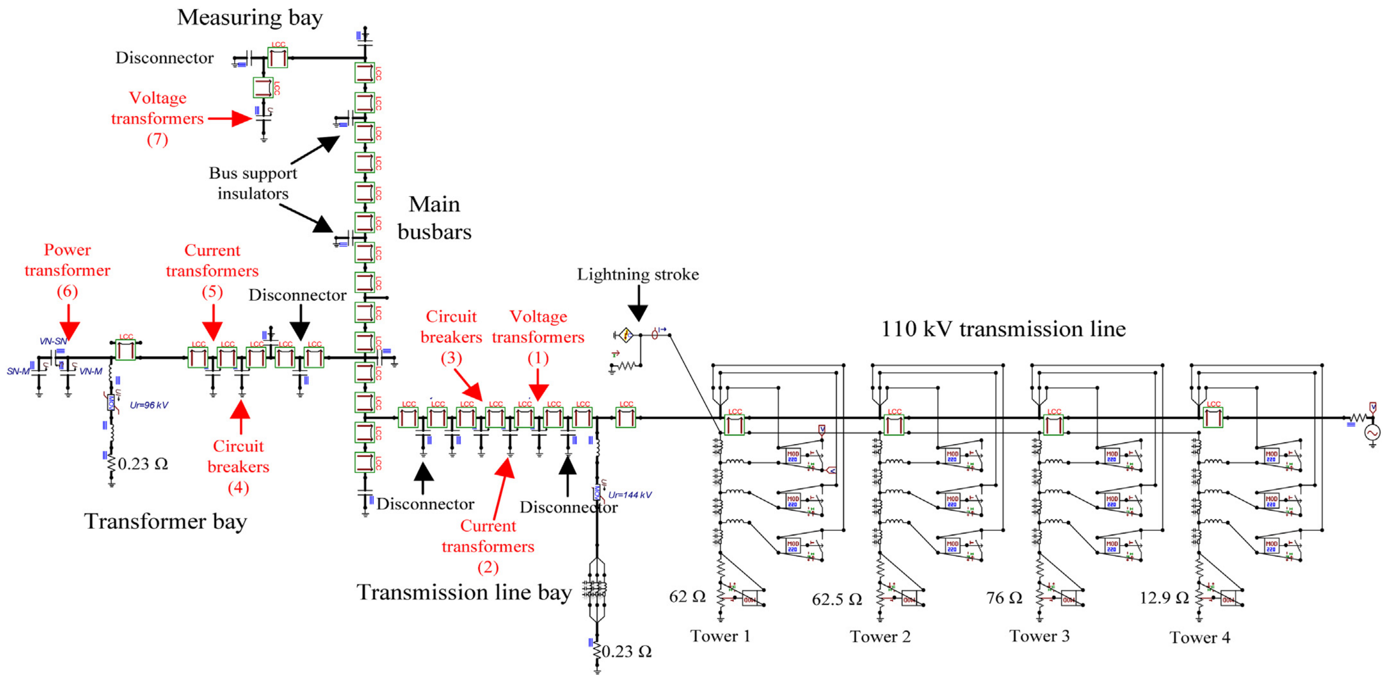

Fig. 4. Model of 110 kV transmission line and substation in EMTP/ATP. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Tower footing resistances were modeled taking into account soil ionization [3] caused by lightning current. Tower grounding was represented as non-linear resistor using MODELS language and TACS-controlled time-dependent resistor.

The important parameter for the behavior of overhead line insulation subjected to lightning overvoltages is its corresponding flashover voltage, which depends on the voltage level and insulation clearances. The flashover mechanism of the transmission line insulators was represented with differential Eq. (4) of the leader progression model selected by the CIGRE WG 33-01[4].

$$v(t) = k_L u(t) \left[\frac{u(t)}{x} - E_0 \right] \tag{4}$$

In Eq. (4), $u(t)$ is the voltage as a function of time, x is the distance of the unbridged gap, E_0 is the gradient at which the breakdown process starts, and k_L is a constant [6]. Insulator flashover was modeled using MODELS language in EMTP/ATP. The calculated volt-time characteristic of a 110 kV insulator string for a standard lightning impulse voltage waveform 1.2/50 µs is shown in Fig. 5.

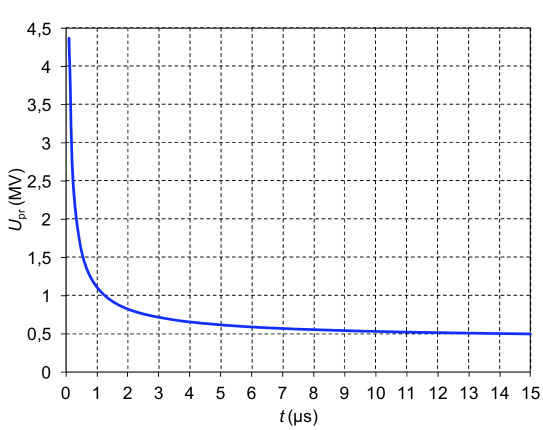

Fig. 5. Calculated volt-time curves of the 110 kV insulator strings (for 1.2/50 µs waveform).

The equipment in high voltage substation was represented by surge capacitances obtained from manufacturer's data, whereas busbars and connecting leads were represented by a frequency-dependent transmission line model [7].

The model of gapless type SA includes non-linear and dynamic behavior of the arrester. The non-linear behavior was represented with the U–I characteristics depicted in Fig. 6. A frequency-dependent SA model [8] was used in simulations. The parameters of the SA model were identified using expressions that require only the data reported in manufacturers' datasheets. The arrester leads were represented by inductance of 1 µH/m taking into account the effects of additional voltage rise across the lead inductance.

The lightning stroke hitting a tower or a phase conductor was represented by a CIGRE concave shape [3] shown in Fig. 7. The peak current magnitude and the tail time are important when observing the SA energy, while the influence of the rise time is hardly noticeable in such a case. In contrast, the current wave front is an important parameter with regard to insulator flashover. The CIGRE concave shape shown in Fig. 7 represents more accurately the concave front of a lightning stroke and usually gives more realistic results.

The majority of lightning flashes comprise multiple strokes which occur a few milliseconds of each other. These lightning strokes can be especially dangerous for SAs because they require

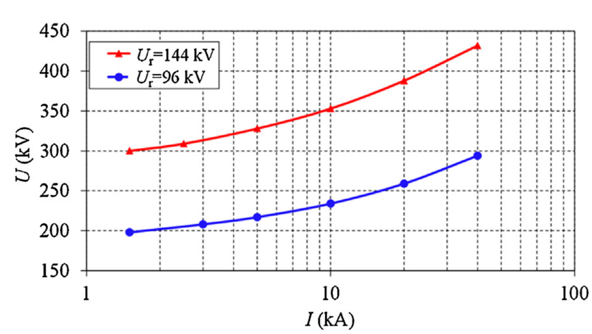

Fig. 6. Nonlinear U–I characteristics of the SAs with U_r = 144 kV and U_r = 96 kV recorded with the current impulse 8/20 µs.

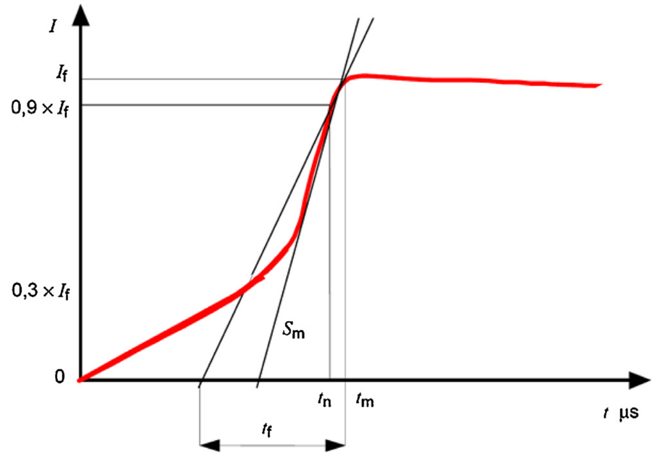

Fig. 7. CIGRE concave shape (I_f is the crest current, S_m is the maximum front steepness, t_f is the equivalent front duration).

dissipation of a large amount of energy which results in heating of metal-oxide blocks. However, SAs must be capable of dissipating multiple lightning strokes without deterioration and therefore it is important to select the appropriate energy class. Two negative lightning flashes were simulated comprising the first and following stroke:

- strokes to tower: first stroke 100 kA, 9.9/200 µs and following stroke 40 kA, 4.5/140 µs;
- strokes to phase conductor: first stroke 14.2 kA, 2.3/200 µs and following stroke 5.68 kA, 1.3/140 µs.

Amplitude and duration of the strokes, i.e. time to half value have the greatest impact on the SA energy [9]. The amplitudes of the first strokes were selected based on the results of EGM, while the amplitudes of the subsequent strokes were assumed to have 40% of the first stroke amplitude. Time to half values for the first and following strokes were selected according to [4], with only 5% probability of being exceeded.

The lightning parameters are essential input variables for estimating the effectiveness of overvoltage protection. More recent direct lightning current measurements were obtained from instrumented towers in Austria, Germany, Canada and Brazil, as well as from rocket-triggered lightning [10]. Further, modern lightning location systems (LLSs) report peak currents estimated from measured electromagnetic field peaks. The available technology for detecting and locating cloud to ground (CG) lightning has significantly improved over the last decades. LLS data have the advantage of covering extended areas on a continuous basis and can therefore observe the related exposure of objects to the lightning threat. Therefore, the analysis of lightning activity around 110 kV substation obtained from LLS was performed.

The lightning activity was observed for a 6 year period within a radius of 10 km from 110 kV substation. This area covers the most exposed part of 110 kV transmission line corridor extending over a mountain area. Data were obtained from LLS [11], which is capable of detecting multiple-stroke flashes where every stroke is represented by individual set of data (current amplitude, discharge time, location, etc.). CG flashes consist of one or several strokes coming in very short temporal intervals and close spatial proximity. The common method for grouping stroke data into flashes is using the thresholds for maximum temporal separation and maximum lateral distance between successive strokes. For this purpose an algorithm for grouping of lightning strokes into flashes (assessment of the lightning stroke multiplicity) was developed in order to determine the current probability distribution of the first and subsequent CG strokes. The multiplicity was calculated for a maximum temporal separation of 200 ms and a maximum lateral distance of 2 km between successive strokes [12]. A total of 7762 negative CG strokes were detected, consisting of 4999 first strokes and 2763 subsequent strokes, with an average stroke multiplicity of 1.55 strokes per flash. Fig. 8 shows the comparison between cumulative frequency distributions of negative CG lightning current amplitudes obtained from LLS and IEEE.

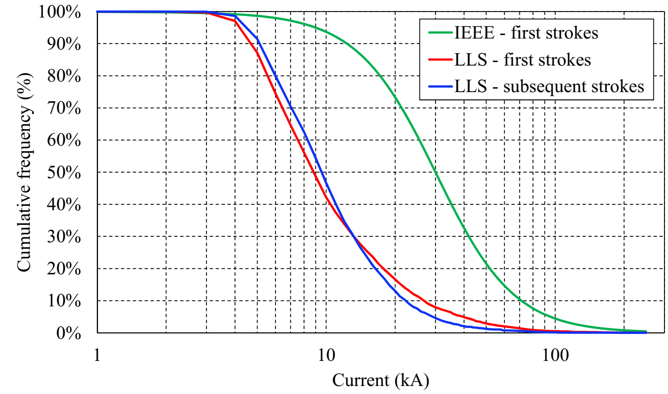

Fig. 8. Comparison between cumulative frequency distributions of negative CG lightning current amplitudes obtained from LLS and IEEE.

Table 1
Parameters of negative first and subsequent strokes.

	Average value LLS (kA)	Median value LLS (kA)	Median value IEEE (kA)
First strokes	13.6	8.8	31.1
Subsequent strokes	12.4	9.5	12.3

Fig. 8 shows that according to data from LLS, there is a significantly higher probability of lightning strokes occurrence with lower current amplitudes, compared to IEEE data. This difference is caused by sensitivity of LLS which is capable of detecting multiple CG strokes with low current amplitudes. Table 1 shows average and median values of all first and all subsequent strokes detected by LLS and according to IEEE.

LLS data gives lower median values of current amplitudes both for first and subsequent strokes. Table 2 shows the average and median values of first and subsequent strokes in shielding failure domain ($I < 13$ kA) and backflash domain ($I \geq 13$ kA) detected by LLS. In backflash domain first strokes have higher median value, while in shielding failure domain subsequent strokes have higher median value. The analysis of LLS data showed that the lightning current parameters of the first and subsequent strokes used in the simulations were conservative and on the "safe side".

4. Simulation results

4.1. Lightning overvoltages

The rated lightning impulse withstand voltage of substation equipment is 550 kV, while the coordination lightning impulse

Table 2
Parameters of negative first and subsequent strokes in shielding failure and backflash domain.

	$I < 13$ kA		$I \geq 13$ kA	
	Average value (kA)	Median value (kA)	Average value (kA)	Median value (kA)
First strokes	7.3	6.9	28.0	20.9
Subsequent strokes	7.8	7.5	22.6	18.6

Please cite this article in press as: B. Franc, et al., Lightning overvoltage performance of 110 kV air-insulated substation, Electr. Power Syst. Res. (2015), http://dx.doi.org/10.1016/j.epsr.2015.12.002

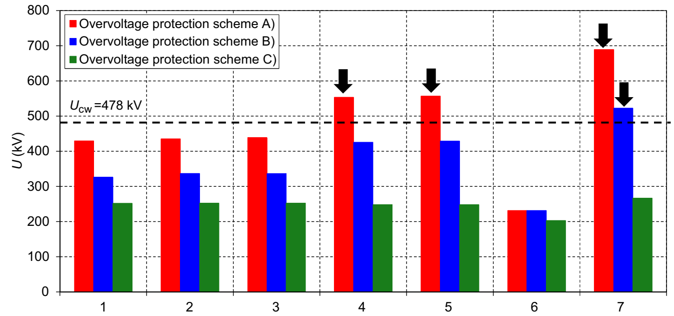

Fig. 9. Overvoltages on substation equipment in case of lightning stroke 50 kA (5.9/77.5 μs) to tower 1.

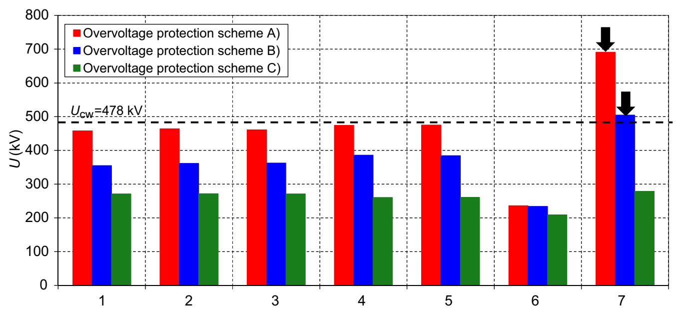

Fig. 10. Overvoltages on substation equipment in case of lightning stroke 75 kA (7.9/77.5 μs) to tower 1.

withstand voltage U_{cw} = 478 kV was determined for safety factor K_s = 1.15 [13]. Overvoltages were calculated on the substation equipment marked with red color at Fig. 4: (1) voltage transformers in line bay; (2) current transformers in line bay; (3) circuit breakers in line bay; (4) circuit breakers in transformer bay; (5) current transformers in transformer bay; (6) power transformer; (7) voltage transformers in measuring bay. Figs. 9–11 show overvoltage amplitudes on substation equipment in case of lightning strokes to tower 1 with current amplitudes 50 kA, 75 kA and 100 kA.

In case of overvoltage protection scheme (A) lightning overvoltages on substation equipment (2, 4, 5 and 7) exceeded critical value of U_{cw} = 478 kV. Overvoltages were highest in this case due to relatively high rated voltage of SAs in line bay.

In case (B) overvoltages were reduced with regard to case (A), due to lower rated voltage of SAs in line bay. However, overvoltages on voltage transformers in measuring bay still exceeded U_{cw}. The calculation results showed that in all cases lightning overvoltages were highest on voltage transformers in measuring bay since they are furthest away from the SAs with respect to other equipment. Also, reflections of traveling waves occurred at the end of 110 kV busbars where voltage transformers were installed.

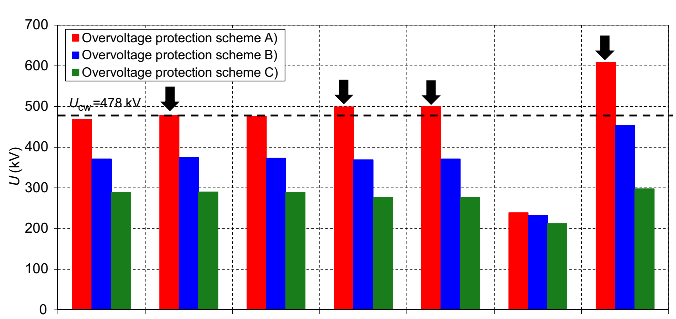

Fig. 11. Overvoltages on substation equipment in case of lightning stroke 100 kA (9.8/77.5 μs) to tower 1.

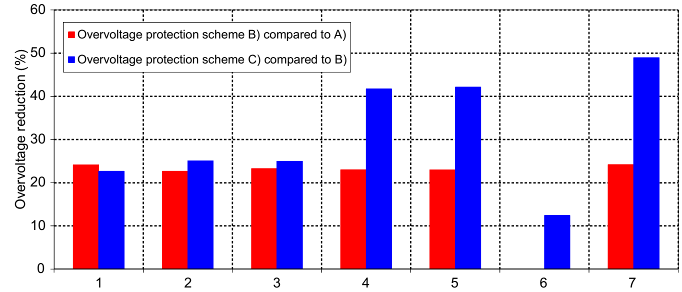

Fig. 12. Percentage reduction of overvoltages on substation equipment in case of lightning stroke 50 kA to tower 1.

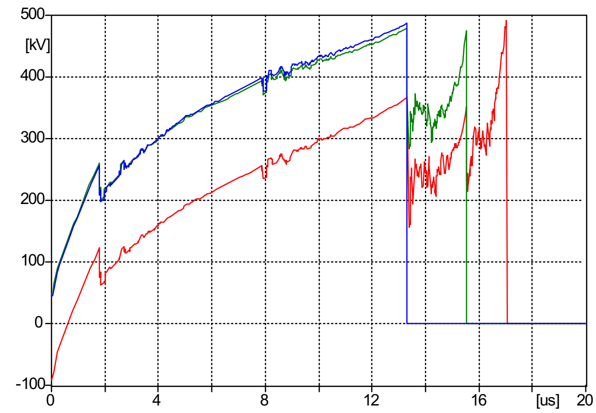

Fig. 13. Overvoltages on insulators of the first tower.

In case (C) overvoltages were further reduced compared to case (B). In this case with LSAs installed in all phases of the first three towers entering the substation, overvoltages on all substation equipment were lower than U_{cw}.

Fig. 12 shows percentage reduction of overvoltages on substation equipment in case of lightning stroke 50 kA to tower 1.

A significant overvoltage reduction on all substation equipment was obtained with application of LSAs, especially on voltage transformers in measuring bay. Figs. 13 and 14 show calculated overvoltages on insulators of the first tower and on voltage transformers in measuring bay in case (A) and 100 kA lightning stroke to first tower. Backflashover occurred in all phases and overvoltages in measuring bay exceeded U_{cw}. Fig. 15 shows overvoltage amplitudes on substation equipment in case of lightning stroke 14.2 kA (2.3/77.5 μs) to upper phase conductor at tower 1.

In this case amplitudes were below U_{cw} for all overvoltage protection schemes. Figs. 16 and 17 show calculated overvoltages on

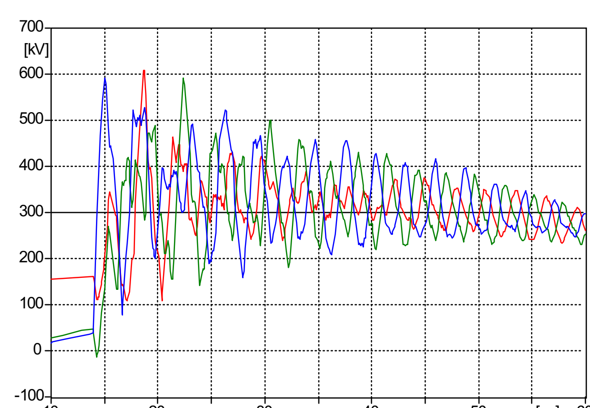

Fig. 14. Overvoltages on voltage transformers in measuring bay.

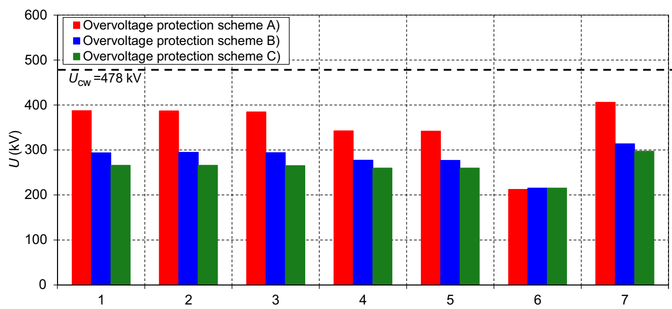

Fig. 15. Overvoltages on substation equipment in case of lightning stroke 14.2 kA (2.3/77.5 μs) to upper phase conductor at tower 1.

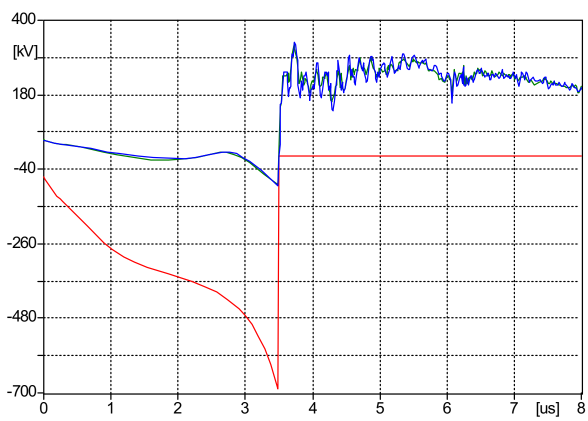

Fig. 16. Overvoltages on insulators of the first tower. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

insulators of the first tower and on power transformer in case (A) and 14.2 kA lightning stroke to upper phase conductor. Flashover occurred in upper phase (marked red on Fig. 16) and overvoltages on power transformer were lower than U_{cw}.

4.2. Surge arrester energy

SA energy was calculated in case of lightning stroke to tower 1 with current amplitudes 30 kA–100 kA and in case of lightning stroke to upper phase with current amplitudes 10 kA and 14.2 kA. SA energies in case of overvoltage protection schemes (A) and (B) are shown in Figs. 18 and 19.

In case (A) (Fig. 18), energy of SAs in transformer bay was higher than in line bay, due to their lower rated voltage. In case (B) (Fig. 19),

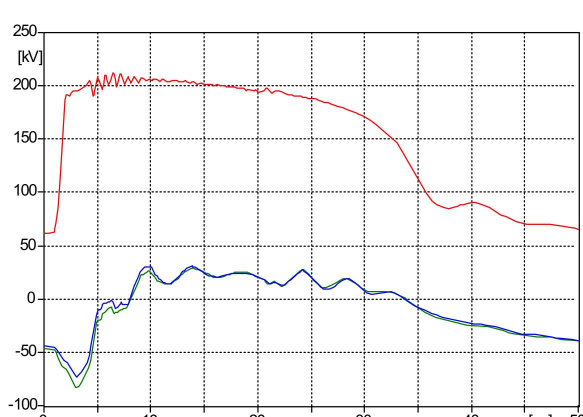

Fig. 17. Overvoltages on power transformer.

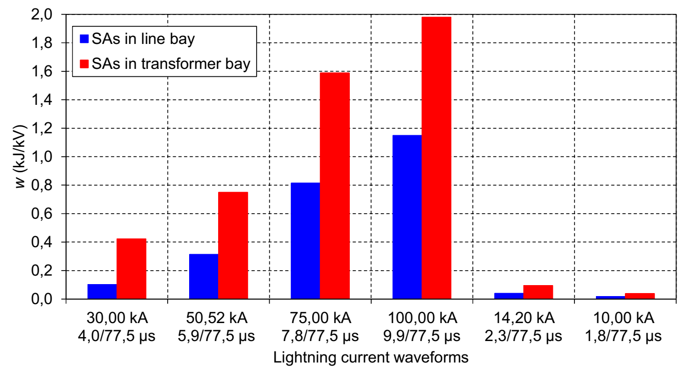

Fig. 18. SA energies in case of overvoltage protection scheme (A).

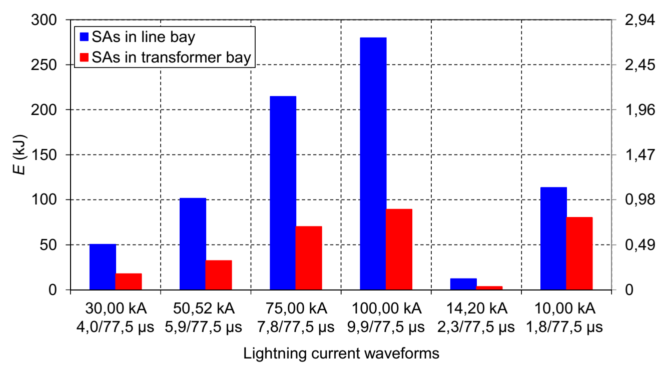

Fig. 19. SA energies in case of overvoltage protection scheme (B).

SAs in line bay absorbed more energy because their rated voltage was equal to SAs in transformer bay and they were closer to lightning stroke position.

Therefore, energy sharing between SAs in line and transformer bay was strongly affected by the value of their rated voltages.

SA energy was calculated in case of two negative lightning flashes comprising the first and following stroke:

- strokes to tower: first stroke 100 kA, 9.9/200 μs and following stroke 40 kA, 4.5/140 μs;
- strokes to phase conductor: first stroke 14.2 kA, 2.3/200 μs and following stroke 5.68 kA, 1.3/140 μs.

Calculation results in cases (A) and (B) show that energy class 4 (w_r = 7 kJ/kV) of station SAs should be selected in order to withstand the energy due to multiple lightning strokes. Fig. 20

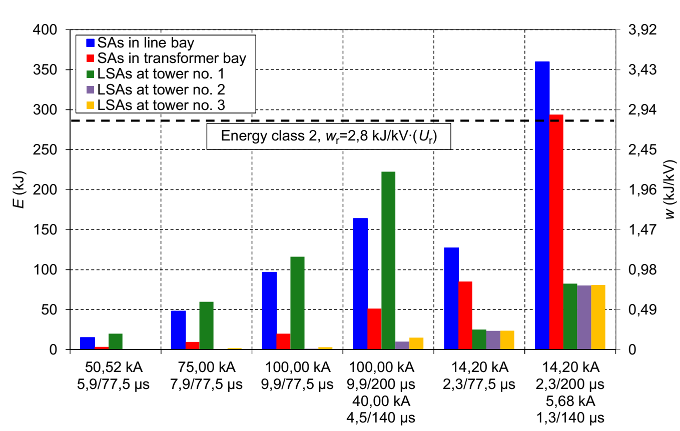

Fig. 20. SA energy in case of overvoltage protection scheme (C).

Please cite this article in press as: B. Franc, et al., Lightning overvoltage performance of 110 kV air-insulated substation, Electr. Power Syst. Res. (2015), http://dx.doi.org/10.1016/j.epsr.2015.12.002

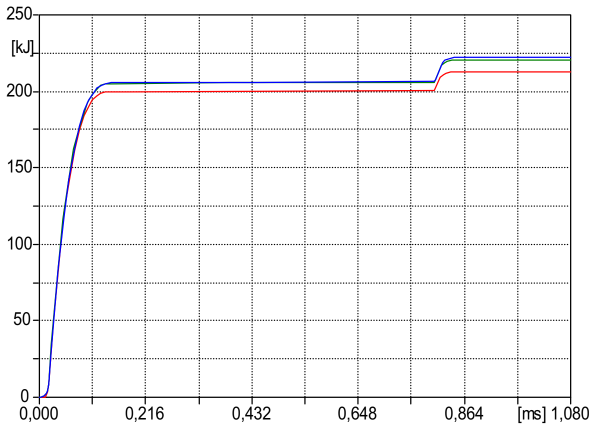

Fig. 21. Case (C) energies of LSAs at first tower in case of first lightning stroke 100 kA, 9.9/200 μs and following stroke 40 kA, 4.5/140 μs.

shows energies of SAs in case (C). SAs in transformer and line bay and LSAs at first three towers with energy class 2 (w_r = 2.8 kJ/kV U_r) withstood the energy caused by lightning except in case of multiple lightning stroke to phase conductor with relatively high amplitude and long duration. According to the results of EGM, this event has a low probability of occurrence. Finally, station SAs with energy class 3 (w_r = 4 kJ/kV U_r) and LSAs with energy class 2 were selected.

Fig. 21 shows energies of LSAs at first tower in case of multiple lightning stroke to tower.

5. Conclusion

This paper presents the analysis of lightning overvoltage performance of 110 kV air-insulated substation. Different overvoltage protection schemes were discussed including station SAs with different rated voltages and energy classes, as well as the application of LSAs on the first three towers of the transmission line entering the substation, with relatively high grounding resistance. For this purpose, the model of 110 kV transmission line and substation was developed in EMTP/ATP.

The conducted simulations showed that SA's rated voltage have significant influence on overvoltage distribution inside the substation and on energy sharing between arresters in line and transformer bay. An optimal protection scheme was proposed considering overvoltage distribution on substation equipment and SA energy due to multiple lightning strokes. This protection scheme includes station SAs with energy class 3 and LSAs with energy class 2, both having the same rated voltage U_r = 102 kV.

Furthermore, the analysis of the lightning activity around 110 kV substation obtained by LLS was performed, which showed that there is a significantly higher probability of lightning stroke occurrence with lower current amplitudes, compared to IEEE data. Therefore, the lightning current parameters of the first and subsequent strokes used in the simulations were conservative and on the "safe side".

Acknowledgements

This work has been supported in part by the Croatian Science Foundation under the project "Development of advanced high voltage systems by application of new information and communication technologies" (DAHVAT).

References

[1] I. Uglešić, V. Milardić, B. Filipović-Grčić, A. Tokić, Preventing flashover near a substation by installing surge arresters, in: 29th International Conference on Lightning Protection, Uppsala, Sweden, 2008.
[2] J.G. Anderson, Lightning performance of transmission lines, in: Transmission Line Reference Book, second ed., Electric Power Research Institute, Palo Alto, California, 1982, chapter 12.
[3] IEC/TR., 60071-4, Insulation Co-ordination—Part 4: Computational Guide to Insulation Co-ordination and Modelling of Electrical Networks, first ed., International Electrotechnical Commission, Geneva, Switzerland, 2004.
[4] CIGRE, Working Group 01 (Lightning) of Study Committee 33 (Overvoltages and Insulation Coordination) "Guide to Procedures for Estimating the Lightning Performance of Transmission Lines, brochure 63, CIGRE, Paris, France, October, 1991.
[5] IEC, 60099-5, Surge Arresters—Part 5: Selection and Application Recommendations, second ed., IEC, Geneva, Switzerland, 2013.
[6] D. Filipović-Grčić, B. Filipović-Grčić, I. Uglešić, Lightning critical flashover voltage of high voltage insulators: laboratory measurements and calculations, Int. Rev. Electr. Eng. 7 (2-part B) (2012) 4321–4328.
[7] A.F. Imece, D.W. Durbak, H. Elahi, S. Kolluri, A. Lux, D. Mader, T.E. McDemott, A. Morched, A.M. Mousa, R. Natarajan, L. Rugeles, E. Tarasiewicz, Modeling Guidelines for Fast Front Transients. Report prepared by the Fast Front Transients Task Force of the IEEE Modeling and Analysis of System Transients Working Group, IEEE Trans. Power Deliv. 11 (1) (1996).
[8] P. Pinceti, M. Giannettoni, A simplified model for zinc oxide surge arrester, IEEE Trans. Power Deliv. 14 (April 2) (1999) 545–550.
[9] I. Uglešić, V. Milardić, B. Filipović-Grčić, A. Tokić, Evaluation of Energy Stress on Line Arresters, CIGRE International Colloquium: Application of Line Surge Arresters in Power Distribution and Transmission Systems, Cavtat, Croatia, 2008.
[10] F. Heidler, Z. Flisowski, W. Zischank, Ch. Bouquegneau, C. Mazzetti, Parameters of lightning current given in IEC 62305—background experience and outlook, in: 29th International Conference on Lightning Protection, Uppsala, Sweden, 2008.
[11] I. Uglešić, V. Milardić, B. Franc, B. Filipović-Grčić, J. Horvat, Establishment of a New Lightning Location System in Croatia, CIGRE C4 International Colloquium on Lightning and Power Systems, Kuala Lumpur, Malaysia, 2010.
[12] B. Franc, I. Uglešić, B. Filipović-Grčić, Application of Lightning Location System Data for Designing the External Lightning Protection System, CIGRE International Colloquium on Lightning and Power Systems, Lyon, France, 2014.
[13] IEC 60071-2, Insulation Co-ordination—Part 2: Application Guide, third ed., International Electrotechnical Commission, Geneva, Switzerland, December, 1996.