Lightning in hybrid cable-overhead lines and consequent transient overvoltages

F. Faria da Silva, Kasper S. Pedersen, Claus L. Bak

***Abstract*—Whereas lines that consist entirely of underground cable are naturally protected from lightning, the phenomenon must be considered for lines that are a mix of overhead lines and underground cables. The difference between overhead lines and underground cables wave impedances may lead to transient overvoltages caused by reflections at the transitions points. This paper explains the phenomenon and analyses the influence of modelling Corona effect, the grounding of the towers and of the cable's screen on the overvoltage magnitude. The analysis is made both for direct strokes on the overhead line phase conductor and for hits on the earth wire, with and without back flashover. For the most common situation, stroke on the earth wire, it is demonstrated that the cable's ground propagation mode is dominant, reducing the impact of the reflections.**

***Keywords*: Hybrid cable-overhead lines, Lightning, Corona, Transient Overvoltages.**

I. Introduction

THE use of underground cables for HVAC transmission became more common in recent years in several countries. Reasons behind this migration from overhead lines (OHL) to underground cables are public opposition to the construction of new OHL or lack of space in urban areas.

A possible line configuration consists in hybrid cable-OHL lines, where the line is subdivided in one or more cable/OHL sections; an example is the Kasso-Tjele line in Denmark that consists in 4 OHL sections and 3 double cable sections. The propagation of electromagnetic transients in hybrid lines present some differences when compared with lines consisting solely of cable or OHL, because of the differences in the characteristic impedances (an OHL's characteristic impedance is often several times larger than a cable's characteristic impedance), which results in reflections and refractions at the transition points.

The study of lightning in these hybrid lines is of particular interest, especially if the line has cable and/or OHL sections of short length, as the magnitude of current or voltage originated by the lightning transients can be substantially augmented or reduced at the cable-OHL transition points. As a result, severe overvoltage may be achieved depending on the relation between the characteristic impedances of the cable and OHL, the length of the cable and OHL sections, the characteristics of the lightning surge, i.e., peak current and rise time, or the equipment connected at the end of the line, among other parameters. This study is of special importance, because a flashover in the cable's insulation will lead to permanent damage.

The proper simulation of this phenomenon is not simple, since aspects as Corona effect, groundings (from both towers and cable's screens, in case of back flashover) and a correct modelling of surge arresters, if present, may have a strong influence in the waveforms and maximum magnitudes. Some of these are not easy to simulate, either because of the lack of information regarding some specific parameters (e.g., the exact impedance of the groundings) when doing the insulation coordination studies or the higher technical level of some modelling aspects (e.g., Corona).

This paper starts by providing a basic explanation of the phenomenon (Section II), followed by a description of the modelling approaches used for Corona effect and the OHL masts, including grounding (Section III). Simulations of lightning hitting a phase of an OHL directly or the earth wire are performed in Section IV, together with an analysis on the consequences of modelling Corona effect, of using a current dependent grounding model, of the cable's length and the type of cable's bonding. The paper concludes with a discussion of the results and a description of future work (Section V).

II. Explanation of Voltage Variation at Overhead Line-Cable Transition points

The variation of the voltage at the transition points is explained by the difference between the characteristic impedances of underground cables and OHLs, with the latter being normally several times larger than the former. As an example, the characteristic impedance of the OHL considered in this paper is 6.7 times larger than the one of the cable. The difference in the surge impedance leads to changes in the waveform, both voltage and current, at the OHL-cable transition points. For the voltage the variation is given by (1), where, V_I is the incident voltage, V_F is the voltage refracted forward, V_R is the voltage reflected back, Z_B is the characteristic impedance of the line to where the wave is going to propagate to and Z_A is the characteristic impedance of the line where the line is propagating. Thus, it can be concluded that the voltage increases when propagating from a cable to an OHL and decreases when propagating from an OHL to a cable, typically. For the line used in this paper, the voltage increases 1.84 times and decreases 6.13 times for the transitions cable-OHL and OHL-cable, respectively. Fig. 1 shows an example of the phenomenon by injecting a

F. Faria da Silva is with Aalborg University – Department of Energy Technology, Denmark (e-mail of corresponding author: ffs@et.aau.dk).

Kasper S. Pedersen is with Energinet.dk, Denmark (e-mail: kpd@energinet.dk).

Claus L. Bak is with Aalborg University – Department of Energy Technology, Denmark (e-mail: clb@et.aau.dk).

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lightning-type waveform close to the transition point at one phase of the OHL and at one conductor of the cable (this is just for example, as it is not possible for the lightning to hit the cable's conductor directly; additionally, the values of lightning's current are multiplied by 10, in order to ease the visualisation).

$$\begin{cases} V_F = V_I \dfrac{2Z_B}{Z_A + Z_B} \\ V_R = V_I \dfrac{Z_B - Z_A}{Z_A + Z_B} \end{cases} \tag{1}$$

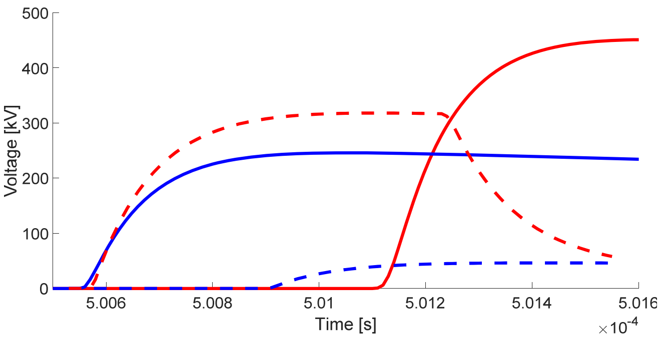

Fig. 1. Voltage in cable (blue) and OHL (red) close to the transition point. Solid lines: wave propagating from cable to OHL; Dashed lines: wave propagating from OHL to cable;

Fig. 1 shows only one refraction/reflection, but multiple may occur if the length of the cable and/or OHL are short between two transition points, be it a cable/OHL transition or one end of the line, which may result in a build-up of the voltage. Fig. 2 shows the voltage at the transition point for a standard 1.2/50µs lightning impulse of 2kA hitting one phase of the OHL at 200m from a cable section. In one of the cases (red line) the cable is 100km long, being 1km long and connected to an OHL that is 100km long in the other (blue line). The case with the shorter cable shows multiple reflections that happen at both ends of the cables, resulting in a maximum peak transient voltage of 178kV, instead of 59kV. The example is with the cable bonded at both-ends, the use of cross-bonding would result in more reflections and potentially an even larger voltage.

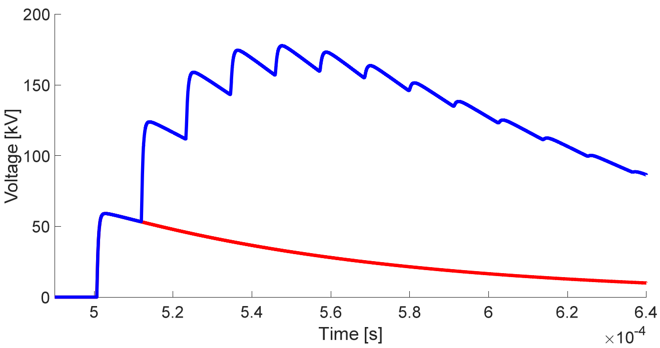

Fig. 2. Voltage at the transition point due to lightning hitting the OHL at 200m. Red: 100km long cable; Blue: 1km long cable

III. FACTORS THAT MAY AFFECT THE RESULTS

The previous section introduced the phenomenon in a simplified way. Normally, only low current lightning hits the phases directly; in the case of this line and according to Energinet.dk internal estimation, the magnitude is 2kA for vertical lightning and 12,3kA for the more rare non-vertical lightning, leading to small overvoltages. Larger overvoltages are attained when a back flashover occurs, which is also more common, making this phenomenon more relevant. However, the simulation of back flashover also requires more details and the waveforms may be influenced by several factors, as the grounding impedance of the towers, the propagation of the wave in the earth wires and reflections at the towers, or the damping due to Corona effect. It is beneficial to evaluate the error of not modelling these aspects, before trying to assess the changes in the overvoltage at the cable.

The phenomenon is first simulated considering current dependent resistances for the towers' groundings, corona effect and the modelling of six towers. The cable is 1km long with both-ends bonding and connected to 1000km OHL at both ends, in order to have reflections only at the transition points. The line is not energised to ease the analysis of the results and the phenomenon; given the short duration of the phenomenon the only difference would be on the magnitude of the voltages. The data of the cable and OHL is the one of the previously mentioned Kasso-Tjele line, but with the lines, both OHL and cable, simplified from double to single circuit, which will result in the back flashover occurring only for very high currents.

A. *Modelling of Corona Effect*

The corona's inception voltage (V_C) is estimated using the Peek's formula (2), [1], where g is the critical strength of the air (30kV/cm, assuming uniform field), m is the surface irregularity factor (0.75), δ is relative air density (1), p is the voltage polarity factor and r in the conductor radius in cm.

$$V_C = gm\delta p\left(1 + \frac{0.308}{\sqrt{\delta r}}\right) \tag{2}$$

The q-V curve of the line for the transient simulation is approximated by a parabolic expression and the dynamic capacitance (C_C) to the ground during corona is given by (3), [2], where Cg is the line geometric capacitance and B is given by (4), where n is the number of bundle conductors. The change in the capacitive coupling between phases and/or ground wires due to Corona are not considered, as well as the resistive losses due to Corona, because of the short duration.

In the software model, Corona effect is modelled via a variable capacitance calculated according to (3), connected via a diode to a DC voltage source with a magnitude equal to the inception voltage. Fig. 3 shows the single-line diagram of the circuit used. The OHL is divided into sections of 50m with the circuit of Fig. 3 added between each of these sections. The distance between sections was obtained by simulating a 200kA standard lightning impulse hitting an OHL and reducing the distance until the results stopped changing.

$$C_C = C_g B\left(\frac{V}{V_C}\right)^{B-1} \quad (3)$$

$$B = \begin{cases} 0.22r + 1.2, & \text{Single Cond. - Positive Polarity} \\ 0.07r + 1.12, & \text{Single Cond. - Negative Polarity} \\ 1.52 - 0.15\ln(n), & \text{Bundle - Positive Polarity} \\ 1.28 - 0.08\ln(n), & \text{Bundle - Negative Polarity} \end{cases} \quad (4)$$

Fig. 3. Circuit used to simulate Corona effect

B. Modelling of Back Flashover and Tower

The insulators are modelled by considering a capacitance of 100pF per insulator's disc, resulting in a capacitance of 4.76pF. The back flashover of the insulators is approximated using volt-time curves that are function of the insulator's length, as given by (5), [3], where L is the length of the insulator. If the voltage at the terminals of the insulators exceeds (5) during the transient initiated by the lightning, a circuit breaker in series with an inductor closes in the simulation short-circuiting the insulator; the inductance value calculated using Energinet.dk's internal guidelines is 3.2µH.

$$V_{BFO}(t) = 400L + \frac{710L}{t^{0.75}} \quad (5)$$

The towers' mast and arms are modelled using Bergeron models, by setting the propagation speed and characteristic impedance. The values are obtained by approximating the tower's mast and arms by cylindrical elements (top of the mast) and conical elements (bottom of the mast and arms) [1].
The towers' groundings are modelled in function of the current, in order to account the soil ionization (6), [4], where R_0 is the resistance at low frequency and low current, I is the current and I_g is the limit current necessary to initialize soil ionization. The grounding at the OHL-cable transition is fixed at 10Ω.

$$R(I) = \frac{R_0}{\sqrt{1 + \frac{I}{I_g}}} \quad (6)$$

IV. SIMULATIONS

Two different scenarios are considered, lightning hitting the phase directly and lightning hitting the tower's mast, i.e., the earth wire. Each scenario is divided into two sub-cases, consisting in having the lightning hitting the OHL at 25m from the cable, which corresponds the tower closest to the cable, and at 375m, which is the location of the second tower from the cable. The surge arresters and instrument transformers at the transition points are not considered, in order to better compare the influence of the different factors.

A. Lightning hitting the phase conductor

The first simulation considers lightning hitting the phase directly with a peak current of 12kA, which is the theoretical maximum for non-vertical lightning in the original line.
The 12kA current is not sufficiently high to induce Corona, as the use of bundled conductors with three-phase conductors (TRIPLEX) results in an inception voltage around 2000kV, whereas it would be around 1000kV for a single conductor of equal radius. Thus, the simulations are repeated with a current of 24kA and the towers' masts not included in the model, as a flashover between phase and mast would occur for this lightning current magnitude. Fig. 4 shows the simulation results for the 24kA lightning. The results for 12kA are similar with the voltage magnitude being approximately half.
The simulations results show that the modelling of Corona is not relevant in this scenario, as the difference for the case where lightning hits at 25m from the transition point, the worst-case, is negligible. When the lightning occurs further away, there is a variation due to Corona, but the error in the estimation of the peak overvoltage for the lightning at 375m was of 2%. The variation in the travelling time was negligible in both cases.

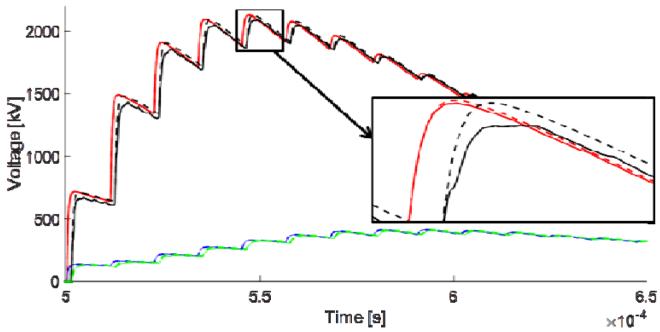

Fig. 4. Voltage at the closest OHL-cable transition for a lightning current of 24kA. Red: Lightning at 25m; Black: Lightning at 375m; Green and Blue: Voltage at sound phase; Dashed line: Without corona; Solid line: With corona

B. Lightning hitting the earth wire

A lightning current of 100kA is first considered, as 97% of the lightning current is inferior to this value [5]. This current magnitude does not lead to a back flashover, but it allows showing some interesting behaviour. It is important to refer that a lightning current of 100kA is expected to result in a back flashover and it will if the tower's original layout is used in the simulations. However, the changes made in the tower's original layout, which affect the coupling between phase conductors and earth wires, the fact that the lines are not energised, the long length of the insulator and the location of the lightning lead to not having back flashover even for this current magnitude. This does not affect the theoretical analysis made in the paper, but results in this unexpected situation.
Fig. 5 shows the voltage in one phase at sending and receiving ends of the cable. The voltage at the receiving end of the cable has an initial magnitude smaller than expected when compared

with the case of lightning hitting the phase conductor and with an initial negative polarity instead of positive. This happens because the ground propagation mode is the main mode being excited at the sending end for a back flashover, with the magnitudes of the coaxial modes being rather small and the ones of the intersheath modes virtually zero. The increase of the voltage at the receiving end (a little after 0.55ms for Fig. 5-up) is the arrival of the ground mode. This topic is addressed in more detail for the case with back flashover. For the readers not familiarised with the propagation modes of a cable, more information is available at references [6]-[8].

Corona effect is more noticeable when the lightning hits further away from the cable, as expected, but this case also corresponds to lower overvoltages, as the energy propagating in the cable direction can flow to the ground in the last tower before the cable, something that is not possible when the lightning hits in front of last tower. The double exponential nature of the lightning waveshape together with short distance between towers also means that the several reflections occur when the voltage waveform is at maximum, as it is observed in the zoom areas from Fig. 5; a surge arrester would operate in this area, further reducing the differences between modelling or not modelling Corona effect. Therefore, it can be proposed that the modelling of Corona effect may be neglected at first and added if the overvoltage is over a defined maximum threshold or if the simulations indicate that the surge arrester's class is not suitable.

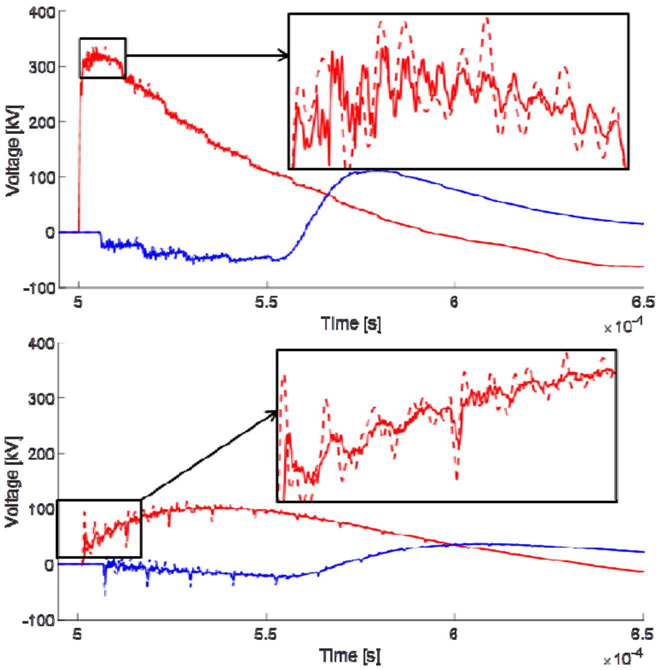

Fig. 5. Voltage in one phase at the sending (Red) and receiving (blue) ends of the cable. Solid lines: With corona; Dashed lines: Without corona; Up: Lightning at 25m; Down: Lightning at 375m

The simulations are repeated for a peak current of 200kA, in order to obtain a back flashover. However, even with this high current back flashover is only attained for lightning hitting the second mast from the cable and so, the length of the insulators is reduced in order to initiate a black flashover. The reason why the two towers appear to have different insulation strengths is that the back flashover happens when the reflection from the neighbour towers arrive. In the case of the second mast, the neighbour towers are exactly at the same distance and reflected voltages add to each other; in the case of the last tower, there is only one neighbour tower at 350m and the other direction connects to the ground at 25m.

Fig. 6 shows the waveforms with a back flashover at 25m and 375m from the cables. Besides the expected larger overvoltage, the waveform is also different from Fig. 5; part of the energy flows from the phase conductors of the OHL into the cable's cores leading to reflections at the transition points alike those of Fig. 4 and a voltage waveform at the receiving end that shows the same polarity of the sending end for the first reflections. Alike before the Corona effect can be neglected for the case of lightning hitting the last tower. However, the results for the lightning hitting the tower at 375m seem to be inaccurate, with the modelling of Corona effect resulting in a large difference, even a larger overvoltage, and a waveshape that does not show large reflections.

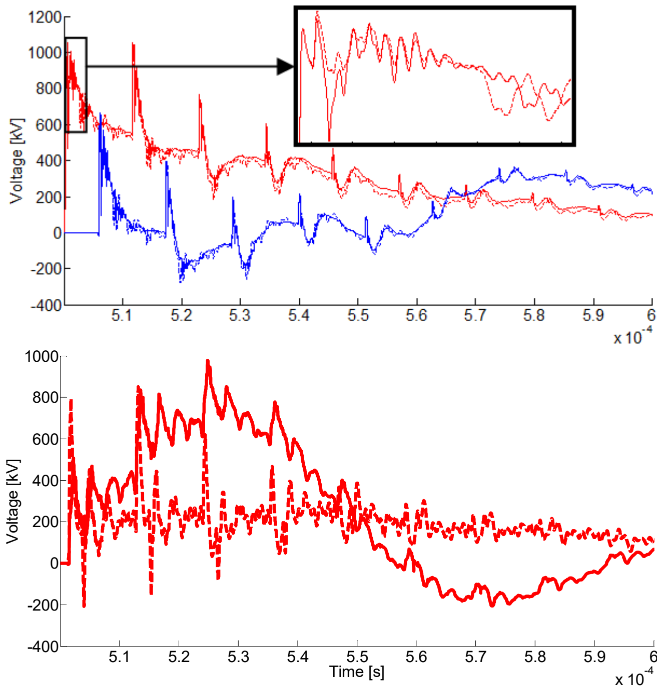

Fig. 6. Voltage in one phase at the sending (Red) and receiving (blue) ends of the cable. Solid lines: With corona; Dashed lines: Without corona; Up: Lightning at 25m; Down: Lightning at 375m

This indicates that the method used to model Corona effect, i.e. the use of shunt branches, may not be suitable for the case of back flashover. The causes of this problem are known and several references indicate that numerical oscillations may occur when this modelling approach is used [1], [9], [10], because of rapid change of voltage and diode switching actions, which lead to big variations in one time step of the shunt capacitance used to simulate corona effect and consequently, to inaccurate waveforms. Fig. 7 shows an example of this situation for the model used in this paper, where it can be observe a jump of the voltage around 0.5029ms, which is a result of a sudden variation of the shunt capacitance, as previously explained. This situation is more likely to occur if a sudden large voltage variation arises in the circuit, as it happens for a back flashover and/or when several voltage reflections/refractions superimpose, which is the case in Fig. 6(down).

This problem also raises the question if the previous simulations that consider Corona effect can be trusted or if they should also be discarded. One characteristic of numerical oscillations as these ones is that one can detect them visually, because of the high sudden voltage and capacitance value variations associated to (see Fig. 7). They can also be present at a small scale, but in that case, the changes will be small and around an average value. This means that the conclusions made for Fig. 4 and Fig. 5 are still valid, as these voltage oscillations caused by numerical problems were not observed in the waveforms; the former, which is for a circuit with long OHLs and it has fewer reflection points, even shows a behaviour alike that registered in measurements of Corona in long lines, as those available in [2]. This situation will be study with more detail in future work where different possible modelling approaches are to be verified.

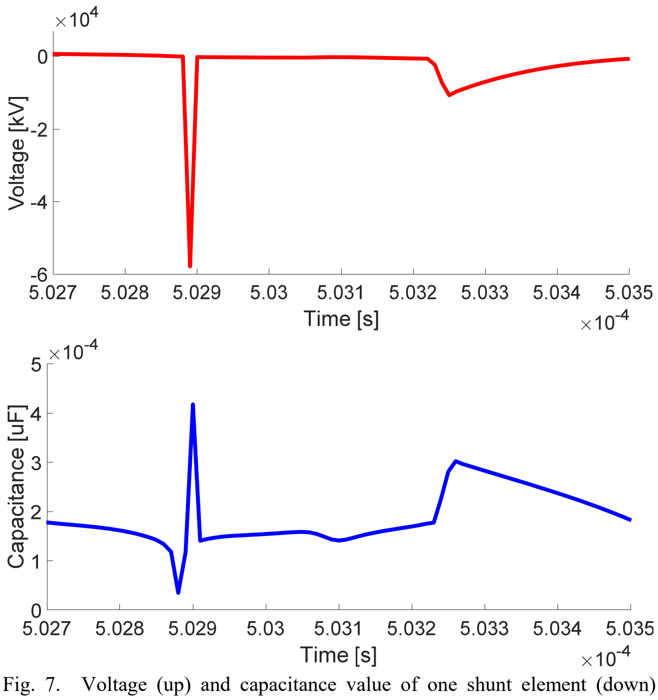

Fig. 7. Voltage (up) and capacitance value of one shunt element (down) during a transient due to lightning

An interesting difference between Fig. 6(up) and Fig. 4 is that the voltage does not build up due to the reflections, with the second main reflection leading to a peak voltage approximately equal to the first and with the voltage peak magnitudes decreasing after that. As previously indicated the cable's ground mode is the propagation mode being more excited, as also shown in Fig. 8(up). The propagation speed of the ground mode is several times lower than the speed of the coaxial modes (a relation around nine is typical) and several reflections of the coaxial modes occur for each reflection of the ground mode, with the latter having also larger attenuation for high frequencies. Thus, the reflections of the ground modes are not relevant for assessing the overvoltages if the cable is three-phase single-core; a possible exception may be situations where an earth continuity conductor is installed, as it may increase the propagation speed and decrease the attenuation of the ground mode; this analysis is left for future work. Fig. 8 (down) demonstrates this conclusion by showing several reflections of the coaxial mode at the receiving end of the cable before the arrival of the ground mode and that whereas the magnitudes of the formers increase from the sending to the receiving ends (observe the first reflection) the latter decreases.

For these reasons the peak overvoltage in the cable caused by back flashover is either immediately at the moment that the wave reaches the transition for the first time or one of the first reflections if the cable is short enough (see section IV.D), not being observed a build-up of the voltage as seen in Fig. 4. Again, the conclusion may change if an earth continuity conductor is present.

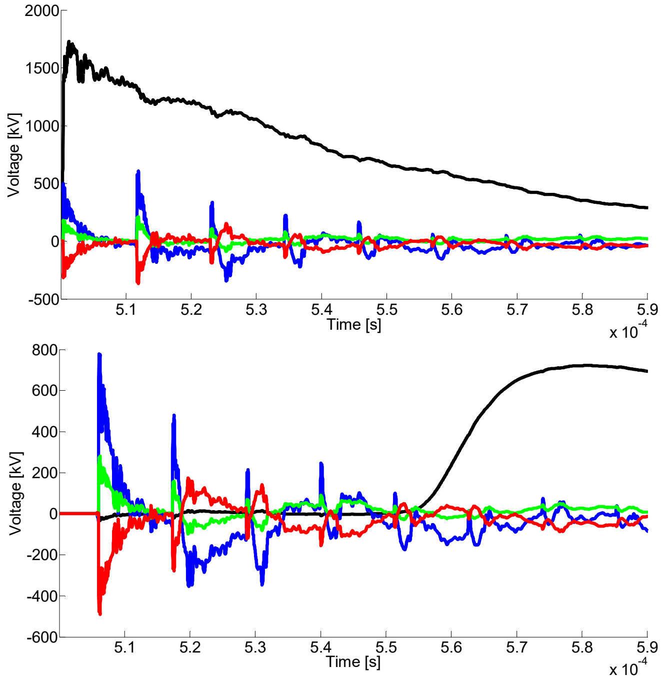

Fig. 8. Voltage propagation modes for a back flashover. Black: Ground mode; Blue, Red and Green: Coaxial modes; Up: Voltage at the cable's sending end; Bottom: Voltage at the cable's receiving end

C. *Influence of Tower's Grounding*

Based on the results of the previous section the simulations made in both this and next sections do not model Corona effect and consider only the case where the lightning hits the tower closest to the cable, with a magnitude of 200kA and a shorter insulator, in order to guarantee back flashover.

Fig. 9 shows the voltage at the transition point for a variable tower's groundings (6) and one fixed at 20Ω (the value for low current magnitude and frequency) showing a large difference between them, up to a maximum of 200kV. It is not shown, but the current dependent resistance decreases to a value of 8Ω during the transient, which explains the difference.

To model a tower's grounding according to (6) is simple and differences in computational time between using a fix resistance and having software performing the operations from (6) are negligible. Therefore, it is suggested to consider always the current dependence for the tower's grounding. Additionally, given these results, one can also argue that the modelling of the grounding resistance common to the earth wires and cable's screens at the transition point, which is normally simulated by a fixed value, should maybe also be modelled in more detail. Fig. 10 simulates a case where these groundings are modelled according to (6) and differences exist in the first instant with an error of 120kV in the estimation of the first peak voltage, which would be the largest one if the cable is long enough. Thus, the previously recommendation of the towers' groundings is also extended for the groundings at the transition points.

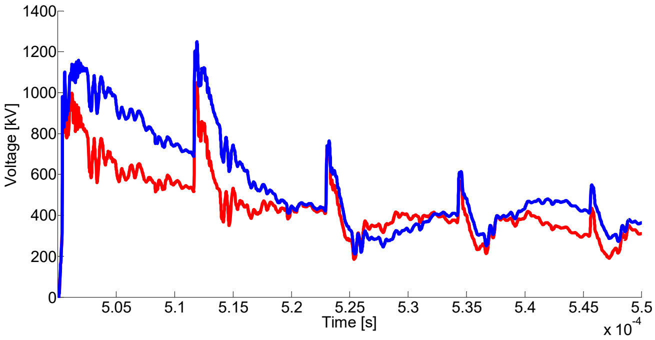

Fig. 9. Voltage in one phase at the sending end of the cable. Red: Current depending grounding at towers; Blue: Fixed 20Ω grounding

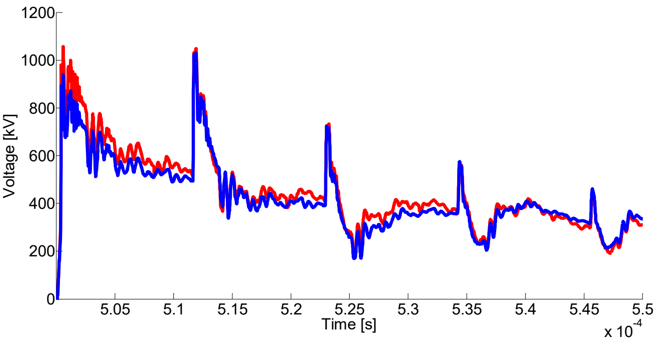

Fig. 10. Voltage in one phase at the sending end of the cable. Red: Current depending grounding only at towers; Blue: Current depending grounding at towers and screen's grounding points

D. *Influence of the Cable's Length and Bonding*

Previous simulations (Fig. 6-up) showed that a second peak overvoltage around 0.512ms whose magnitude is similar to the first overvoltage around 0.5ms. The magnitude of the first overvoltage is not dependent on the cable's length or bonding, but the magnitudes of later peak voltages are. Fig. 11 shows the influence of the cable's length on the waveform, whereas Fig. 12 shows the influence of the bonding for a 9km cable, to use realistic lengths associated to cross-bonding.

It was previously demonstrated that ground mode is dominant for back flashover and that the maximum overvoltage is at the instant that the wave generated by lightning reaches the transition point. However, if the cable is sufficiently short it allows the reflection(s) of the coaxial mode to build up sufficiently and lead to a larger overvoltage. Fig. 11 shows that only for cable with lengths inferior to 1000m is the maximum overvoltage due to a reflection. This is not sufficient to conclude that 1000m is the reference length for all cases, as the reflection/refraction coefficients depend on the characteristic impedances of the cable and OHL, whereas the propagation's speed and attenuation of the different modes depends on the cable (however, the differences in these two quantities between typical single-core HV cables should be minor at high frequencies).

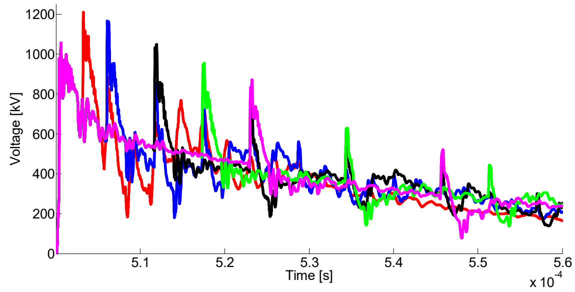

Fig. 11. Voltage in one phase at the sending end of the cable for different cable lengths. Red: 250m; Blue: 500m; Black: 1000m; Green: 1500m; Magenta: 2000m

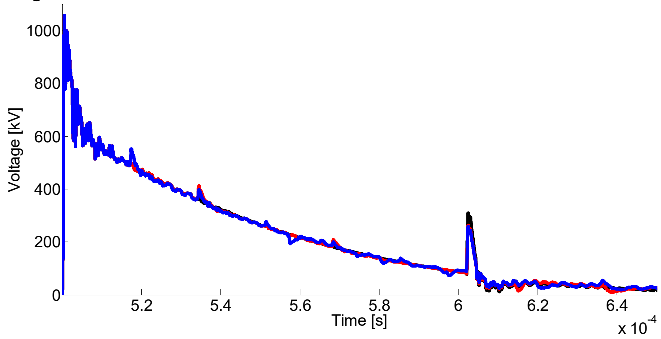

Fig. 12. Voltage in one phase at the sending end of the cable for different cable bondings for a 9000m cable. Black: Both-ends bonding; Red: 1 major cross-section; Blue: 2 major cross-sections

V. Discussion and Conclusions

This paper intended to study the phenomenon of lightning in hybrid cable-OHL lines and the potential rise of large overvoltages due to reflections and/or refractions at the cable-OHL transition points. The case of lightning hitting the OHL's phase is similar to a normal switch-on energisation, but with potentially larger overvoltages, showing a build-up of the voltage caused by several reflections at the two ends of the cable. The case of back flashover is more interesting, both because it is more likely to happen than a direct hit into the phase and because the voltage waveform shows a distinct behaviour. The fact that the largest part of the energy is not flowing in the conductors of the OHL, but the earth wire(s), means that the main propagation mode being excited at the cable is the ground mode. This leads to two potential scenarios:

- the cable is sufficiently long for the largest overvoltage peak be the one that occurs when the wave hits the transition point for the first time, with the overvoltage depending mainly on the lightning's current magnitude and on the relation between the characteristic impedances of OHL and cable, being independent of the cable's length;

- the cable is short and the maximum overvoltage occurs later at one of the reflection instants. This means that the cable length influences the expected overvoltage and thus, the evaluation of surge arresters may be more important for short cable lines.

The limit cable length in this paper between the two scenarios was 1000m, but the length will vary depending on the characteristic impedances of the OHL and cable.

It was also demonstrated that the modelling of Corona effect is not required if the lightning hits the last tower before the cable, whereas the model of the tower's grounding has a substantial influence in the simulated overvoltage and that simulation without current dependent grounding is a worst case consideration.

Several aspects are left for future work, because of page limitation and the need to introduce the problem main characteristics first. More specifically:

- the changes in the results when using surge arresters, which will reduce the different between reflection overvoltages and the overvoltage at the moment that energy reaches the transition point, for the cases where the former is larger.
- the influence of an earth continuity conductor, which may lead to an increase of the overvoltage caused by reflections of the ground's propagation mode.
- the modelling of Corona using other modelling approaches and potential changes of the waveforms.
- a general expression for estimating the critical length based on the relation between the surge impedances of the OHL and cable will be researched.

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