Insulation Coordination for HVAC Cable Sheath Bonding Systems in Mixed OHL-UGC Connections Using the Lightning Statistics: A Case Study for the Dutch 110 kV Transmission Grid

K. Velitsikakis, I. Tannemaat

***Abstract*--In mixed/Syphon connections, the cable system as a whole can be subjected to fast-front overvoltages due to lightning strikes, either directly on the phase conductors or on the shield wires of the overhead line(s) connected to the cable. In this paper, a methodology is presented that facilitates the calculation of the failure rate performance of a cable's sheath bonding system due to lightning strikes on the connected overhead line(s).**

***Keywords*: bonding lead, lightning performance, MTBF, sheath bonding system, SVL , Syphon connection**

I. Introduction

Syphon or mixed connections, i.e., connections consisting of both overhead line (OHL) and underground cable circuits (UGC), become more common in the HV and EHV grids. In these connections, the cable system can be subjected to fast-front overvoltages due to lightning strikes, either directly on the phase conductors or on the shield wires of the overhead line(s) connected to the cable [1-4].

Typically, surge arresters are installed at the cable termination towers to provide sufficient protection for the cable main insulation against lightning overvoltages [5]. The same applies for the cable sheath bonding system, where -depending on the bonding design- sheath voltage limiters (SVLs) are installed to limit the transient overvoltages on the metallic sheath to acceptable levels. In general, sheath bonding systems should have an appropriate insulation coordination design, where the material or insulation medium used are capable to ensure the required performance under transient overvoltage conditions. The insulation coordination of these systems should, therefore, consider the recommendations given in [6-7]; one of the main recommendations is that the bonding leads should be as short as possible and should have a maximum length of 10m. However, the impinging overvoltages in a cable system due to lightning strikes on the connected overhead lines are directly related to the design of the transmission towers and the specific lightning characteristics (e.g., lightning flash density, lightning current distribution, etc.). Consequently, there could be cases, where detailed calculations may be required to evaluate the sheath bonding system performance against fast-front overvoltages. For instance, in cases when the link boxes need to be installed at distances to the cable joint larger than 10m (e.g., due to land access limitations), or in areas with high lightning activity or even in cases an overhead line has a poor lightning performance (e.g., due to high tower footing impedance values).

In this paper, a methodology is presented that facilitates the calculation of the failure rate performance of a cable's sheath bonding system due to lightning strikes on the connected overhead line(s). The methodology consists of two steps: 1) detailed ATP simulations for the calculation of the minimum critical lightning current that results in the exceedance of the defined insulation withstand levels of the sheath bonding system and 2) the calculation of the failure rate performance based on the (national) lightning statistics. As an example, for the application of the methodology, the paper presents the findings and conclusions of a practical study case in the Dutch 110 kV transmission grid. This case refers to a double-circuit Syphon connection, where the bonding leads of the cables' sheath bonding systems could reach lengths of up to 35m due to land access limitations. Last but not least, the main modelling assumptions in ATP and the study starting points are also discussed.

II. Description Of The System Under Study

TenneT, the Transmission System Operator in the Netherlands and in part of Germany, is realizing the new 380 kV overhead line connection in the north of the country [8]. The 40km long overhead transmission line consists of four circuits and 121 towers of the Wintrack pylons design. Two circuits will connect the 380 kV substations Eemshaven and Vierverlaten. Temporarily, the other two circuits connected to the Eemshaven380 substation will partly remain de-energized while at the other end they will be connected to the 110 kV substation Vierverlaten (noted as Substation C in Figure 1). The latter two circuits will be connected to a small 110 kV ring structure, as shown in Figure 1. At Substation B, two existing 12km underground cables are connected, circuit #1 noted in yellow and circuit #2 noted in red.

In circuit #1, a new 1.5km underground cable will be connected between the existing cable and the existing 110 kV overhead transmission line circuit that consists of lattice towers. For the sheath bonding system of the new cable, the direct cross-bonding scheme was selected. In this scheme, there is one major section divided in three minor sections of equal lengths

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and no SVLs are applied at the cross-bonding points. At the termination tower side, the earthing box is placed at a distance of approximately 10m from the cable terminations. It needs to be noticed that the earthing grid of the cable termination field is not connected to the earthing of the cable termination tower. At the other end of the major section, the earthing box is placed at a distance of 35m from the cable joints. Figure 2 presents the simplified schematic of circuit #1.

In circuit #2, a new 0.9km underground cable will be connected between the existing cable and the new overhead transmission line circuit that consists of Wintrack pylons. The new cable is single-bonded; at the termination tower side, the cable metallic sheath is left ungrounded and the SVL box is placed at a distance of approximately 10m from the cable terminations. Similarly to circuit #1, the earthing grid of the cable termination field is not connected to the earthing of the termination pylon. At the other end of the cable, the earthing box is placed at a distance of 35m from the joint. An earth continuity conductor (ECC) is connected between the two earthing ends of the new cable section. At the cable termination tower, 110 kV line insulator sets are installed and the rest of the Wintrack pylons are equipped with 380 kV line insulators. Figure 3 presents the simplified schematic of circuit #2.

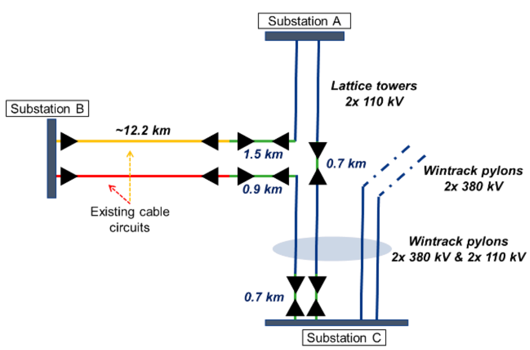

Fig. 1. Schematic of the 110 kV grid under study

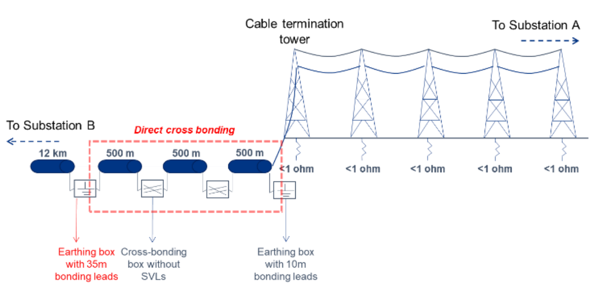

Fig. 2. Simplified schematic of cable circuit #1

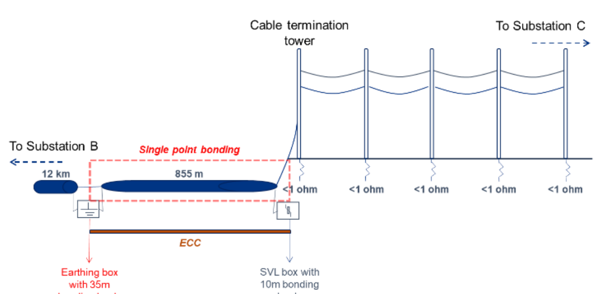

Fig. 3. Simplified schematic of cable circuit #2

III. Methodology For Calculating the Failure Rate

A. *Impinging surges in a cable sheath bonding system due to lightning*

In general, lightning overvoltages could stress the main insulation of the cable as well as that of the metallic sheath in the form of either impinging travelling waves, following strikes on the overhead line circuits connected to the cable, or induced voltages, following strikes on the ground in the vicinity of the cable [9-10].

- *Shielding failures*: the downward leader bypasses the shield wire(s) and terminates on one of the phase conductors. The voltage wave will travel through the phase conductor to the cable conductor, resulting in the excitation of coaxial coupling mode between the cable conductor and the metallic sheath [11] and, therefore, in induced overvoltages in the latter.
- *Back-flashovers*: the downward leader terminates on the shield wire or the tower structure. The potential of the earthed metallic structure rises due to the flow of the lightning current through the tower body and its earthing impedance. Should this potential be high enough, a flashover will occur from the structure across one or more insulators to the phase conductors. Also in this case, coaxial coupling mode is excited between the cable conductor and the metallic sheath. The resulting induced overvoltages are, typically, much higher than in the case of shielding failures.
- *Lightning currents in the metallic sheath:* in many cases, the earthing electrodes of the cable termination tower and of the cable sheath bonding system are connected to each other. Should a lightning strike the tower or the shield wire, part of the current flowing down the structure will enter the cable sheath bonding system (depending on the applied bonding scheme). Consequently, overvoltages will occur in the metallic sheath.
- *Lightning currents in the ground*: the downward leader bypasses the shield wire(s) and the phase conductors and terminates on the ground. A Ground Potential Rise (GPR) occurs; depending on the lightning current amplitude, the soil characteristics and the position of the cable relatively to the stroke point, the GPR could stress the insulation withstand of the cable's outer sheath.

As explained below, the methodology presented in this paper considers lightning overvoltages in the cable metallic sheath only under back-flashover conditions.

B. *MTBF calculation process*

In mixed OHL-UGC connections, the magnitude of the lightning overvoltages in the metallic sheath of a cable, at sheath sectionalization points or at ungrounded sheath ends are to a large extent defined by the lightning performance of the overhead line(s) connected to the cable. Next to that, important parameters that may define the resulting sheath overvoltages are [4,6]: the cable type, the cable circuit length, the major section length in a cross-bonded cable system, the location of the grounded sheath end in a single-bonded cable system, the type of the sheath bonding leads, i.e., single-core or coaxial, the bonding leads length, the protective level of the selected cable surge arresters and SVLs and, as last, the earthing resistance of the link boxes.

The principles of the IEC 60071 [12-13] set of standards are followed to determine the stress and the performance of the cable sheath bonding system against lightning overvoltages due to back-flashovers on the overhead line(s). According to [5], only lightning strikes hitting the overhead lines within a distance of 1 km from the substation, or in this case from the cable circuit, were to be considered for calculating the outage performance. This is because lightning strikes at greater distances are regarded less important due to attenuation effects, of which corona is the most dominant. Figure 4 illustrates an example of the decrease in the wave steepness and the amplitude caused by corona. Therefore, this methodology considers lightning strikes on the cable termination tower and on the first four towers of the line. At each tower the following are considered:

- The lightning current amplitude is varied in the range of [10… 340] kA in steps of 10 kA;
- For each lightning current, the phase angle of the power frequency system voltage is varied in the range of [0… 360] degrees in steps of 20°, resulting in 540 simulations.

For each structure, the minimum lightning current is determined that results in exceedance of the defined insulation withstand level of the cable metallic sheath and the cable system's accessories. Then, the calculated minimum currents are combined with the lightning statistics to determine the risk for failure. In Figure 5, an overview of the stepwise process is given with respect to the MTBF calculation [14-15].

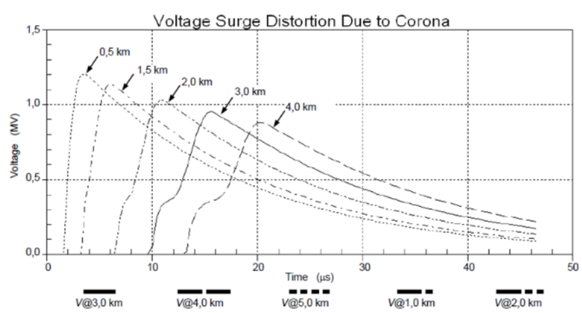

Fig. 4. Surge voltage waveforms at various distances from the strike location due to corona attenuation [5]

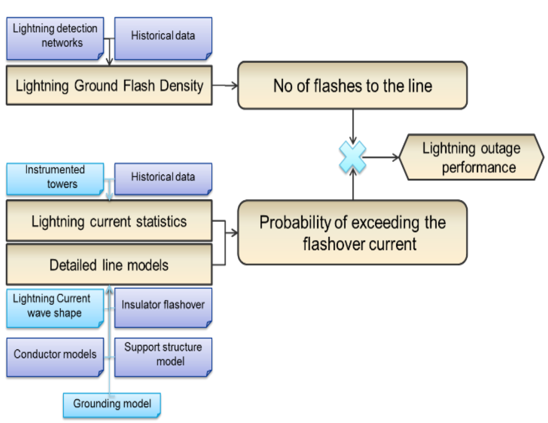

Fig. 5. Lightning outage performance methodology flowchart

Equation (1) gives the total number of lightning strikes per year that terminate on a tower and its span [16]:

$$N(G)_{tower} = 0.6 \cdot N_g \cdot \frac{28 \cdot h_t^{0.6} + S_g}{10} \cdot S_{tower} \quad (1)$$

where N_g is the ground flash density (flashes/100 km^2/year)
h_t is the tower height (m)
S_g is the distance between the shield wires (m)
S_{tower} is the span length (km)

The probability $P(I \geq I_c)$ that the lightning current is equal to or greater than the calculated minimum critical lightning current is given according to the Cigré log-norm distribution [17]. For each tower, the total number of flashovers that result in unacceptably high overvoltages in the cable metallic sheath and bonding system is calculated according to equation (2):

$$N_{tower} = N(G)_{tower} \cdot \sum_{\theta=0}^{340} P(I \geq I_c) \cdot P(\theta) \quad (2)$$

where $P(\theta) = \frac{20}{360} = 0.0556$

The sum of the number of flashovers at each tower, which results in exceedance of the given insulation withstand level, defines the mean time between failures (expressed in years), as given in equation (3):

$$MTBF = \frac{1}{\sum_{i=1}^{5} N_{tower}} \quad (3)$$

IV. Modelling Assumptions & Study Starting Points

For the purpose of the study, a detailed model was built in ATP that facilitated the calculation of the representative lightning overvoltages in the metallic sheath of the 110 kV cable circuits. Modelling guidelines given by IEC [18] and [7, 19-22] were applied.

Overhead transmission lines and tower structures

For the overhead transmission lines, detailed information was considered related to a) the position of the phase conductors and shield wires, b) the average conductor sag, c) the average span and d) the geometrical and electrical characteristics of the conductors. Tables I-III summarize the overhead transmission line data. In this study and according to [17], the constant parameter representation (i.e., Bergeron) was utilized for the modelling of the transmission line sections. Since the study focused on the simulation of back-flashovers, the dominant transient frequency was set equal to $f_{Bergeron}$ = 400 kHz [17, 25].

The tower structures (stricken and neighboring) were represented by their lossless surge impedance [23] to better capture their response under lightning conditions. The lattice towers were divided in several elements connected in series and the constant distributed parameter line model was applied, where the surge impedance of each section was calculated as:

$$Z_T = 60 \cdot \left(ln \left(2 \cdot \sqrt{2} \cdot \frac{h}{r} \right) - 2 \right) \quad (4)$$

Where h is the average height of each tower section above ground (m)
r is the tower section average radius (m)

The Wintrack tower design consists of two steel tubular pylons, which are electrically connected through the grounding and reinforcing mesh in the tower foundation, as shown in the schematic of Figure 6. The pylons were modelled as five series connected segments with mutual coupling; similarly to the transmission line sections, the 'Line Cable Constants' routine was used, based on the Bergeron model ($f_{Bergeron}$ = 400 kHz).

TABLE I
OVERHEAD TRANSMISSION LINES INPUT DATA

Data	Lattice tower	Wintrack pylon
r_{phase} [cm]	1.092	1.62
r_{shield_wire} [cm]	0.7	1.0885
R_{DC_phase} [Ohm]	0.0123	0.052
R_{shield_wire} [Ohm]	0.3065	0.1194

TABLE II
LATTICE TOWER CONFIGURATION

Conductor	Horizontal position [m]	Vertical position [m]
Phase A1	-11.05	10.8
Phase B1	-7.65	10.8
Phase C1	-4.25	10.8
Phase A2	4.25	10.8
Phase B2	7.65	10.8
Phase C2	11.05	10.8
Shield wire 1	-8.65	14.8
Shield wire 2	0	17
Shield wire 3	8.65	14.8

TABLE III
WINTRACK PYLON CONFIGURATION

Conductor	Horizontal position(1) [m]	Vertical position [m]
Phase A1	4.85	43.8
Phase B1	4.85	34.8
Phase C1	4.85	25.8
Phase A2	19.65	25.8
Phase B2	19.65	34.8
Phase C2	19.65	43.8
Shield wire	15.75	44.1

(1) These values refer to one pylon; the horizontal positions of the conductors in the other pylon are mirrored.

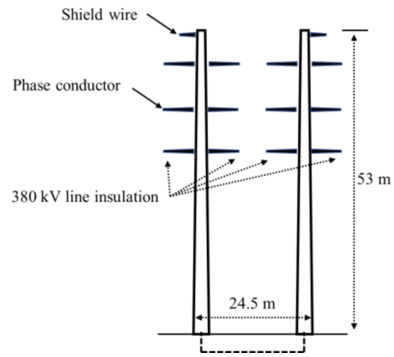

Fig. 6. Simplified schematic of the Wintrack pylons

Tower footing impedance

In the Netherlands, conventional low frequency methods (i.e., in the range of 5 kHz) are used for the measurement of the transmission tower earthing electrodes. In 2021, a measurement campaign was conducted that considered impulse measurements (targeted around 120 kHz) and a desktop study [24]. One of the main findings of the analysis was that it is regarded sufficient to represent the tower earthing electrode by means of a lumped current-independent resistance. Therefore, for the purposes of this study, the earth electrode at the base of each tower structure was represented by a resistance. The values for the tower footing resistances were based on available measurement data and, for the most structures, they were in the range of 0.1-1 Ohm.

Insulator flashover model

The flashover behavior of the line insulation is dependent on the magnitude and shape of the applied overvoltage. Although the insulation of the power system components is tested against the standard lightning impulse waveshape, i.e., 1.2/50 μs, the line insulation is subjected to lightning conditions, where the actual waveshapes are very different to the standard impulses. For that reason and as described in [17], the Leader Progression Model (LPM) was applied for the representation of the line insulation in ATP. The LPM is based on the principle that the breakdown strength of an insulator is time dependent for a certain peak voltage of the applied impulse shape. The parameters of this model were selected according to the Cigré guidelines and an estimate of the 50% lightning impulse flashover (U_{50}). The latter was determined through the equations provided in [13] and based on the assumption that the U_{50} of the insulator corresponds to a time to breakdown of 6 μs.

For the 110 kV and 380 kV voltage levels, the insulation clearances were defined according to the arcing distance of the insulator sets, as given in Table IV.

TABLE VII
ARCING DISTANCE OF INSULATORS

Voltage level [kV]	Arcing distance [m]
110	1.1
380	2.8

Lightning current waveshape

The lightning impulse was modelled as a Norton current source with an internal channel impedance of Z_{ch}=2000 Ohm. This value is based on the assumption that the channel impedance is significantly higher than the transmission line earthing system [17]. The Cigré waveshape was applied, as shown in Figure 7. This waveshape is defined by the front rise-time t_f, the maximum steepness S_m and the tail-time t_b; the values of these parameters are summarized in Table V.

TABLE V
LIGHTNING WAVESHAPE PARAMETERS

Symbol	Quantity	Value
I_s	Peak current	[kA]
S_m	Maximum steepness	$1.4\times I_p\times 0.77$ [kV/μs]
t_f	Front rise-time	$0.82\times I_p\times 0.75$ [μs]
t_b	Tail-time	ca. 100 μs

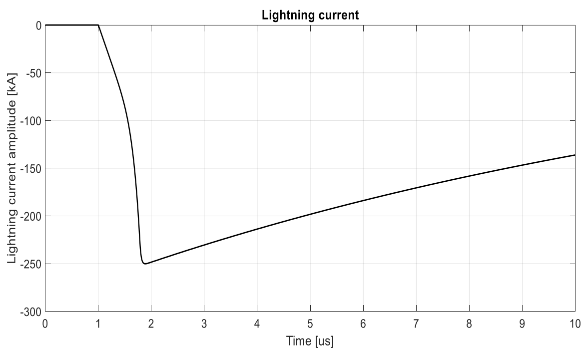

Fig. 7. Example of the applied lightning current waveshape in ATP

Underground cables, ECC and bonding leads

For the underground cables and the ECCs, detailed information was considered related to a) the geometrical characteristics of the cable layers, b) the electrical characteristics of the cable conductor, insulation and metallic sheath and c) the laying configuration and depth. Tables VI and VII summarize the cable and ECC main input data. Similar to the representation of the overhead transmission lines, the Bergeron model was used based on a tuning frequency of $f_{Bergeron}$ = 400 kHz.

The sheath bonding system was modelled according to the chosen design of each cable circuit. In the Netherlands, TenneT TSO applies single core cables for the bonding leads. In this study, the bonding leads were represented by means of lumped inductances, based on a value of 1 μH/m [6-7].

TABLE VI
UNDERGROUND CABLE & ECC GEOMETRICAL DATA

Component	$r_{conductor}$ [m]	r_{sheath_inner} [m]	r_{sheath_outer} [m]	R_{cable} [m]
Cable	0.02855	0.0447	0.0465	0.0515
ECC	0.01	n/a	n/a	n/a

TABLE VII
UNDERGROUND CABLE & ECC ELECTRICAL DATA

Component	$\rho_{conductor}$ [Ohmm]	ρ_{sheath} [Ohmm]	$\varepsilon_{insulation}$
Cable	3.6e-8	2.83e-8	2.3
ECC	1.68e-8	n/a	2.3

Cable surge arresters and SVLs

The cable surge arresters and the SVLs were modelled in ATP by means of MOV elements, based on their voltage-current characteristic in the high current region. The main characteristics of these components are summarized in Table VIII. It needs to be noted that the transient model also considered the flexible lead connections between the surge arresters and the cable terminations. Moreover, the surge arrester housing and installation base ($L_{housing+base}$= 4m) were modelled as a lumped inductance of 1 μH/m. A lumped resistance of 2 Ohm was used for modelling the earthing resistances of the surge arrester and the link boxes respectively.

TABLE VIII
CABLE SURGE ARRESTER & SVL INPUT DATA

Component	U_r [kV_{rms}]	$U_{residual}$ @5 kA [kV_{peak}]	$U_{residual}$ @10 kA [kV_{peak}]	$U_{residual}$ @20 kA [kV_{peak}]
Cable surge arrester	123	273	290	322
SVL	10	14.6	15.4	17.6

Lightning flash density in the Netherlands

According to the currently applied policy of TenneT TSO, the ground flash density in the Netherlands is considered equal to 1.5 flashovers/km^2/year. This value is based on a study that was conducted in 2020 and it analyzed the measurement data that were available at that time from an international lightning detection system. The study considered data dating back to 01-01-2010 up to 21-12-2019 and it covered both cloud-ground and cloud-cloud lightning discharges. A value for the number of striking points was also provided, on which the applied value is based.

MTBF requirement

According to [5] and the currently applied policy of TenneT TSO, the cable systems, including the sheath bonding system and its accessories, are non-self-restoring components. Therefore, they are regarded as station components and, as such, they are governed by the minimum acceptable requirement for an MTBF equal to or greater than 300 years.

Metallic sheath insulation withstand level

According to [6], the Lightning Insulation Withstand Level of the cable metallic sheath is equal to LIWL=75 kV_{peak}. This value is corrected, by applying the following factors:

- Safety factor k_s = 1.15, refers to internal insulation and it compensates for the statistical nature of the lightning overvoltages and possible ageing effects that might result in insulation deterioration;

- Correction factor k_a = 1.0, compensates for the decrease of the external insulation at higher altitudes. The correction factor is calculated based on an altitude of 1000 meters.

The corrected LIWL is then calculated according to equation (5):

$$LIWL_{corrected} = \frac{LIWL}{k_s \cdot k_a} = 65\ kV_{peak} \quad (5)$$

V. MTBF Analysis Results

For the cable circuits #1 (direct cross-bonded system) and #2 (single-bonded system), the lightning overvoltages are calculated at the following measuring points: a) location “sending end”, which refers to the sheath end at the termination tower side, b) location “receiving end”, which refers to the sheath end connected to the 35m bonding lead. Table IX presents the calculation results at the two ends of the cable circuits. For both cable circuits and in both locations, the MTBF values are higher than the minimum defined requirement of 300 years.

What is interesting to note is that, in these two configurations, the sheath bonding system of cable circuit #2 exhibits a worse MTBF performance compared to that of cable circuit #1. In first place, this can be explained with the help of Figures 8 and 9 that show the calculated peak overvoltages at the sheath receiving end in relation with the lightning current amplitude for strikes on the cable termination towers. For strikes at the lattice termination tower, the sheath $LIWL_{corrected}$ is exceeded for lightning currents greater than 310 kA. For strikes at the Wintrack termination pylon (with 110 kV line insulation), the sheath $LIWL_{corrected}$ is exceeded for lightning currents greater than 80 kA. Another factor is related to the total number of lightning flashes per year on each tower type. According to equation (1), the lattice termination tower is characterized by a lower number (0.337 flashes/year) compared to the Wintrack termination tower (0.502).

TABLE IX
MTBF Analysis Results

Circuit	MTBF $Location_{sending}$ [years]	MTBF $Location_{receiving}$ [years]
#1	7800 >> 300	298000 >>> 300
#2	480 > 300	630 > 300

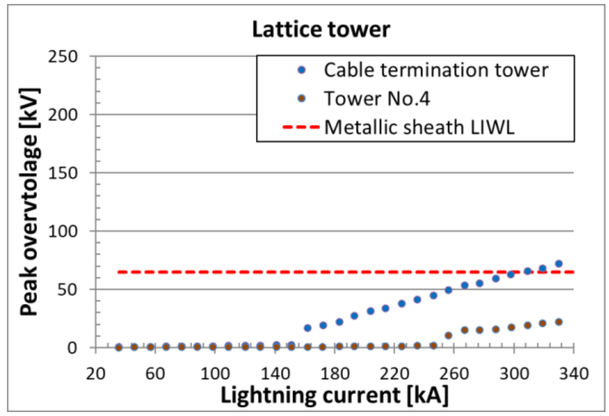

Fig. 8. Sheath peak overvoltages for lightning strikes on the lattice cable termination tower and on tower No.4

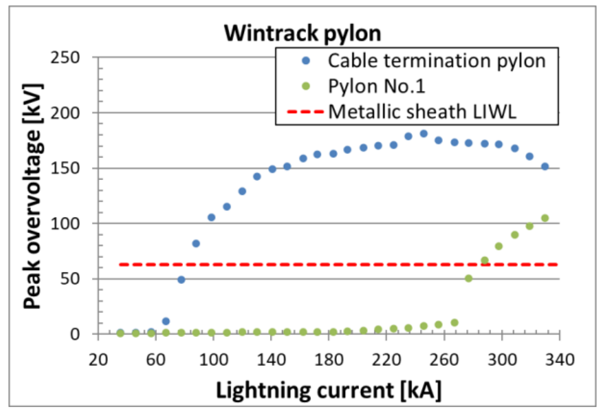

Fig. 9. Sheath peak overvoltages for lightning strikes on the Wintrack cable termination pylon and on pylon No.2

It needs to be noticed that for strikes on the neighboring towers of the termination one, much higher critical currents are calculated compared to the ones calculated for strikes on the termination tower. This could be explained by the very low tower footing resistance values and it applies for both circuit #1 and #2 respectively. Especially for the Wintrack pylons, another parameter is the fact that, except for the cable termination pylon, all the rest of the pylons are equipped with 380 kV insulator sets. Consequently, in the two configurations under study it is shown that the MTBF performance of the cable sheath bonding system is mainly defined by the lightning performance of the cable termination tower/pylon.

The simulation analysis for circuit #2 is repeated for two additional sub-cases:

- In the first sub-case, the calculations are performed for a bonding lead length of 10m. Table X summarizes the calculated MTBF values for the reference case and the sub-case. As expected, the shorter bonding lead length resulted in a better MTBF performance compared to the case of 35m lead lengths. Finally, the simulation analysis showed that the length of the bonding leads at the receiving end of the cable circuit did not have an impact on the MTBF performance at the sending end location.

TABLE X
MTBF ANALYSIS RESULTS FOR DIFFERENT BONDING LEAD LENGTHS

Bonding lead length [m]	MTBF Location$_{sending}$ [years]	MTBF Location$_{receiving}$ [years]
35	480 > 300	630 > 300
10	480 > 300	1400 > 300

- In the second sub-case, the calculations are performed for tower earthing resistances of 11 Ohm, which is the maximum allowable value for 380 kV tower structures, as defined in the TenneT insulation coordination policy. Higher tower footing resistances result in lower critical lightning currents and, thus, lower MTBF values. This is illustrated in Figure 10, which shows the critical lightning currents for strikes on the Wintrack termination current in relation with the power frequency voltage phase angle.

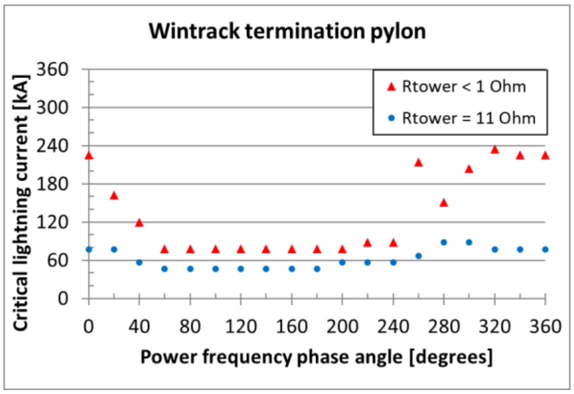

Fig. 10. Critical lightning currents for strikes on the Wintrack cable termination pylon

VI. CONCLUSIONS

This paper presents a methodology that facilitates the calculation of the failure rate performance of a cable's sheath bonding system within a Syphon connection due to lightning strikes on the connected overhead line(s). The methodology considers a) detailed ATP simulations for the calculation of the minimum critical lightning current that results in the exceedance of the defined insulation withstand levels of the sheath bonding system and b) the calculation of the failure rate performance based on the (national) lightning statistics. The analysis of an example case is discussed, referring to a double-circuit Syphon connection in the Dutch 110 kV transmission grid. In this case, the bonding leads of the cables' sheath bonding systems could reach lengths of up to 35m due to land access limitations, exceeding by this way the international standard and best practice recommendations.

The analysis concluded in acceptable MTBF performance of the cables' sheath bonding systems. Overall, it could be concluded that the MTBF performance of a cable's bonding system strongly depends on a) the lightning performance of the connected overhead line(s) and b) the selected bonding scheme and its design.

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