

Lightning overvoltages on a DC transmission line, calculated based on measured bipolar lightning strokes

A. Xemard, E. Sellin, R. Tarafi, A. Bertinato, P. Verrax

***Abstract*— A key principle of insulation coordination is to compare the stress which could potentially be applied to equipment when it is in service with its withstand level. The withstand level is known based on standard tests. For AC systems an important knowledge exists at international level and numerous reference documents are available. In addition, the IEC 60071 has standardized the rated impulse withstand voltage to be used for equipment and proposed for each value of highest voltage for equipment preferential values regarding impulse withstand voltage. The situation is not the same for DC systems. Less experience has been shared within the international community and there is no standardization of the withstand voltage. In addition, with regard to AC lines their structure is different. All these elements lead to a careful reassessment of hypotheses, which are usually accepted as valid when performing AC system insulation coordination studies. In this paper, the influence of lightning current shape on overvoltage is examined. A 500 kV bipolar DC overhead line is considered. The overvoltages due to bipolar lightning strokes based on measurements are calculated. Measurements available in literature have been used. These overvoltages are compared with calculations based on the use of the CIGRE wave shape as it is usually the case when performing insulation coordination studies and analyzed from an insulation coordination point of view.**

***Keywords*: DC transmission line, EMTP-like program, lightning, insulation coordination.**

I. Introduction

A key principle of insulation coordination is to compare the overvoltage, which could potentially be applied to equipment in service, with its insulation withstand level. The withstand level is known from standard tests. For AC system an important knowledge exists at international level and numerous reference documents are available. In addition, the IEC 60071 [1] and some IEC equipment standards have standardized the rated impulse withstand voltage to be used for equipment and proposed for each value of highest voltage for equipment preferential values regarding impulse withstand voltage. The situation is not the same for DC systems. Less experience has been shared within the international community and there is no standardization of the withstand voltage. In addition, the structure of DC lines is different. All these elements lead to a careful reassessment of hypotheses, which are usually accepted as valid when performing AC system insulation coordination studies. In this paper, the influence of lightning current shape on overvoltage is examined. A 500 kV bipolar DC overhead line is considered. The overvoltages due to lightning are calculated when lightning, whose current shape is based on measurements, strikes a pole directly (this is a so-called shielding failure). They correspond to bipolar lightning strokes (their currents exhibit a positive and a negative pulse as shown in Appendix B). Measurements performed in Corsica on a telecommunication tower have been used [2]. These overvoltages are compared with calculation based on the use of the CIGRE wave shape to represent the lightning current. This wave shape is recommended by CIGRE to represent negative downward lightning strokes when conducting insulation coordination studies [3][4]. In this study, we consider more specifically the lightning incident wave, which propagates along a pole and is able to stress the equipment in the substations located at the end of the overhead line. This incident wave is different from the overvoltages, which stress the apparatuses in the substations and are related to their electromagnetic transient behavior.

The organization of the paper is the following. Section 2 presents the way the bipolar lightning current measurements were performed. It is followed by a description of the DC transmission line on which the overvoltages due to lightning are calculated (section 3) and by a presentation of the electromagnetic transient modelling used in the study (section 4). Then in section 5, the calculated lightning incident waves are shown and analyzed. The paper ends with a conclusion section.

II. Specificities of Bipolar Lightning Discharges

Even if natural lightning downward discharges can also be bipolar, upward leaders from tall object usually initiate them [4]. Bipolar lightning discharges are much less common than negative ones but they may not be less common than positive ones according to Rakov [5]. As an illustration, 21 upward-initiated bipolar lightning flashes were observed among a total of 652 lightning (around 3%) flashes at the Gaisberg tower over the period 2000-2009 [6].

As they usually originate from tall objects, they are of particular interest for overhead lines with high towers like UHV lines or lines with towers located at the top of hills. They

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Paper submitted to the International Conference on Power Systems Transients (IPST2021) in Belo Horizonte, Brazil June 6-10, 2021.

are more frequent during winter and can lead to severe energy issues because of their high charges [15][16][18][19]. Nowadays, the physics of bipolar lightning is not well known [4] and research is essential to improve knowledge.

III. Measurements used in the study to represent lightning current

The measurements were performed at the telecom base station Miluccia in Corsica with a 500 kA maximum input range current transformer (Pearson model 2093) installed at the lightning rod located at the tower top [7][8], see Fig. 1. The measurement system includes an acquisition unit with a 4-channel card whose acquisition speed and vertical resolution are respectively 50 M samples per second per channel and 12 bits. The measurement system transfers data to the user with mobile Internet with an effective data rate of 56 kbits/s. A timing of measurements is performed using an integrated GPS receiver.

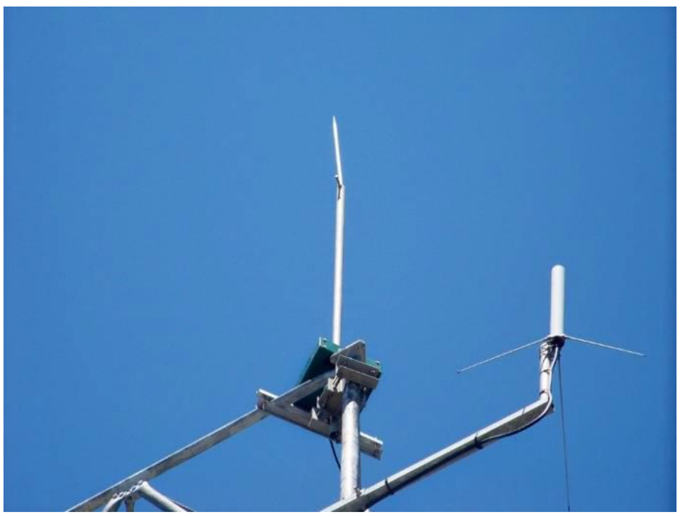

Fig. 1. Current transformer installed at the lightning rod of the telecom base station Miluccia in Corsica (photo taken from [2]).

The system has been designed by the company Sadovic Consultant.

During a recording period of one and a half year, 13 bipolar strokes have been measured by the system.

IV. Description of the considered configuration

A 500 kV bipolar configuration is considered. The pole to ground overvoltages (incident waves) at different distances from the lightning point of impact and for different lightning stroke currents are estimated with an EMTP-like program according to Fig. 2 and Fig. 3 below. The segments of line just before the substations are sufficiently long to prevent the reflection of the lightning overvoltages at the substations from influencing the overvoltage measurements. In this study, the incident waves due to the lightning strokes which propagate along the poles are considered and not their effects on the substations.

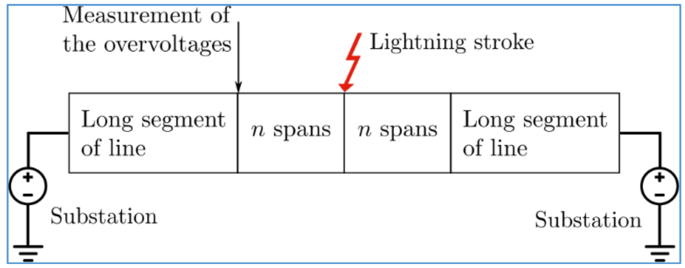

Fig. 2. Representation of the system considered in the study.

The line is without metallic return, it is equipped with 2 sky wires. The poles are constituted of 4 ACSR subconductors. The characteristics of sky wires and subconductors, and their position at towers and midspans are respectively given in TABLE I and TABLE II of appendix 1. The span length is uniform along the line and equal to 500 m. The length of the insulator strings is 5m, except when otherwise mentioned in the text.

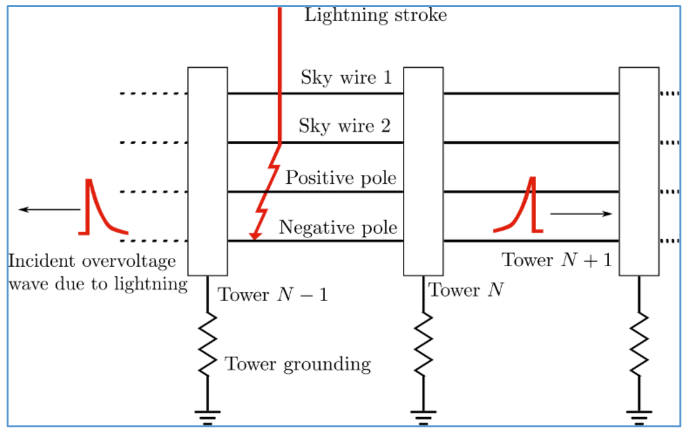

Fig. 3. Representation of the line near the point of impact.

V. Modelling of the system

The modelling of the system is performed according to the IEC application guide 60071-4 [9].

A. Spans close to the point of impact

Spans close to the point of impact are modelled with the Wide-band model [13], which represents transient wave propagation, coupling between conductors and skin effect with frequency dependent parameters. Corona effect is not taken into account in the study [10]. Consequently, calculation results are certainly slightly overestimated.

B. Spans far from the point of impact

Spans far from the point of impact are represented with the wide band model as a transmission line sufficiently long to avoid a non-physical reflection of the electromagnetic wave at its end.

C. Tower

The body of the tower is represented by a propagation line, crossarms are represented as inductances (1 µH /m).

D. Grounding impedance of towers

The grounding electrode of towers is modeled as a resistance. This model is adequate when the electrode is small and when the resistivity of the ground is not too high [11].

E. Insulator strings

Insulator strings are represented based on the model developed by T. Shindo and T. Suzuki [12] for the exact time of flashover occurrence. This model applicable for long air gap considers the predischarge current and represents the propagation of the leader. The insulator string is represented as an ideal switch, which closes, when the flashover conditions are met.

F. Lightning current

Lightning stroke currents are represented as a current source. The impedance of the lightning channel is not taken into account in the study.

VI. OVERVOLTAGE CALCULATION AND ANALYSIS

The paragraph focuses mainly on the shape of overvoltages due to specific bipolar lightning strokes from an insulation coordination point of view. The energy of the incident overvoltages is also calculated based on the formula below:

$$E = \int |v(t)|^2 dt$$

This quantity gives an image of the energy constraint applied to an equipment subject to the incident wave v.

It should be pointed out that the lightning strokes considered in this paper have a low charge compared to bipolar lightning strokes with millisecond scale current waveform [15][16], which could potentially give rise to much more energetic incident overvoltages.

A. Lightning stroke N°1 with an air gap length of 5m

The lightning stroke N°1 is applied to the negative pole at a position close to tower N (lightning stroke waves are shown in Appendix B, see Fig. 12, Fig. 13 and Fig. 14). Fig. 4 gives the overvoltages at the tower N close to the point of impact and at the 3 following successive towers N+1, N+2 and N+3.

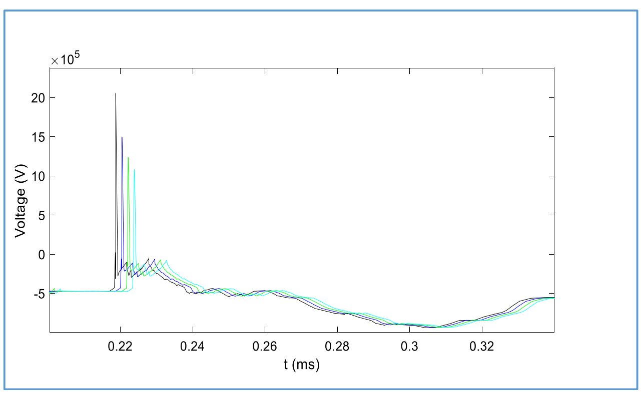

Fig. 4. Pole to ground overvoltage at the negative pole at the impacted tower N (—) and at tower N+1 (—), N+2 (—) and N+3 (—) when lightning N°1 strikes the negative pole close to tower 3.

This lightning stroke is not strong enough to lead to the flashover of an insulator string, considering the high insulation of the line. The first peak presents a high spike (more than 15 kA) during which the leader represented in the insulator string model moves rapidly because of the severe overvoltage between the terminal of the insulator string, but its duration is quite short and consequently the leader represented in the insulator string model does not have enough time to cross the airgap and to lead to a flashover. Consequently, the shape of the overvoltage, which propagates along the line, is similar to the shape of the lightning current. This first peak exhibits a strong attenuation when propagating, as it can be seen in Fig. 4. The negative oscillation of the current has a front duration of 42 µs, a time to half value of 50 µs and a crest value of 2.855 kA. The crest value of the negative oscillation of the overvoltage generated at the impacted tower is of the order of 920 kV. This overvoltage can be classified as a slow front overvoltage because of its long front duration. To evaluate the risk of damaging equipment related to this lightning stroke the critical front time strength U_{50} is calculated.

For positive polarity, U_{50} can be approximated by the following equation as proposed in [13]:

$$U_{50} = K \times 1080 \ln(0.46d + 1)$$

where d is the length of the air gap and K is the gap factor. For K=1.4 and d = 5m, U_{50}= 1800 kV.

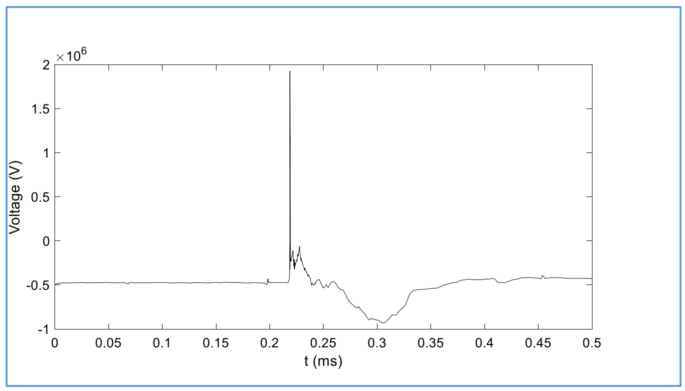

Fig. 5. Overvoltages between the terminals of the insulator string of the negative pole when lightning N°1 strikes this pole close to tower N.

The crest value of the overvoltage between the terminals of the insulator string of the impacted pole does not exceed 930 kV, if the first peak of very short duration is not considered because of its brief duration (see Fig 5.). Consequently, the overvoltages due to this lightning stroke do not exhibit a sufficiently strong enough crest value to be of interest from an insulation coordination point of view in this particular context, except maybe the first narrow peak in presence of wound equipment, but it has been shown in Fig. 4 that this peak is rapidly damped when propagating along the line.

The total charge transfer of the lightning stroke current is 0.26 C. (in the paper the total charge transfer is considered, here the sum of the absolute value of the positive and negative charge transfers). This value is quite low considering that the charge transfer of some bipolar lightning strokes can have a value of several hundreds of C [15][16]. The energy of the overvoltage at the impacted pole (tower N) is 135 10^6 V^2.s pole to ground. To assess the severity of this value, it is considered that the lightning withstand voltage of the 500 kV DC equipment at the terminal substations is 1550 kV. The energy of the 1.2/50 µs voltage wave used to test the equipment is of the order of 87 10^6 V^2.s pole to ground. This value is slightly lower than the energy of the calculated lightning overvoltage. The severity of lightning overvoltage can be explained by the fact that the shielding failure does not lead to a flashover of the insulator string, which would have reduced the level of overvoltage, and by the relatively long duration of the lightning stroke current. Regarding this aspect, the air gap model is quite important. The model used in this paper takes the dynamic of the leader propagation into account (see V. E.).

The conclusions would have been different if, as a simplification, we had supposed that the insulator string flashover when the overvoltage between its terminals reaches a value U_{90} such as:

$$U_{90} = U_{50}(1 + 1.3\sigma)$$

With σ (0.03 U_{50}) standard deviation of the flashover probability of the airgap [17].

U_{90} corresponds to the crest value of the standard lightning impulse, which leads to a flashover probability of 90% [17] and is equal to 1870 kV.

It would have been found that the insulator string flashovers and consequently less severe overvoltages would have been calculated. Hence numerical simulations show that the incident wave which would propagate along the pole stroked by lightning would have a lower energy: 50 10^6 V^2.s instead of 135 10^6 V^2.s

B. Lightning stroke N°2 with an air gap length of 5 m

In this paragraph, the lightning stroke N°2 strikes the negative pole at tower N.

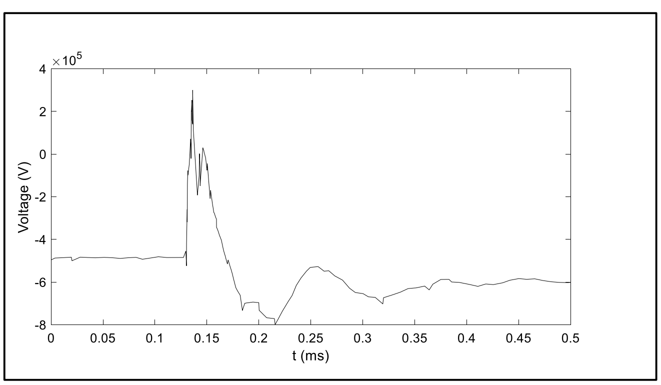

Fig. 6. Pole to ground overvoltage at the negative pole at the impacted tower when lightning N°2 strikes the negative pole close to tower N.

The pole to ground overvoltage at tower N is shown in Fig. 6. There is no flashover, consequently the overvoltage has a shape similar to that of the lightning stroke current. The surge impedance of the pole of the order of 350 Ω (this relatively low value is related to the presence of 4 subconductors) explains why the positive and negative crest values of the overvoltage are quite limited. A first (positive) oscillation whose front of a few µs compares to the one of a standard lightning impulse is followed by a negative oscillation with a front of the order of 70 µs, which can compare to the one of a standard switching impulse. This shape does not appear as critical regarding insulation coordination.

C. Lightning stroke N°3 with an air gap length of 5m

Fig. 7 shows the phase to ground overvoltages at tower N on the negative pole when this pole has been stroked by lightning (lightning stroke N°3), near this tower. As in the previous paragraph, there is no insulator string flashover and the shape of the overvoltage is similar to the shape of the lightning current. When a similar lightning strike impacts the the positive pole (see Fig. 8), the positive component of the lightning overvoltage adds up with the DC voltage and as a consequence the crest value of the total overvoltage reaches a higher value compared to a lightning striking the negative pole.

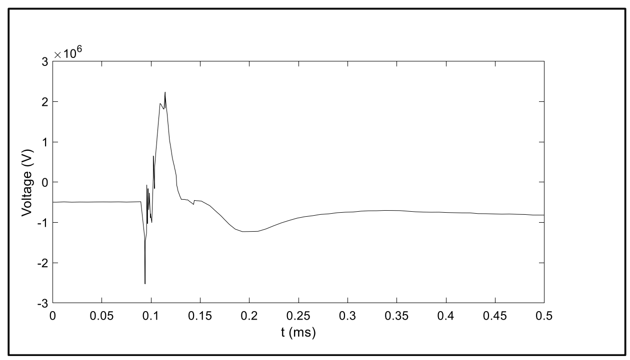

Fig. 7. Pole to ground overvoltage at the negative pole at the impacted tower when lightning N°3 strikes this pole close to tower N.

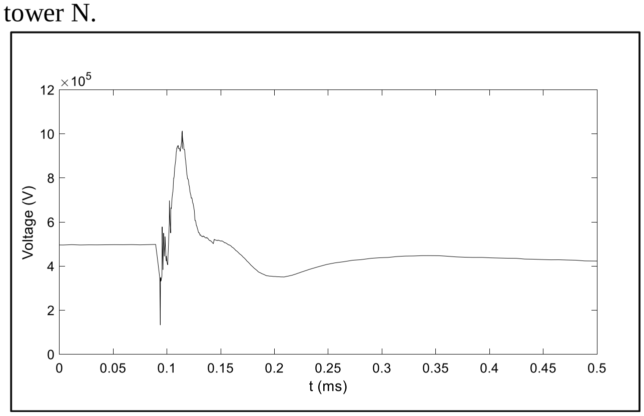

Fig. 8. Pole to ground overvoltage at the positive pole at the impacted tower when lightning N°3 strikes the negative pole close to tower N.

Nevertheless, the overvoltages are not severe enough to lead to a flashover because of the length of the insulator strings.

D. Lightning stroke N°3 with an air gap length of 3.8 m

In that configuration the insulator string length is reduced to 3.8 m. When lightning strikes the negative pole, there is no flashover, consequently the shape is similar to the shape obtained in the subsection above (see Fig. 9). When the positive pole is stroked (see Fig. 10), the insulator string at tower N flashover and the incident pole to ground overvoltage exhibits a severe front. However, the flashover occurs on the tail of the negative oscillation because of the flashover physics. Therefore, the duration of the positive overvoltage oscillation is slightly reduced, but the crest value has not changed.

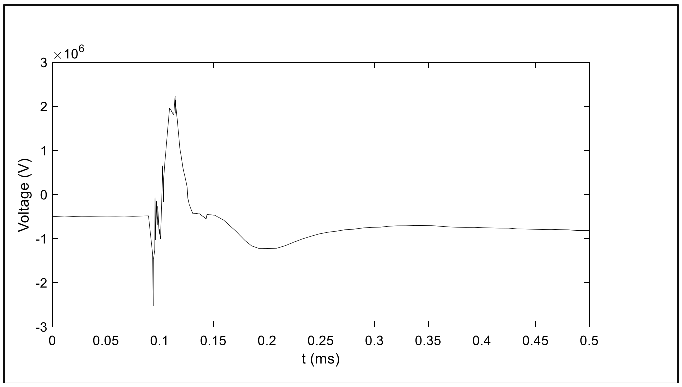

Fig. 9. Pole to ground overvoltage at the negative pole at the impacted tower when lightning N°3 strikes this pole close to tower N.

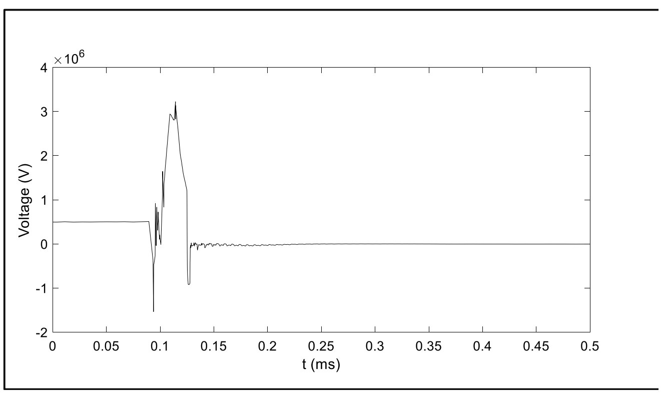

Fig. 10. Pole to ground overvoltage at the positive pole at the impacted tower when lightning N°3 strikes this pole close to tower 3.

E. Lightning stroke CIGRE concave comparable to lightning stroke 3 with an air gap length of 5m

Lightning strikes the positive pole near tower N. The shape of the current is CIGRE concave wave shape [9] with a crest value of 18 kA, similar to the one of stroke N°3. The other parameters of the shape are taken equal to the medium value of the derivative distributions (/If) [11]. The time to half value is 77.5 µs. Fig. 11 shows the phase to ground overvoltage at the positive pole close to tower 3. This lightning overvoltage exhibits 23 µs after its beginning a severe negative front, which corresponds to the flashover of the insulator string. The overvoltage due to lightning stroke N°3 does not exhibit such a front for the same length of the insulator string because the duration of the positive overvoltage pulse is not long enough to lead to a flashover [12].

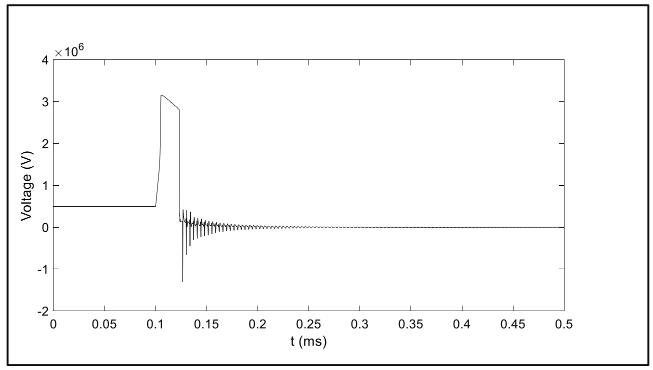

Fig. 11. Pole to ground overvoltage at the positive pole at the impacted tower when lightning strikes this pole close to tower N. The current of the lightning stroke is CIGRE concave (crest value 18 kA).

VII. Conclusions

When conducting an insulation coordination study, the risk of failure of equipment is based on comparisons between overvoltages estimated via EMTP-like software programs and the withstand level of equipment based on standard tests. One difficulty of the approach is related to the fact that the overvoltages and the standard test voltage does not have the same shape. In the paper, the issue is explored in a configuration in which bipolar lightning strikes a 500 kV DC overhead line. Lightning was represented based on the result of measurements conducted at a telecommunication tower. The lightning strikes were supposed to be at the origin of shielding failures. EMTP-like simulations show that they generate relatively high overvoltages with 2 components exhibiting different shapes: one can be compared to a lightning standard test and the other one to a switching standard test. The flashover of the insulator string, if it occurs, creates a severe front but does not necessarily diminish the crest value of the overvoltages because of the dynamic of the leader propagation through the airgap.

The overvoltages calculated correspond to an incident wave, which propagate toward the substations at the end of the overhead line and interact with them. This wave can be problematic for some equipment. For instance, many HVDC are equipped with reactors on the DC side. The electromagnetic transient behavior of these reactors subject to this incident wave should be carefully studied [14].

VIII. Appendix

A. Description of the overhead line

TABLE I
CHARACTERISTICS of the POLE'S SUB-CONDUCTORS and SKY WIRES

	External diameter (cm)	Diameter of the steel core (cm)	Lineic resistance (Ω/ km).
Sub-conductors (poles)	3	0.8	0.00996
Sky wires	2.04	0.765	0.1024

The distance between subconductors is 45 cm.

TABLE II
POSITION of POLES and SKY WIRES at TOWERS and SKY WIRES

	Horizontal distance (m)	Height at tower (m)	Height at midspan (m)
Sky wire 1	-5.15	37	22
Sky wire 2	5.15	37	22
Pole 1	6.85	28	13
Pole 2	-6.85	28	13

B. Measured lightning currents

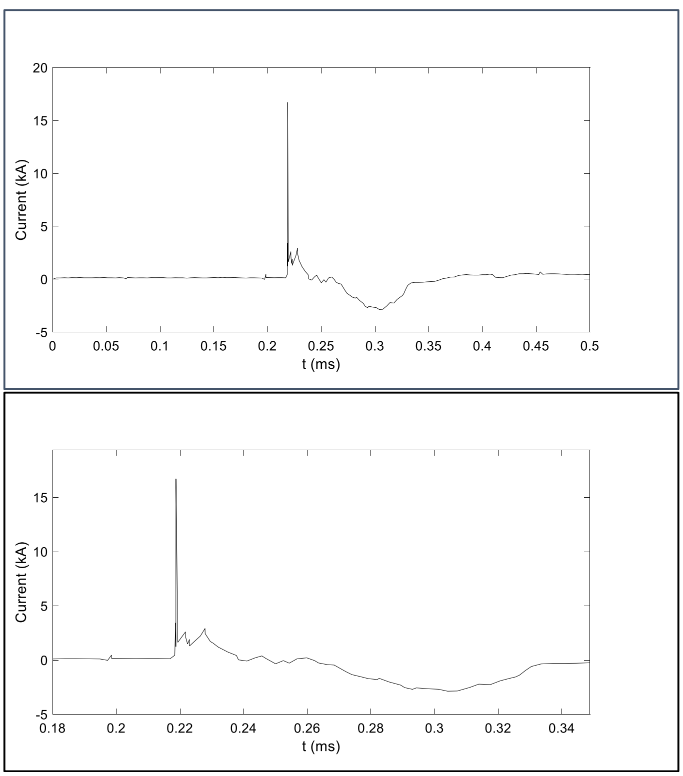

Fig. 12. Lightning current measurement N° 1. The lower figure is a zoom on the first part of the current.

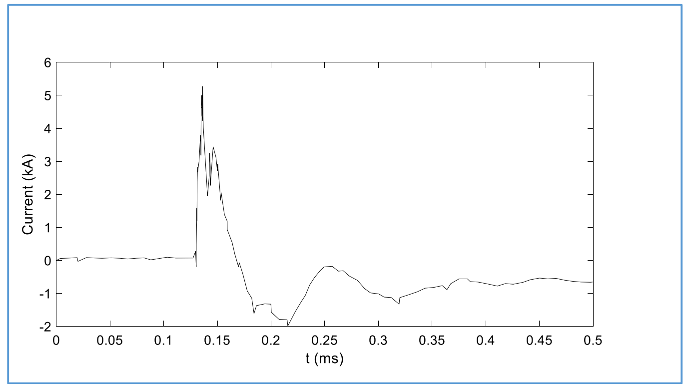

Fig. 13. Lightning current measurement N° 2.

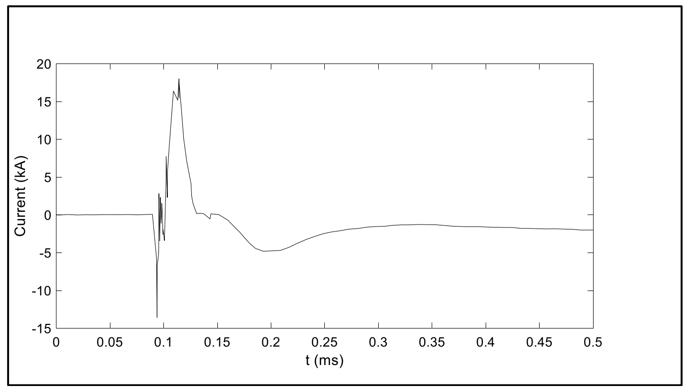

Fig. 14. Lightning current measurement N° 3.

Acknowledgment

The authors gratefully acknowledge the contributions of S. Sadovic and T. Sadovic, who designed and installed the lightning measurement system used to perform the measurements exploited in this paper. This work was funded by SuperGrid Institute, an institute for the energetic transition (ITE). It is supported by the French government under the frame of "Investissements d'avenir", No. ANE-ITE-002-01.

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