Lightning current field measurement on a transmission line, comparison with electromagnetic transient calculations

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Abstract- **A lightning experiment is conducted on the 123 kV single-circuit transmission line Ston – Komolac located in the area of Dubrovnik (Croatia), which has a very high lightning ground flash density. This line is equipped with gapless line arresters. This experiment has been operational for 6 years and presently includes, after several upgrades, the following elements: On two towers the shape of the transient currents circulating through the 3 line surge arresters are measured with Pearson's sensors; in addition a specially developed Rogowski coil has been installed around both towers to measure the lightning current circulating through them. These sensors are connected to a real time monitoring system, energized by a solar panel, with a communication system making use of a mobile phone network to transmit the measurement data to a remote server, in order to avoid the burden of on-site visits to get the measurements. This monitoring system had been presented in previous papers [1][2]. At the line remote end substations some Rogowski coils measure the lightning current through the station arresters, and measurements of currents and voltage at the secondary side of the measuring transformers are made too.**

All the lightning measurements are compared with the data obtained from the lightning detection system covering Croatia (LINET). It was shown that the consistency of these 2 sources of information is quite satisfactory.

Since the beginning of the experiment many measurements have been obtained, some of them corresponding to very strong lightning strokes. In this paper we are presenting examples of measurements, some statistics of the transient currents circulating through the line arresters and some comparisons between measurements and EMTP-like calculations.

***Keywords*: Lightning measurements, line arresters, electromagnetic transients, EMTP-RV.**

I. Introduction

This paper presents some elements of a research project devoted to studying the effect of lightning on transmission systems. This project is conducted under the framework of a partnership between HOPS (Croatian transmission system operator), RTE (French transmission system operator) and Electricité de France (electricity producer), it has led to equip the line Ston-Komolac with a measuring system recording the shape of lightning currents at various locations along the line. The measurements recorded by the system are used to get a better insight on the fast front over-currents, which might exist along a line equipped with line arresters as well as at its substations. The paper starts with a brief presentation of the line Ston-Komolac, followed by a description of the main elements of the experiment. Then some measurements obtained recently are analyzed. The paper ends with statistics about the transient current circulating in line arresters, and with a comparison between some measurements of the current circulating in line arresters and numerical simulations performed with EMTP-RV.

II. Presentation of the line Ston-Komolac

The 110 kV overhead line Ston-Komolac is an important element of the Croatian transmission system because its outage leads to a significant risk of interruption of electricity supply in the south part of the country. This is a single circuit line equipped with 1 sky wire (see Appendix 1), which is 44 km long. The line is located in a mountainous region near the sea, of high lightning activity. The average ground flash density is around 10 lightning stroke / km^2 / year. The region is very rocky and consequently the soil resistivity is particularly high and does not allow for the installation of grounding electrodes with low impedances everywhere. Therefore the grounding resistance of the towers is often higher than 60 Ω and before the installation of line arresters the lightning flashover rate of the line was very high.

In June 2007 110 line arresters have been installed along the line. The towers and phases where they are installed were selected based on the application of the electrogeometric model, and on electromagnetic transient calculations.

The characteristics of the line arresters are the followings:

- MCOV 86 kV;
- Rated voltage 108 kV;
- IEC Class 2;
- Housing silicone rubber.

Further to the lightning calculations performed, the decision was taken to adopt the following rules for the installation of the line arresters:

- no arrester for a tower grounding resistance lower than 10 Ω ;
- for a grounding resistance between 10 Ω and 30 Ω, a line arrester is installed on the lower phase (this choice has been made because the coupling between this phase conductor and the sky wire is the lower) ;
- if the grounding resistance is higher than 30 Ω, a

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line arrester is installed on the middle phase and on the lower phase.

Some readjustment of the location of line arresters were done over the years based on data about line tripping, relay protection, and experience.

An improvement of the lightning flashover rate of more than 50% was achieved.

III. THE MEASUREMENT SYSTEM

The measurement system has been presented in several other papers [1][2]. The goal of this paragraph is to stress facts essential for the understanding of the next paragraphs.

A. Measurement technique used for transmission towers

The transient current circulating in line arresters are measured with Pearson sensors on two towers of the line (towers Nr. 38 and 110). Additionally since June 2012 a specifically developed Rogowski coil has been installed around both towers in order to monitor the transient current circulating through them.

Fig. 1. Monitoring of the towers with the Rogowski coil.

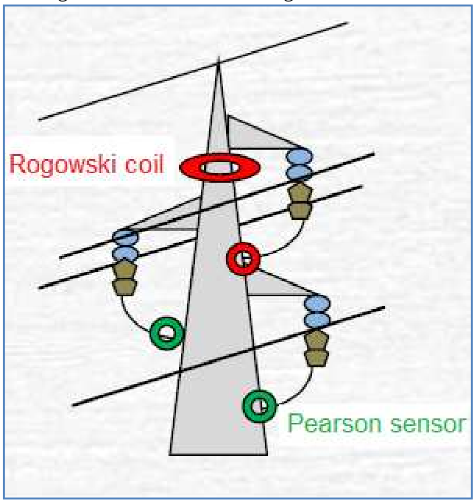

Fig. 2. Monitoring of the towers. The Rogowski coils are in red and the Pearson sensors are in green.

B. Measurement technique used for station arresters.

The system for the arrester transient current monitoring in both substations is the same as that one described previously for towers but in addition an electronic card has been installed for the arrester real time leakage current shape measurement. The only major difference is that the monitoring system is directly energized from the substation power supply, without solar panels, charge controllers and batteries.

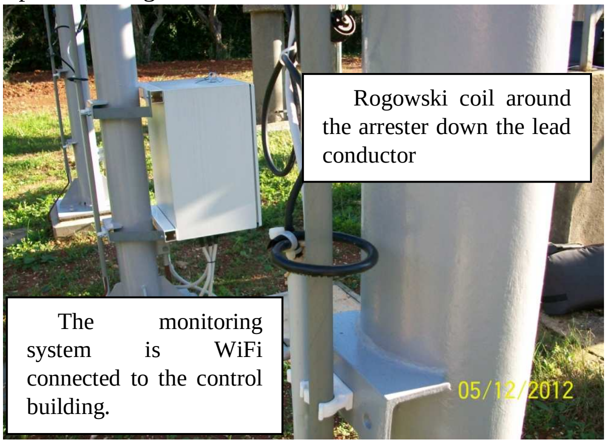

Fig. 3. Monitoring of the station arresters.

C. Measurement performed at the secondary side of the voltage and current transformers in the substation Ston

One measurement system was installed on the secondary side of the voltage and current transformers of the 110 kV / 35 kV substation Ston. Its goal is to help understand the whole chronology of events triggered by lightning when it strikes the line.

D. Lightning location system

The data supplied by the Lightning Location System (LLS) LINET of the company nowcast has been used for more than 2 years. [13] LINET provides with the following data for each lightning stroke:

- GPS date and time with 100 ns resolution;
- Latitude and longitude coordinates of the stroke with location error;
- Current amplitude and polarity of the stroke;
- Type of discharge, cloud to ground (CG) or cloud to cloud (CC).

IV. RESULTS

Numerous significant measurements have been recorded since the beginning of the experiment. One major difficulty with natural lightning measurements is that the initiating phenomena (in other words the lightning stroke) cannot be directly known. The simultaneous existence of the different sources of information detailed in the previous paragraph constitutes a strong help in understanding the results of measurements. From November, 2013 to September, 2014 16 significant lightning events have been recorded.

A. Event recorded on April 15, 2014.

On April 15, 2014, lightning stroked the line. The event was detected by the measurement system, and led to measurements. The table 1 below presents the time at which each sensor performed its measurement. The LINET record presented in the table was selected because of its time agreement with the measurement performed at tower Nbr 38. According to the LINET system this is a cloud to ground lightning stroke, whose crest current is equal to 50.2 kA and whose point of impact is at a distance of 300 m from tower Nbr 22. However we can see from the table I below that the precision on time is not sufficient to reflect the delay taken by the electromagnetic wave to propagate from tower Nbr 38 to tower Nbr 110. If we consider that the span length is around 200 m, the electrical distance between both towers is of the order of 14 km and corresponds to a propagation time of 46 µs, much lower than the precision with which figures are given in table 1.

TABLE I
TIME AT WHICH EACH SENSOR DETECTED THE LIGHTNING EVENT OF APRIL 15, 2015

Origin of the measurement	Time
Substation Ston	06:02:36.7517 (GMT+2)
Plausible Linet Record	06:02:36.751 (GMT+2)
Tower 38	06:02:37.867 (GMT+2)
Tower 110	06:02:36.757 (GMT+2)

The figure 4 presents the voltage and currents at the substation Ston (see III. C.). We can see that the lightning stroke is at the origin of a 3 phase fault with a short-circuit current, which lasted around 90 ms before the opening of the breakers. This 3 phase fault is in agreement with the fact that tower 22 and several neighboring towers are not equipped with arresters. Considering that the tower resistances are usually high along the line because of the rocky soil, a lightning stroke with a current of the order of 50 kA is likely to cause a 3-phase-fault.

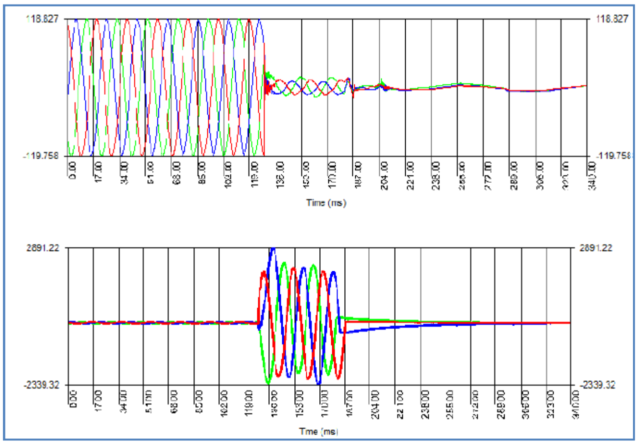

Fig. 4. Voltage (top) and current (bottom) at the substation Ston.

The figures 5 and 6 present the measurements respectively recorded at tower Nbr 38 and tower Nbr 110. The measurements of tower Nbr 110, which is, according to the LINET measurement, separated from the point of impact by many spans, exhibit a lot of oscillations caused by the huge number of reflections of the electromagnetic waves at towers. Nevertheless the current in the arresters is relatively high, considering the number of spans separating the tower Nbr 110 and the point of impact (its crest value is higher than 1700 A) but does not lead to a significant amount of energy transferred in the arrester. The bottom arrester of tower Nbr 38 exhibits, after some strong oscillations lasting 12 µs a plateau of around 200 A lasting 35 µs. The fact that the strongest current circulates through the bottom arrester is in agreement with theory: the coupling between the sky wire and the bottom phase conductor being smaller than for the other phase conductors it increases the current circulating through the arrester of this phase.

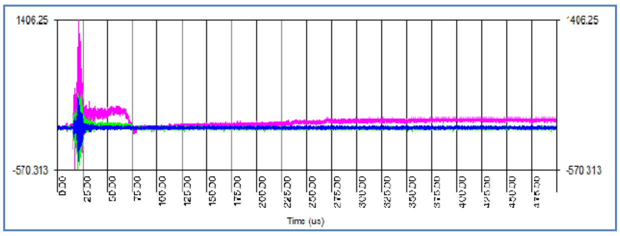

Fig. 5. Measurement performed at the tower 38. __ top arrester, __ middle arrester, __ bottom arrester.

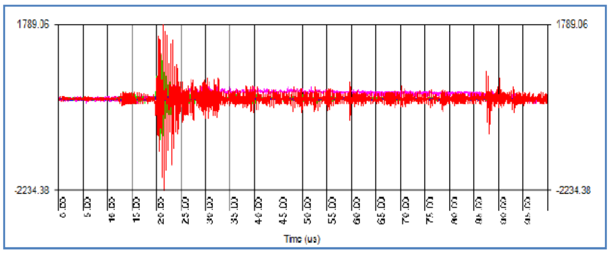

Fig. 6. Measurement performed at the tower 110. __ top arrester, __ middle arrester, __ bottom arrester, __ total tower.

B. Current statistics

A basic statistical study was conducted based on the measurements obtained from October, 2013 to September 2014. The crest value of the transient current circulating in the line arresters of both towers was considered. The different strokes corresponding to each lightning event were accounted for separately (the same event can correspond to a first lightning stroke followed by several subsequent strokes). This approach led to consider 28 samples, corresponding each to the transient current circulating in the line arresters of tower Nbr 38 or tower Nbr 110. The table II below gives for bottom, middle and line arresters the average of the transient current's crest value. We can see that, according to this data, the top arrester is significantly more stressed than the other 2 arresters. This fact is corroborated by the data presented in table III, which focus more specifically on the highest currents circulating through the arresters. This phenomenon, which contradicts the fact that the top arrester should be less stressed because of the higher electromagnetic coupling between its phase conductor and the sky wire, compared to the other phase conductors. Among the plausible explanations there are:

- The fact that there are more arresters on the lower phase and therefore a higher reduction of the measuring constrain.

- The facts that the sky wire might not be completely effective because of the mountainous region, and that some parts of the line can be above or in the cumulonimbus during a thunderstorm. This fact should be studied further.

TABLE II
AVERAGE VALUE OF THE CURRENT'S CREST VALUE CALCULATED USING THE MEASUREMENTS RECORDED BETWEEN NOV 2013 AND SEPT 2014.

Arrester location	Average value of the current (A)
Bottom	705
Middle	487
Top	3530

TABLE III
AVERAGE VALUE OF THE 3 HIGHER CURRENT'S CREST VALUE CALCULATED USING THE MEASUREMENTS RECORDED BETWEEN NOV 2013 AND SEPT 2014.

Arrester location	Average value of the current (A)	Maximum value (A)
Bottom	2650	3640
Middle	1660	1840
Top	16000	16000

V. COMPARISONS BETWEEN SIMULATIONS AND MEASUREMENTS

Some comparisons between EMTP-RV simulations and the measurements detailed in the paragraph IV are presented here. The beginning of the paragraph is devoted to a presentation of the principles of the modeling used. This is followed by a description of the configuration and a presentation of the results of the comparison.

A. Modeling used

References [4][9][10][11] presents a detailed description of the modelling to be used when performing this type of study, the goal of this sub-paragraph is to provide a summary of the main elements of modelling:

- Each span of the line is represented separately between the point of impact and the tower 38 where the measurements are performed (shield wire and phase conductors). Each span can be represented as a multi-phase unbalanced distributed-parameter line section with frequency-dependent parameters.
- The line termination at each side of the above model, requested to avoid unphysical reflections that could affect the simulated over-voltages and over-currents around the point of impact, is represented by means of a long enough section, whose parameters are calculated as for the line wires.
- The lower part of the tower's body is represented as an ideal single-conductor distributed-parameter line, its upper part is represented with inductances (1 µH / m).
- A lightning stroke is represented as an ideal current source with a concave waveform. A return stroke waveform is defined by the peak current magnitude, I_{100}, the rise time, t_f (= 1.67 ($t_{90} - t_{30}$)), and the tail time, t_h, that is the time interval between the start of the wave and the 50% of peak current on tail.
- The arresters are represented by their non-linear characteristic in series with an inductance.
- The grounding electrodes are represented by their low frequency resistance.

B. Description of the configuration considered for the simulations

This paragraph describes the representation used to perform the electromagnetic transient calculations. The span length is supposed to be constant and equal to 200 m. We have supposed that all the towers after tower Nbr 42 have a grounding electrode of 50 Ω. For the towers from Nbr 34 to Nbr 42, measurements of the grounding resistances were used. Both parts of the line from the substation Ston to tower Nbr 13 and from tower Nbr 42 to the substation Komolac are represented by a long line. According to the LINET record, it was considered that a 50 kA lightning strikes tower Nbr 22. Arrester transient currents are calculated at tower 38 where the measurements are performed. The figure 7 presents the EMTP-RV configuration considered in the simulations.

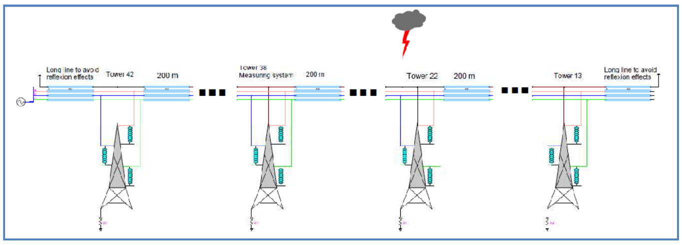

Fig. 7. Configuration considered for the simulations

The appendix gives the description of the configuration with the position of the conductors at towers and their characteristics (Table IV).

C. Results and conclusions

The currents circulating through the arresters of tower 38 calculated by EMTP-RV are presented in figure 8. It is observed that the currents through the lower and middle arresters are negligible compared to the current flowing through the top arrester. That is probably due to the fact that there is no arrester on the top phase between towers 22 and 38, whereas there are seven and ten arresters in the middle and lower phases respectively.

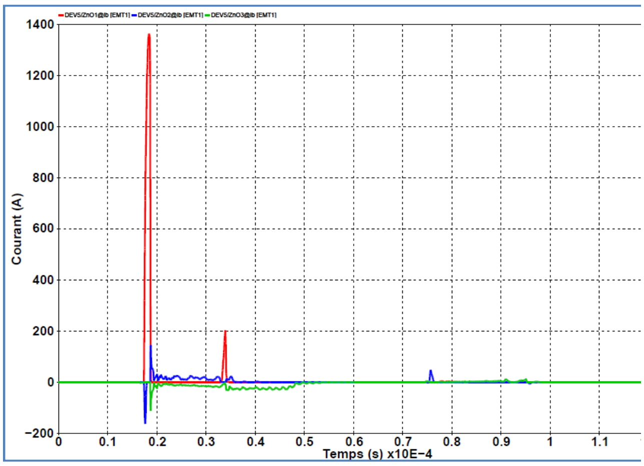

Fig. 8. Simulation results at the tower 38. __ top arrester, __ middle arrester, __ bottom arrester

Figure 9 shows a comparison between the highest measured and simulated currents at the tower 38. A good match can be observed between the crest current obtained by simulation (1363 A) and the measured current (1406 A). Nevertheless we can see that the classical modeling used does not allow to reproduce adequately the oscillations found in measurements. But it should be pointed out that the lightning stroke current at the origin of the measurements is not known and that we have used a very simplified representation of towers (see paragraph V.A). In practical terms, these differences have no consequences because the energy consumed by the arresters is quite low.

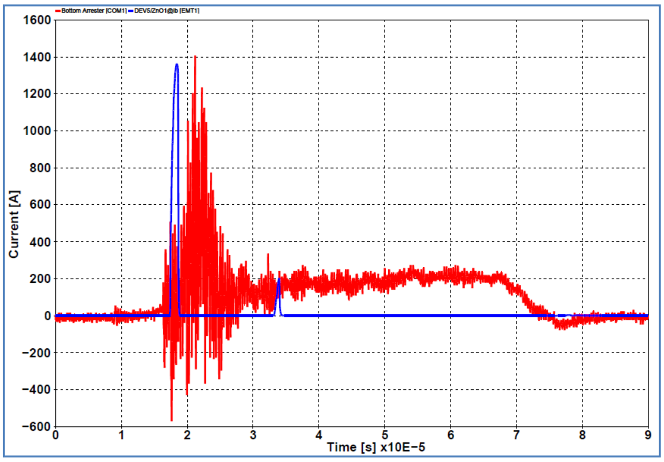

Fig. 9. Measurement versus Simulation at the tower 38

VI. Conclusions

The paper has presented various elements of an experiment aiming at better understanding the effect of lightning on transmission systems and the protection provided by line and station arresters. This experiment has allowed to record a significant amount of lightning current samples related to natural lightning.

After a brief description of the experiment, some latest measurements are analyzed and statistics about the transient currents circulating through line arresters are provided. The measurements show that relatively significant currents can circulate through line arresters even for lightning, which strikes the line far from them. Moreover in our configuration it was seen on the measurements that the stress applied to the line arresters depends on the phase that the arrester protects. Arresters installed on the top phase appear to experience higher lightning currents than the others.

A comparison between measurements and EMTP-RV simulation was made on one case. The same orders of value were found for the crest value, in spite of the long distance between the point of impact and the tower where the measurements were performed. To enhance the accuracy regarding the shape, important research directions would be the improvement of the representation of towers, the consideration of the fact that some parts of the line can be above or in the cumulonimbus (or at least to model with EMTP-RV the coupling between the lightning channel and the overhead line). The use of finite-difference time domain techniques should also be investigated as a possible option [12].

VII. Appendix

Description of the 110 kV line Ston-Komolac.

The line Ston-Komolac is a single circuit line equipped with 1 sky wire. The average length of the spans is 200m. The position of the conductors at towers is given in the table 1 below.

TABLE IV

Lineic resistance and position of conductors

DC resistance (Ω/km)	Outside diameter (cm)	Horizontal distance (m)	Vertical height at tower (m)
0.455	0.9	0	28.9
0.144	1.708	2.5	22.7
0.144	1.708	-3	20.5
0.144	1.708	3.5	18.3

VIII. Acknowledgment

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