# Overvoltage Protection Performance of the 110 kV Overhead Lines after the Line Surge Arresters Implementation

M. Mesić, I. Uglešić, B. Filipović-Grčić, S. Piliškić, M. Mijoč, B. Franc

***Abstract*-- The overview of the outages of 110 kV overhead lines has been given in this paper. Correlation of the relay protection tripping data and lightning location systems (LLS) data has shown the impact of the lighting on the operation reliability of the overhead line. The EMTP/ATP software has been used for simulation and analysis of power system performance with respect to lightning overvoltages in cases with and without line surge arresters. The input data for the simulation are data on lightning strokes which caused the relay tripping of the overhead line obtained from the relay protection system and LLS. Simulations have proved the relay protection system and LLS performance.**

***Keywords*: 110 kV transmission line, outages, flashover characteristics, lightning performance, line surge arrester, lightning location system, EMTP/ATP simulations.**

## I. INTRODUCTION

AFTER successfully conducted pilot project of the line surge arresters (LSA) installation to the overhead line 110 kV and the fulfilment of the main goal of the project which was improvement of the reliability of the overhead line operation, the experience was gained for the further implementation of the overvoltage protection solutions of such kind in the transmission network [1], [2].

Moreover, the experience from the operation of the LSAs showed that the efficiency of such configuration obtained by the computer simulation mostly depends on the accuracy of the towers footing resistance data, access to the towers and specifics of the line location environment. Having in mind that the reliability of the transmission network is important operator's tasks, it has been decided that the gained experience will be used to continue with the arresters' application where appropriate with the goal to minimize the number of the outages.

The substation 110/35 kV Nerežišća and the 110 kV overhead lines connect the island of Brač with the rest of the electricity power system of Croatia. Due to the specific geographical location and geological characteristics of the island the 110 kV transmission network in this area is exposed to significant climate and lightning impacts. The analysis of the transmission network operation has shown numerous disturbances and failures of the line operation caused by the lightning activities in the recent period. The security of supply of the concerned area was particularly threatened by the frequent faults which cause operation interruption of the lines and of the substation and corrective maintenance cost. The need for improvement of the lightning performance and overvoltage protection was recognized. As an optimal solution, for the overvoltage protection of the 110 kV overhead lines the application of LSAs has been chosen.

The operation of the substation and overhead lines using the relay protection tripping data was analysed and the lightning performance of the overhead lines has been calculated. The correlation of relay protection tripping data with the lightning location system (LLS) has proven the correlation between outages and the lightning activity. The LSAs configuration has been determined based on the experience from the previous project where the towers footing resistance data, access to the towers and specifics of the line location environment, such as altitude and the surrounding terrain characteristics, proved to be of critical importance for the LSAs configuration. The results of computer simulations showed that the application of LSAs for the overvoltage protection of the 110 kV overhead lines would decrease the flashover rate of the lines to the 4 flashovers/100 km/year approximately [3].

## II. INSTALLATION OF LINE SURGE ARRESTERS

The 110 kV network of the island comprises of the substation 110/35 kV with two 20 MVA power transformers, connected with the two 110 kV lines to the substation on the mainland and with the 110 kV line to the substation on the neighbouring island of Hvar. All the lines comprise of the overhead line and undersea cable sections.

Initially, the LSA application was planned to be implemented to all of the 110 kV overhead lines of the island Brač. One of the 110 kV overhead lines to the mainland is out of the operation due to the damage of the undersea cable for a

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).

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Paper submitted to the International Conference on Power Systems Transients (IPST2015) in Cavtat, Croatia June 15-18, 2015

longer period of time, so decision has been taken for the time being to implement LSAs' application only to the 110 kV overhead lines which are in normal operation, i.e. 110 kV line 1 (substation to mainland) and 110 kV line 2 (substation to neighbouring island).

Application of zinc oxide surge arresters with silicone polymer-housed insulator has been chosen with characteristics given in Table I.

TABLE I
ZINC OXIDE SURGE ARRESTERS CHARACTERISTICS

| | |
|---|---|
| Max. continuous operating voltage (IEC) | 78 $kV_{rms}$ |
| Rated voltage | 108 $kV_{rms}$ |
| IEC Class | II |
| Nominal discharge current (IEC) | 10 kA |
| Discharge current withstand strength (4/10 μs) | 100 $kA_{peak}$ |
| Short-circuit/Pressure relief capability | 50 $kA_{sym}$ |

Final LSA configuration was determined based on the results of previously performed computations with the slightly modifications applied on the configuration by the experienced specialists due to the difficult access to the towers and specifics of the line location environment.

Three installation configurations of LSAs were used:

a) LSAs installed in all phases;
b) LSAs installed in the bottom and middle phases;
c) LSA installed in the bottom phase.

According to [3], the initial LSAs configuration on the 110 kV overhead line 1 would comprise of two LSAs installed on the first and last tower for the purpose of the overvoltage protection of the substation and cable equipment and one LSA installed on the each of the rest towers with exception of those with the satisfactory footing resistance. The installation of the LSAs was not considered for the towers of the 110 kV overhead line 2 with the lower values of the footing resistance. The proposed configuration for this line was installation of three LSAs, i.e. in each of three phases, for the first and last tower for the same before mentioned purposes and two LSAs for the 11 of towers near the substation and with higher values of footing resistance.

The final LSA configuration on the 110 kV overhead line 1 comprises of 20 LSAs and the final LSA configuration on the 110 kV overhead line 2 comprises of 25 LSAs.

## III. FAILURES OF THE 110 KV OVERHEAD LINES DUE TO THE LIGHTNING

For the purpose of this paper the failures of the 110 kV overhead lines of the island Brač transmission network were analysed using relay protection operation reports and LLS data during the time period from 2009 to now on. The outages data were analysed in two different respects, before and after LSAs installation.

Since the 110 kV overhead line Nerežišća – Dugi Rat I is out of operation since the beginning of the year 2011 due to the physical damage of the undersea cable and the LSA application was not installed, the statistical analysis has not been performed for this overhead line, but only for those lines for which operational data were available and for which the LSA application was applied, i.e. 110 kV overhead lines 1 and 2.

From the detailed relay protection operational report it is possible to find the data about failures of the line for the period 2009-2014. During the observed period relays registered 78 failures on the observed lines including automatic reclosures and definite disclosures of the circuit breakers. The 63 events or 80 % were assumed to be caused by atmospheric discharge. The correlation between the events registered by the protection relays and the LLS showed the 81 % coincidence between the data from these two sources. This means that LLS registered the lightning stroke within the alarm zones of the respective overhead line in the time close to the time of the failure registered by the relay for the 51 cases out of the 63 failures assumed to be caused by the lightning.

Fig. 1 shows the yearly distribution of total number of failures and those caused by the lightning on the observed overhead lines. The lengths of the overhead line sections are 5.929 km and 8.228 km for the overhead lines 1 and 2, respectively.

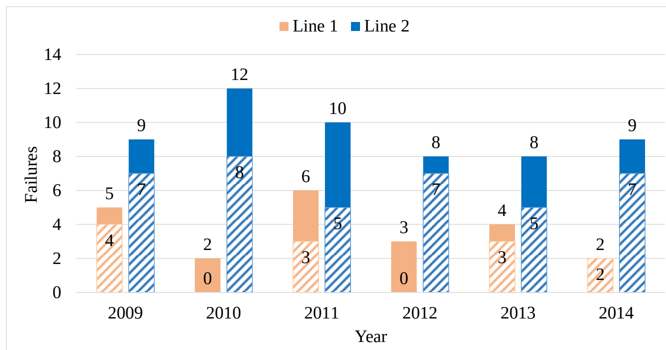


Fig. 1. Number of the total failures and failures caused by the lightning in period 2009-2014

It is important to emphasize that all of the failures due to the lightning in year 2014 occurred after LSA installation to the observer overhead lines. This fact might lead to the wrong conclusions regarding overvoltage protection performance, but the analysis of the lightning activities in the observed area within the next chapter has provided reasonable explanation.

## IV. LIGHTNING ACTIVITY IN THE OBSERVED AREA

LLS has been established in Croatia at the end of the year 2008 as a part of LINET network. Application of LLS in power system control of Croatian Transmission System Operator enables lightning activity tracking and spatial-time correlation with incidences (faults, automatic reclosures, outages) registered by the relay protection system [4], [5]. Also, it is possible to obtain the lightning statistics from LLS database.

Fig. 2 represents the lightning stroke distribution registered by the LLS within the alarm zones around the observed overhead lines for the time period 2009-2014, while Fig. 3

shows the lightning stroke distribution within the alarm zones for the year 2014.

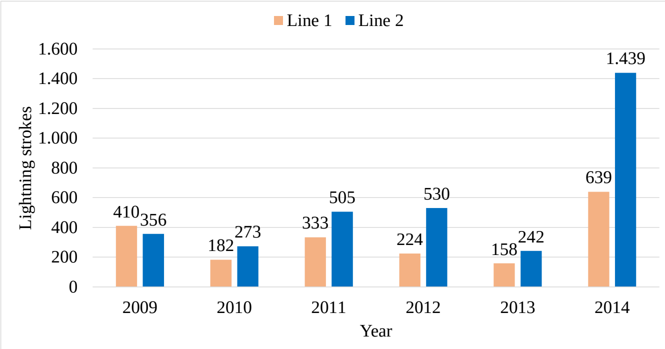


Fig. 2. Number of the lightning strokes within the alarm zones (2009-2014)

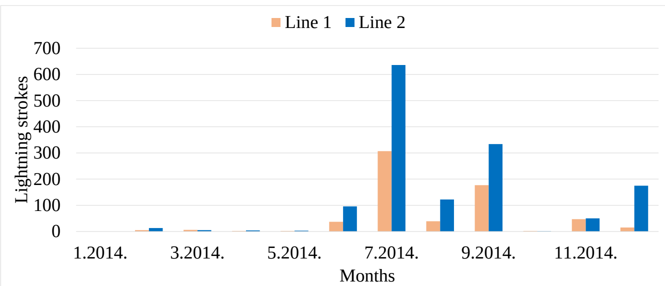


Fig. 3. Number of the lightning strokes within the alarm (2014)

Distributions of the lightning strokes represented on the Figs. 2 and 3 show that the unexpected high number of the failures after LSAs installation was probably caused by the extreme climatological conditions and increased lightning activity during the last six months of the year 2014.

Fig. 4 shows that the LLS measured up to 32 lightning days per year for the area surrounding the observed overhead lines. The time period of six years might be insufficient to obtain the credible statistics. By comparing these values with the ones from the previous year [3], it is possible to see how much statistics could be influenced by the climatologically extreme year.

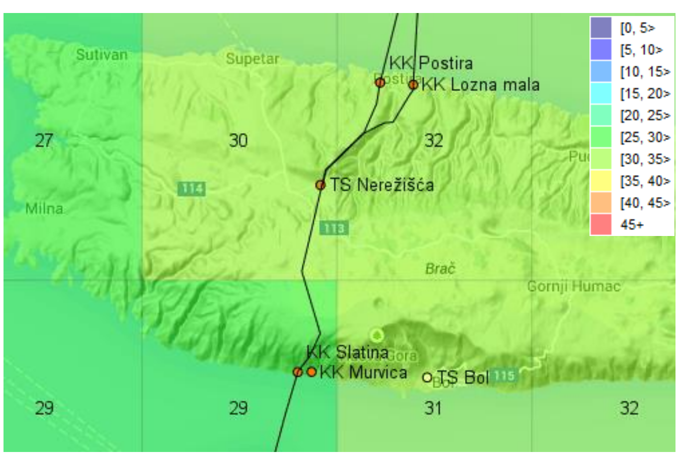


Fig. 4. Keraunic map (lightning days per year) of the observed area (2009-2014)

Fig. 5 shows the map of cloud to ground stroke density for the observed area. The ground stroke density varies between 6.59 – 8.26 strokes/km$^2$/year. The majority of lightning flashes comprise multiple strokes which occur a few milliseconds of each other. According to the LLS data, the observed area had an average stroke multiplicity of 1.58 strokes per flash. The values on the map shown in Fig. 5 correspond to the values of 4.17 – 5.23 flashes/km$^2$/year.

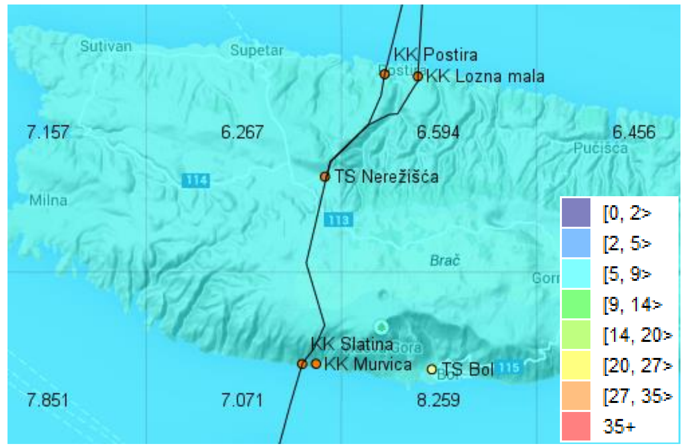


Fig. 5. Ground stroke density [1/km2/year] map of the observed area (2009-2014)

## V. Lightning Stroke Simulation

For the simulations of the two lightning strokes hitting a tower of the 110 kV overhead line, two real cases of failures were considered. In both cases, the relay protection recorded the failures on 110 kV line that were correlated with the LLS data proving that the lightning was the cause of the failure. First event occurred before installation of LSAs and the second after, but in both cases the flashover occurred on the towers without LSAs.

In [4] and [5], for the case where the protection relays have been GPS synchronized and had fault distance calculation function implemented, it was shown that time-spatial correlation can be used for identifying the cause of transmission line outage. The protection relays of the observed overhead lines were not GPS synchronized and had no fault distance calculation function implemented until recently, but time correlation of the events registered by the relays with the LLS data has indicated the 81 % of coincidence.

For the purpose of this paper, time and spatial correlation of the observed overhead lines' failures were performed. For the failures for which time correlation between relay protection system and LLS data proved the lightning was cause, lightning stroke location was determined from LLS data and overhead lines design documentation.

In order to check the correlation results, simulations were performed using EMTP/ATP software.

The lightning stroke hitting a tower was represented by a CIGRE concave shape [6] with the following parameters: the crest current $I_f$, the maximum front steepness $S_m$ and the equivalent front duration $t_f$. The peak current magnitude and the tail time are important when observing the line arrester energy stress, 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 transmission line conductors and shield wire were represented by frequency-dependent model in EMTP/ATP. Three spans from both sides of a struck tower were taken into account. To avoid reflections of travelling waves, line is terminated with multiphase matching resistance at both ends.

Surge impedances of the transmission line towers were determined according to [6] and [7].

The important parameter for the behaviour of overhead line insulation subjected to lightning overvoltages is its corresponding flashover voltage, which depends on the voltage level due to different insulation clearances. The flashover mechanism of the transmission line insulators was represented with differential equation of the leader progression model the selected by the CIGRE WG 33-01[8].

Flashover was modelled using MODELS language in EMTP/ATP.

Tower footing resistances were modelled according to expression (1) taking into account soil ionization [6] caused by lightning current:

$$R_i = \frac{R_o}{\sqrt{1+\left(\frac{I}{I_g}\right)}}, \tag{1}$$

where $R_o$ is footing resistance at low current and low frequency (50 Hz), $I$ is lightning current through the resistance and $I_g$ is limiting current needed to initiate sufficient soil ionization. The tower footing resistance remains $R_i=R_o$ if $I<I_g$ and varies according to the given equation if $I>I_g$. The limiting current is given by expression (2):

$$I_g = \frac{\rho \cdot E_0}{2 \cdot \pi \cdot R_o^2}, \tag{2}$$

where $\rho$ is soil resistivity and $E_0$ soil ionization gradient (recommended value of 400 kV/m used in simulations). Tower grounding was represented as non-linear resistor using MODELS language and TACS-controlled time-dependent resistor.

### A. Case 1

The relay protection system and corresponding LLS data for the Case 1 are given in the Table II, while the time- spatial correlation between relay protection system and LLS data are shown on the Fig. 6.

According to the overhead line design documentation it was determined that the tower on the given distance between the substation and the lightning stroke location was tower number 17. Measured tower's footing resistance was 16 Ω.

TABLE II
RELAY PROTECTION SYSTEM AND LLS DATA FOR THE FAULT EVENT, CASE 1

| | | | |
|---|---|---|---|
| 110 kV overhead line 2 | | | |
| Relay protection system data: | | | |
| Fault event time | 23.11.2013. 22:00:35.133 | Tripping time | 23.11.2013. 22:00:35.204 |
| Fault type | Automatic reclosure | Fault in phase | C |
| LLS data: | | | |
| Lightning stroke time | 23.11.2013. 22:00:35.075 | | |
| Lightning current (kA) | -101.1 | Distance (km) | 4.861 |

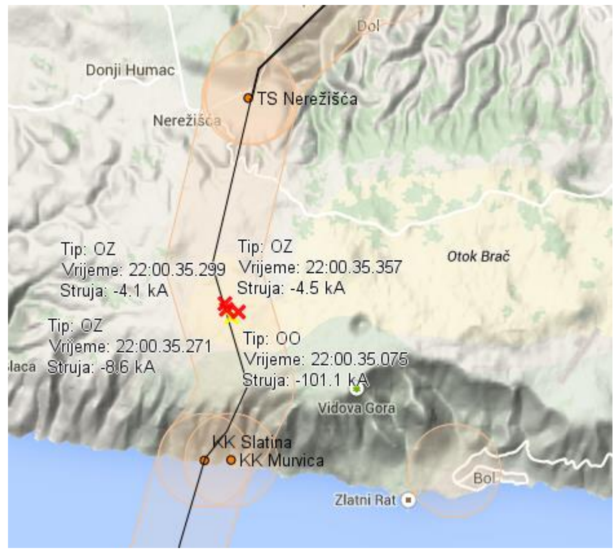

Fig. 6. Time and spatial correlation between relay protection system and LLS data, Case 1

The calculations of lightning overvoltages were carried out in case of lightning stroke to tower 17. For the simulations purposes, three spans from both sides of the struck tower were modelled in the EMTP software (Fig. 7). Lightning stroke with amplitude of 100 kA was simulated. Median values of front time $t_f$=5.5 μs, time to half $t_h$=77.5 μs and maximum front steepness $S_m$=24 kA/μs of the lightning current waveform were selected according to [8].

Simulations for the tower footing resistance of 16 Ω and lightning current amplitude of 100 kA have shown that there is no flashover at the bottom phase as it was registered by the relay protection system.

The results in Table III show that, for the tower footing resistance of 16 Ω, flashover would occur only at the bottom phase (C) for the lightning current amplitude of 77 kA or lower and for the certain voltage angle.

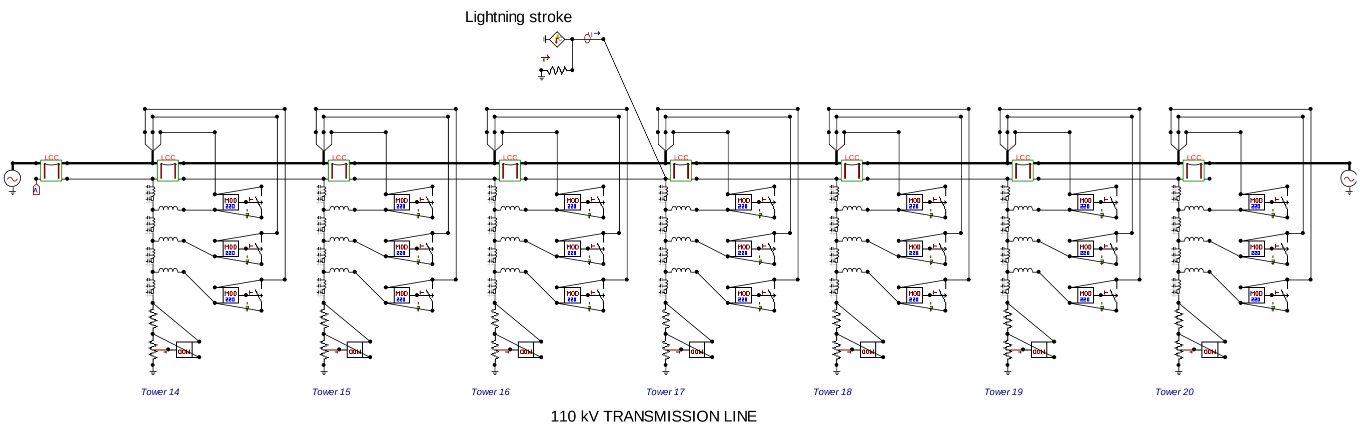


Fig. 7. Model of 110 kV transmission line in EMTP/ATP

TABLE III
RESULTS OF THE SIMULATIONS FOR DIFFERENT $I_F$ AND $R_G = 16\ \Omega$

| Case 1 | $R_g = 16\ \Omega$ | | | | |
|---|---|---|---|---|---|
| $I_f$ (kA) | 100 | 90 | 80 | 77 | 75 |
| Voltage angle in phase A (degrees) | Insulator flashover in phase | | | | |
| 0 | C,B | C,B | C,B | C,B | C,B |
| 30 | C,B | C,B | C,B | C,B | C,B |
| 60 | C,B | C,B | C,B | C | C |
| 90 | C,A,B | C,A | C,A | C | C |
| 120 | C,A,B | C,A | C,A | C,A | C,A |
| 150 | A,C,B | A,C | A,C | A,C | A,C |
| 180 | A,B,C | A,B,C | A,B | A | A |
| 210 | A,B,C | A,B | A,B | A,B | A,B |
| 240 | B,A,C | B,A | B,A | B,A | B,A |
| 270 | B,A,C | B,A | B,A | B,A | B,A |
| 300 | B,C | B,C | B,C | B,C | B |
| 330 | B,C | B,C | B,C | B,C | B,C |

Taking into the consideration that the tower footing resistance can vary due to the different environmental conditions, simulations were performed for the case where the tower footing resistance was 11 Ω.

Simulations were performed for the different voltage angles in the case without LSAs installed at the tower 17, with LSA installed in the bottom phase (C) and with LSAs installed in bottom and middle phases (B and C). The results of the simulations are shown in Table IV.

Bottom phase with the lowest coupling factor has the highest probability of flashover (for voltage angles 50º - 95º in phase A) in the case without LSAs.

As expected, in cases where LSA is installed in bottom phase or in the case where LSAs are installed in bottom and middle phases, no flashover would occur in bottom phase. In the first case, flashover would occur in the top or middle or both top and middle phases depending on the voltage angle. In the latter case, flashover would occur in top phase or would not occur at all depending on the voltage angle, which means that in such case the probability of flashover occurrence on this tower would be minimalized.

TABLE IV
RESULTS OF THE SIMULATIONS FOR $I_F$=100 KA AND $R_G$=11 Ω

| Case 1 | $I_f$ = 100 kA, $R_g$= 11 Ω, $\rho$ = 300 Ω/m | | |
|---|---|---|---|
| Voltage angle in phase A(degrees) | Insulator flashover in phase | | |
| | Without LSA | LSA in phase C | LSAs in phases B and C |
| 0 | C, B | B | - |
| 30 | C,B | B | - |
| 60 | C | B | - |
| 90 | C | A | - |
| 120 | C, A | A | A |
| 150 | A, C | A | A |
| 180 | A | A | A |
| 210 | A, B | A | A |
| 240 | B, A | B,A | A |
| 270 | B, A | B | - |
| 300 | B | B | - |
| 330 | B, C | B | - |

Fig. 8 shows calculated overvoltages on insulators of the struck tower. Back flashover occurs in bottom phase of the struck tower and adjacent towers as well.

Power frequency voltage source was represented with a cosine function. It was assumed in the simulations that the lightning stroke occurred at instant of power frequency voltage peak in bottom phase (voltage angle 60° in phase A), since the potential difference across the insulator string is highest in this case.

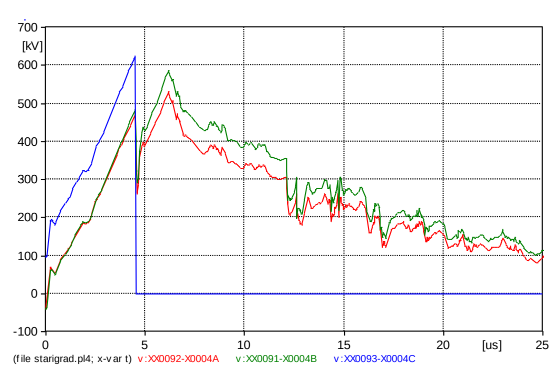


Fig. 8. Overvoltages on insulators of the tower number 17 during back flashover at bottom phase C ($I_f$ = 100 kA, $R_g$= 11 Ω)

### *B. Case 2*

The relay protection system and corresponding LLS data for the Case 2 are given in the Table V and the time and spatial correlation between relay protection system and LLS data are shown in the Fig. 9.

TABLE V

RELAY PROTECTION SYSTEM AND LLS DATA FOR THE FAULT EVENT, CASE 2

| 110 kV overhead line 2 | | | |
|---|---|---|---|
| Relay protection system data: | | | |
| Fault event time | 05.12.2014. 17:19:36.180 | Tripping time | 05.12.2014. 17:19:36.274 |
| Fault type | Definite disclosure | Fault in phase | B,C |
| LLS data | | | |
| Lightning stroke time | 05.12.2014. 17:19:36.171 | | |
| Lightning current (kA) | -103.1 | Distance (km) | 6.116 |

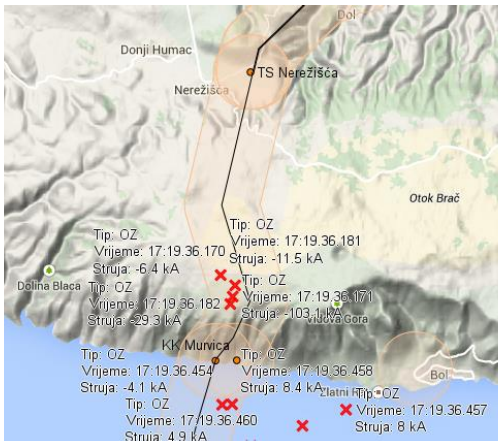


Fig. 9. Time and spatial correlation between relay protection system and LLS data, Case 2

According to the overhead line design documentation it was determined that the tower on the given distance between the substation and the lightning stroke location was tower number 21. Measured tower's footing resistance was 7 Ω.

In this case, simulations for the tower footing resistance of 7 Ω and lightning current amplitude of 103 kA have shown that no flashover occurs at the bottom and middle phases as it was registered by the relay protection system. Results of the simulations performed for the case where the tower footing resistance was 7 Ω and for the different lightning current amplitudes showed that for the given tower footing resistance, flashover would occur at the bottom and middle phases for the lightning current amplitude of 125 kA or higher, for the certain phase voltage angle (Table VI).

Simulations performed with lightning stroke of 103 kA amplitude have shown that the in the case without LSAs installed flashover could occur at bottom and middle phases (B and C) for voltage angle 0º in the phase A and the tower footing resistance of 9 Ω. The results of the simulations are shown in Table VII.

TABLE VI

RESULTS OF THE SIMULATIONS FOR DIFFERENT $I_F$ AND $R_G$ = 7 Ω

| Case 2 | $R_g$ = 7 Ω, $\rho$ = 150 Ω/m | | | |
|---|---|---|---|---|
| | Without LSA | | LSA in phase C | LSAs in phases B and C |
| $I_f$ (kA) | 103 | 125 | 125 | 125 |
| Voltage angle in phase A (degrees) | Insulator flashover in phase | | | |
| 0 | B | B,C | B | - |
| 30 | C | C | - | - |
| 60 | C | C | - | - |
| 90 | C | C | - | - |
| 120 | C | C | A | - |
| 150 | A | A | A | A |
| 180 | A | A | A | A |
| 210 | A | A | A | A |
| 240 | B | B | B | - |
| 270 | B | B | B | - |
| 300 | B | B | B | - |
| 330 | B | B | B | - |

TABLE VII

RESULTS OF THE SIMULATIONS FOR $I_F$ = 103 KA AND $R_G$ = 9 Ω

| Case 2 | $I_f$ = 103 kA, $R_g$= 9 Ω, $\rho$ = 200 Ω/m | | |
|---|---|---|---|
| | Without LSA | LSA in phase C | LSAs in phases B and C |
| Voltage angle in phase A (degrees) | Insulator flashover in phase | | |
| 0 | B,C | B | - |
| 30 | C | B | - |
| 60 | C | - | - |
| 90 | C | - | - |
| 120 | C | A | - |
| 150 | A | A | A |
| 180 | A | A | A |
| 210 | A | A | A |
| 240 | B,A | B | - |
| 270 | B | B | - |
| 300 | B | B | - |
| 330 | B | B | - |

For both analysed cases the calculation results showed that the failures recorded by relay protection system could be caused by insulator flashover due to lightning stroke to tower. However, the simulations were carried out for a certain range of tower footing resistance and lightning current amplitude, in order to obtain the relevant results. This was necessary because the input data were not known exactly since they contain uncertainties.

Since that the tower footing resistance can vary significantly depending on the environmental conditions and measurement method, the variation in the range up to 5 Ω is acceptable. Lightning current amplitude was varied, up to the 23 % of the value given by the LLS.

In both presented cases, a flashover occurred on the towers located on the highest and most exposed part of the transmission line corridor extending over mountain area on the south side of the island towards the sea. Moreover, the time and spatial correlations indicated that no failure occurred at the line sections with installed LSAs. All failures registered in the recent period occurred on the highest and most exposed towers without LSAs.

## VI. Conclusion

LSAs installation on the 110 kV overhead lines of the island Brač was proposed as an optimal solution to improve the operation reliability of this part of the transmission network.

It is still premature to bring major conclusions of the transmission lines lightning performance, since lines are in operation only six months after LSAs installation. Nevertheless, some analyses of the operational performance of the lines have been performed, so preliminary conclusions of the efficiency of the applied lightning protection can be made.

Time and spatial correlation of the relay protection tripping data and LLS data has clearly indicated the connection between the lightning activities and the failures of the overhead lines. The significant number of failures occurred on the observed 110 kV overhead lines after the LSAs installation due to the extreme lightning activity in the same period. The correlation proved the efficiency of the LSAs, since no failure occurred at the towers with installed LSAs. According to the spatial correlation, the towers located on the higher altitude and on the south side of the island are in particular threatened by the atmospheric discharges.

The EMTP/ATP software has been used for simulation and analysis of power system performance with respect to lightning overvoltages. Both cases for which simulations of flashovers were performed showed that recorded failures were caused by lightning stroke to tower. Simulations also showed that the installation of the LSAs decreases the possibility of the flashover occurrence.

More accurate and reliable statistics and conclusions on the efficiency of the LSAs application to the observed 110 kV overhead lines would be possible after the longer period of the operation.

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