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Statistical Lightning Simulations for a HV "Mixed" Overhead-Cable Line: Preliminary Studies

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***Abstract*—The paper addresses the statistical simulation of the backflashover performance of an Italian 150 kV - 50 Hz mixed overhead-cable subtransmission line, focusing on direct lightning strokes to the overhead-cable transition tower. An ATP-EMTP-based Monte Carlo procedure, developed by the authors, has been applied to assess the backflashover rate (BFR) of the mixed line (ML). In addition, the procedure was applied to the statistical evaluation of some ML components’ stresses, such as the energy duty of metal oxide surge arresters (MOSAs) installed at the transition tower, the energy duty of sheath voltage limiters (SVLs) connected to the cross-bonded cable sheaths and the cable sheath voltages near the cable entrance. The backflashover response of the overhead portion of the ML differs from an all-overhead line only at the transition tower, so that the overall performance practically coincides with that of an all-overhead line. A non-negligible probability of damage to SVLs installed at the first minor cross-bonding section is found, whereas a much lesser energy stress is associated to MOSAs. Lastly, maximum cable sheath over-voltages are always well below 50 kV.**

Keywords-backflashover; ATP-EMTP; Monte Carlo; surge arresters; sheath voltage limiters

I. INTRODUCTION

The use of underground cables is steadily increasing in the HV and EHV ac power networks of industrialized countries. Especially at HV subtransmission level, new lines are often made of cables to assuage public opposition; for the same reasons, existing overhead lines (OHLs) are often "undergrounded" due to urban expansion. The higher cost of cable lines (CLs), compared to OHLs, often causes that only portions of a given line are actually undergrounded, giving rise to "mixed" overhead-cable lines (MLs). The paper studies the effect of direct lightning strokes to the overhead portion of a 150 kV – 50 Hz single-circuit ML, based on components typically used in Italy (closely resembling several such realizations).

The study relies on a powerful Monte Carlo statistic simulation tool, which uses ATP-EMTP as its computation engine. Statistically treated variables include lightning parameters (peak current I_P, front time t_F, time-to-half-value t_H), OHL insulation withstand, lightning location and phase angle of the impressed power frequency voltages. The Monte Carlo procedure is applied to assess the backflashover rate (BFR) of the ML and to statistically evaluate the effects of backflashovers on all the ML components. Among the observed items, the energy duty of non-linear metal oxide surge arresters (MOSAs) protecting the OHL-CL transition and the smaller sheath voltage limiters (SVLs) connected to the cross-bonded cable sheaths are paramount. The paper is structured as follows: Section II describes the simulated system; Section III outlines the simulation tool and the underlying ATP-EMTP system model; Section IV briefly recalls the ATP-EMTP based Monte Carlo procedure and simulation results are presented in Section V.

II. SYSTEM DESCRIPTION

A. Overhead Line

The overhead line portion of the typical standard Italian 150 kV – 50 Hz ML is 47 km long. Single, 31.5 mm ACSR phase conductors and a 11.5 mm steel shield wire are used. 31 m tall towers were considered, allowing for a minimum 11 m ground clearance along the simulated 400 m spans (shield wire sag is 9.7 m, instead). Tower head is shown in Fig. 1a, whereas Table I reports the phase and shield wire conductors. Phase insulator strings are 1600 mm long.

In keeping with the relatively high value of soil resistivity (ρ_g ≅1000 Ωm) along the line right of way, horizontal counterpoises were considered for the tower grounding systems, yielding a ≅19 Ω ground resistance. Fig. 1b shows the 26 m long counterpoises’ arrangement based on an Italian design (note that the branches’ terminal segments, 1.4 m long, are sloped 45° downward).

B. Underground Cable

The underground portion, 7.4 km long, of the simulated ML relies on 1600 mm^2 aluminium, single-core XLPE-insulated cables, laid in horizontal flat configuration (0.155 m spacing) at 1.2 m depth. Cables are transposed, with sectionalized cross-bonded sheaths. Fig. 2 shows the cable cross-section, whereas geometrical – physical data are reported in Table II. Note that, following Italian practice, a 750 kV BIL was specified for the 170 kV class cables.

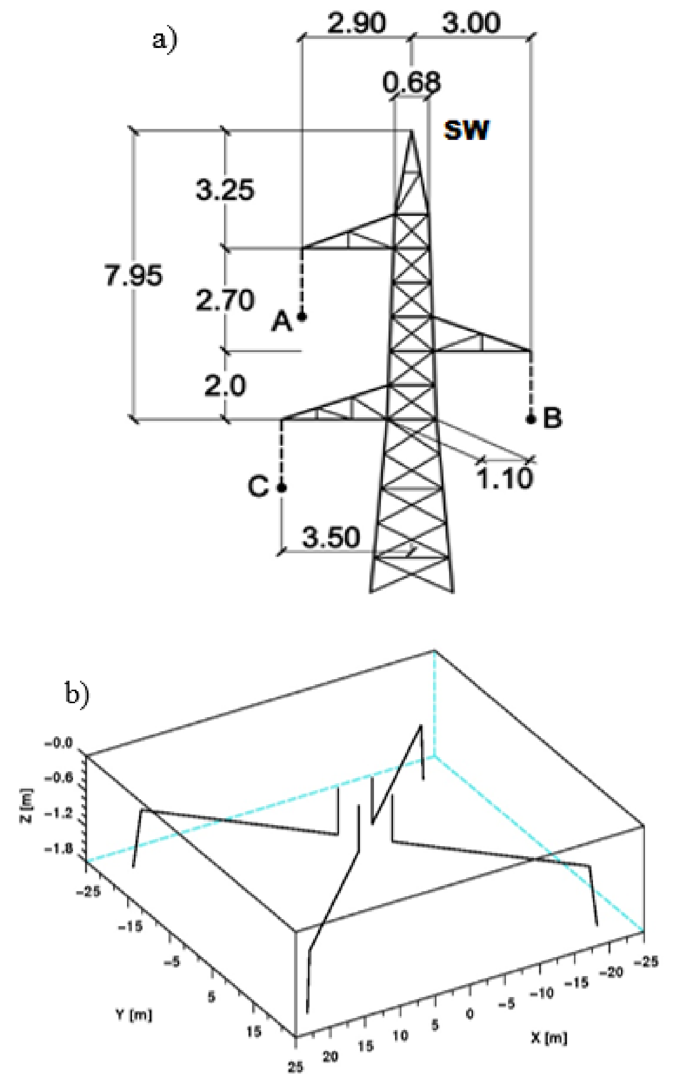

Figure 1. a) Outline of the OHL tower head (dimensions are in m; the tower height is 31.1 m). b) Simulated grounding system.

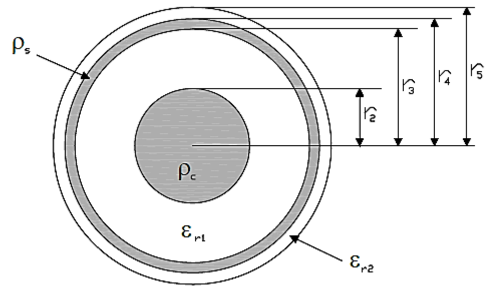

Figure 2. Cable cross-section.

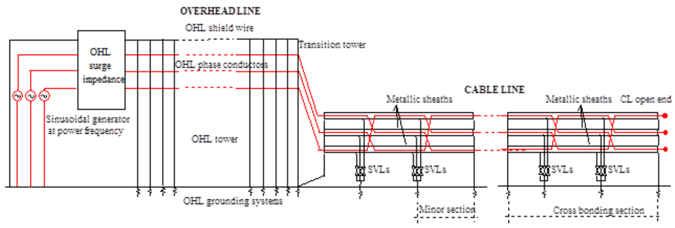

Figure 3. Outline of the 150 kV ML model for lightning response analysis.

TABLE I. PHASE AND SHIELD WIRE CONDUCTOR COORDINATES

	A	B	C	SW
x (m)	−2.9	3	−2.5	0
y (m)	25.4	23.4	21.4	31.1

TABLE II. GEOMETRICAL AND ELECTRICAL DATA OF 1600 MM^2 AL CABLE (SYMBOLS REFER TO THE CROSS-SECTION IN FIG. 2)

r_2 (mm)	26	ε_{r1}	2.4
r_3 (mm)	46.5	ε_{r2}	2
r_4 (mm)	48	**ρ_c (Ωm)**	$2.84\cdot10^{-8}$
r_5 (mm)	52.5	**ρ_s (Ωm)**	$2.84\cdot10^{-8}$

III. SYSTEM MODELING

The outline of the 150 kV ML model, used in the paper for lightning response analysis, is shown in Fig. 3.

A. Overhead Line

The last 25 OHL line spans and towers have been simulated, with the struck tower (i.e. the OHL-CL transition tower) and the two adjacent ones are represented in detail (tower wlwments and phase insulation). Notably, tower elements (segments and crossarms) are represented as single-phase, lossless transmission lines, with Z_T=200 Ω [1] and c≅$3\cdot10^8$ ms^{-1}. The 400 m long spans are modeled by means of "JMarti" frequency-dependent blocks, calculated for ρ_g=1000 Ωm around a 100 kHz main frequency, whereas the remaining 37 km long OHL is modeled by longer "JMarti" segments. The line model is connected to its multiphase surge impedance matrix; the phase conductors are then terminated on a three-phase 150 kV – 50 Hz voltage system, whereas the shield wire is solidly grounded. Moreover, at the struck tower and the two adjacent ones, phase insulation is simulated with the CIGRE Leader Progression Model (LPM), implemented within ATP-EMTP by means of the "MODELS" programming and simulation language [2]:

$$\frac{dl}{dt} = k\cdot u(t)\left[\frac{u(t)}{d_G - l(t)} - E_0\right] \qquad (1)$$

where $l(t)$ (m) is the leader length, d_G (m) is the gap length, $u(t)$ (kV) is the voltage across the gap and E_0 (kV·m^{-1}) is the critical electric field (depending on impulse polarity), whereas the speed parameter k (m^2·kV^{-2}·s^{-1}) is $1.2\cdot10^{-6}$ and $1.3\cdot10^{-6}$ for positive and negative flashes, respectively. The gap length d_G is 1.46 m.

B. OHL Tower Grounding System Model

At all OHL towers, the grounding system is simulated with the authors' simplified pi-circuit [3]-[5] shown in Fig. 4, obtained by synthesizing the full circuit model described in [6]. The linear part of the circuit fits the behavior of the non-ionized grounding system for all frequencies of interest (from 0 Hz to 1 MHz). Frequency dependence of soil parameters has been disregarded. The non-linear effects of soil ionization are accounted for by ideal voltage-controlled current sources G_1 and G_2, implemented as (i = 1, 2):

$$G_i(t) = \frac{V_{Ri}(t)}{F_i(t)} - \frac{V_{Ri}(t)}{R_i} \quad (2)$$

where

$$F_i(t) = R_i - \alpha_i \cdot \log\left(10^{-4} + \beta_i \frac{V_{R_i}(t)}{R_i}\right),\ F_i \in \left[10^{-4}; R_i\right] \quad (3)$$

and $V_{R_i}(t)$ is the voltage across the resistor R_i. The model was subsequently validated by comparing it with two different models, one based on an electromagnetic full-wave approach, the other adopting hybrid circuit-field approach [7], yielding very good results even when subsequent strokes are injected. In the simulations reported in the paper, numerical values of pi-circuit parameters are: R_1=34.12 Ω, R_2=43.27 Ω, R=0 Ω, L=12.5 μH, C_1=3.32 nF, C_2=9 nF, α_1=0.406 Ω, α_2=0.285 Ω, β_1=1654.9 A^{-1}, β_2=931 A^{-1}.

C. Cable Line

The actual OHL-CL transition is supposed to occur at the foot of the transition tower, with the physical connection between OHL and CL (downleads) represented by short, uncoupled transmission lines. The cable entrance is protected by MOSAs, installed at ground level and connected between phase and ground (i.e. the local tower grounding system). The 168 kV MOSA is simulated as a type-92 piecewise non-linear resistor, with the conservative "front of wave" *i-v* characteristic reported in Table III. Minor cross-bonding sections of the 150 kV underground CL, each 820 m long, have also been simulated with the appropriate "JMarti" model, achieving a good fitting in the frequency range of interest, as reported in [8,9]. Total cable length is 7.4 km, that is, 3 major sections each 2.47 km long. Both cable transposition and sheath sectionalized cross-bonding are reproduced: for the latter, bonding leads are simulated as lumped *R-L* elements, with an inductance value, l_{BL}=12 μH conservatively large to represent long leads [10]; this is also used for the connections between cable sheath and transition tower foot. Sheaths are connected to the local ground via metal oxide SVLs, with U_r=9 kV, at minor cross-bonding sections: *i-v* characteristic is reported in Table IV. Sheath earthing resistance is 50 Ω at all sheath sectionalizing and bonding locations.

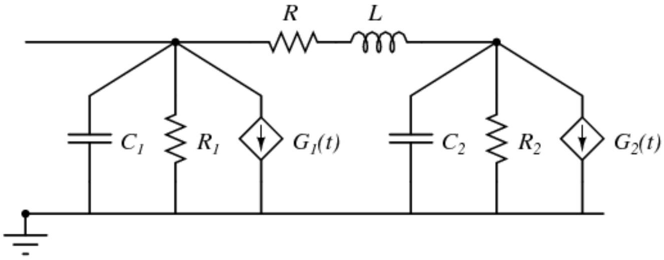

Figure 4. Simplified tower grounding system pi-circuit model.

TABLE III. CURRENT-VOLTAGE CHARACTERISTICS OF THE SIMULATED MOSAS (U_R=168 KV)

i (A)	*v (kV)*
1	314.4
10	329.9
100	349.9
500	327.7
1000	385.4
2000	401.2
5000	430.8
10000	455.0
15000	482.7

TABLE IV. CURRENT-VOLTAGE CHARACTERISTICS OF THE SIMULATED SVLS (U_R=9 KV)

i (A)	*v (kV)*
0.001	15
0.01	16.5
0.1	18
1	18.75
10	19.05
100	19.5
1000	21.75
10000	27.75
100000	41.25

IV. ATP-EMTP MONTE CARLO PROCEDURE

A. BFR Calculation

The study was carried out using the authors' ATP-EMTP-based Monte Carlo procedure [11]-[13], originally aimed at the evaluation of a line's BFR. The Monte Carlo procedure assesses the line's BFR by statistically generating a large population of N_{tot} lightnings, which are assumed to fall within a 1 km-wide swath centered on the OHL. The subset of N_{lin} direct line strokes (actually, only strokes to tower peak are considered) is extracted by means of the Eriksson's electro-geometric model [14] and such strokes are individually simulated by means of the ATP-EMTP system model, described in Section III, to investigate the occurrence of backflashover. The simulation time for each of the N_{lin} direct line strokes is at least twice the time-to-half-value and not less than 70 μs. After convergence of the procedure, the BFR (referred to 100 km of line-year) can be calculated as

$$BFR = 0.6 \cdot \frac{N_{BFO}}{N_{tot}} \cdot N_g \cdot 100 \tag{4}$$

being N_{BFO} the total flashovers and N_g the ground flash density (flashes/km^2-year), whereas 0.6 is a multiplicative coefficient accounting for strokes terminating within the span [15]. The convergence of the procedure is reached when the difference (in absolute value) between the ratio N_{BFO}/N evaluated at the nth iteration and the one evaluated at the iteration n-1 is lesser than a specified value, typically 0.1%. Statistical inputs of the procedure are:

- lightning polarity, treated as a uniformly distributed random variable assuming that 90% of flashes to ground are negative;
- lightning strokes parameters (peak current I_P, front time t_F, time-to-half-value t_H), treated as random numbers following the log-normal distributions in [16];
- critical electric field E_0, taken as a log-normal distributed random number, according to [1];
- phase angle of the supply voltage, considered as a uniformly distributed variable between 0° and 360°.

An in-depth description of the Monte Carlo procedure may be found in [11]-[13].

B. Application of the Procedure to the Case Study

In the case study, the lightning performance of a ML is evaluated. For a ML, it can be reasonably assumed that the underground portion's contribution to the overall BFR is nil. The only deviations from the well-known OHL behavior can be expected to occur at the transition tower and, possibly, at those immediately adjacent. However, these are likely to leave the BFR practically unchanged: it will be shown in the next section that the comparison of Monte Carlo results obtained considering the transition tower with those yielded by the full overhead line model essentially confirms the assumption. In addition to its originally intended use, the Monte Carlo procedure was applied to the statistical evaluation of other components' stresses, such as the energy duty of both MOSAs and SVLs, and CL sheath voltages near the cable entrance and along the first minor cross-bonding section. Therefore, cumulative probability curves of MOSAs and SVLs energy absorptions, as well as of CL sheath voltages, may be plotted by using the Monte Carlo procedure, and will be shown in the next Section.

V. Results

A. BFR Results

Simulations confirm that the length of the underground portion of the line is long enough to ensure that, as it is well known, CL itself is "self-protected" against incoming lightning surges, thanks to its low transient impedance in comparison to the OHL.

Figure 5a compares the ratios $(N_{BFO}/N)\cdot 100$ obtained for strokes to any tower of the ML excluding the transition one (yielding $(N_{BFO}/N)\cdot 100 = 1.454$), to that obtained considering only strokes to the transition tower (yielding $(N_{BFO}/N)\cdot 100 = 0.321$). It could be shown that the 'black' (i.e. "other towers") curve coincides with the corresponding curve obtained for an all-overhead line. The immediate conclusion is that the transition tower contributes very little to the overall BFR; most importantly, when a backflashover occurs the behavior of the overhead portion of the ML is practically identical to that of a normal OHL having the same length. Figure 5b shows transition tower contribution to BFR, considering the presence of cable-entry MOSAs, i.e. the red curve of Fig. 5a, as well as the corresponding curve obtained without such MOSAs. The comparison evidences that the cable-entry MOSAs practically do not affect the transition tower's response to direct lightning: the ratio $(N_{BFO}/N)\cdot 100$ increases from 0.321 to 0.323 when cable-entry MOSAs are not simulated. Results confirm the findings of previous, deterministic studies, by the authors [10] among others. On the other hand, such studies evidenced a substantial MOSAs' effect in case of shielding failure near the transition tower: these will be the object of further analyses. Note that in Figs 5a and 5b the ratio $(N_{BFO}/N)\cdot 100$ over N is plotted for all the generated lightnings (N_{tot}=692801, in order to obtain N_{lin}=100000), thus showing the stability of the Monte Carlo procedure.

B. Components' stresses results

The Monte Carlo simulation results also include quantities such as cable sheath voltages or MOSA and SVL energy absorption. In practice, the value of such variables only become of interest in case of strokes to the transition tower. Figure 6 shows the cumulative probability of cable-entry MOSAs energy absorption, referred to the most stressed phase arrester in each simulation. Considering a relatively low 5 kJ/kV MOSA energy duty, it can be seen that the energy absorption endangers the MOSA only rarely, i.e. in less than 0.01 % of the simulated strokes to tower. Except for very large current peaks, the high-energy occurrences are associated to backflashovers, involving very large phase voltages. Similar curves, relative to SVL energy absorption, are reported in Fig. 7. The monitored SVLs are those closest to the cable entry, i.e. installed at the first cross-bonding minor section. Curves in Fig. 7 clearly show that cable-entry MOSAs ensure a significant reduction of maximum SVL energy absorption, but only at very low probability levels. Considering instead a realistic SVL energy capability (e.g. 3.6 kJ/kV as per [17]), the probability of exceeding it is practically unaffected by the presence of cable-entry MOSAs, i.e. it is about 0.7 %. Lastly, Fig. 8 shows the cumulative probability of maximum cable sheath overvoltage, measured at cable entry, with respect to the local (i.e. tower) ground. Even the highest calculated voltages, with 10^{-5} cumulative probability, are just below 40 kV (without MOSAs; under 30 kV if MOSAs are present, values well within the 50 kV minimum lightning impulse withstand dictated by IEC 60229 [18] for optional factory testing of cable oversheaths).

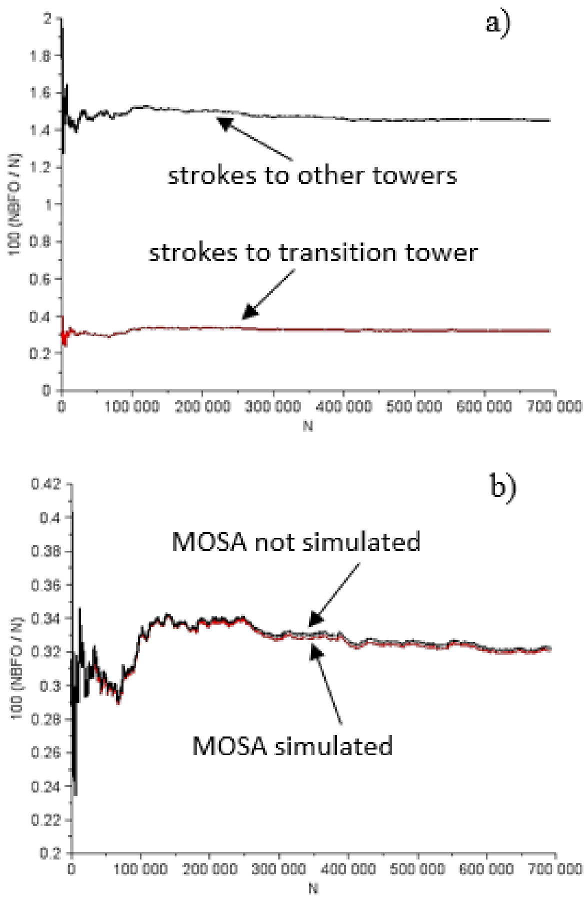

Figure 5. Monte Carlo procedure: calculated 100·(N_{BFO}/N) ratio vs. N. a) Comparison between strokes at transition tower (cable-entry MOSAs) and strokes to adjacent tower. b) Stroke at transition tower (with and without cable-entry MOSAs).

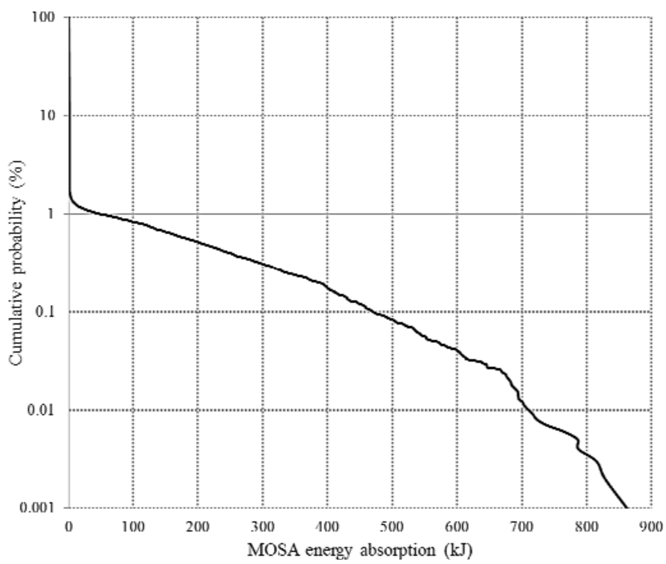

Figure 6. Strokes to transition tower: calculated cumulative probability of maximum MOSA energy absorption.

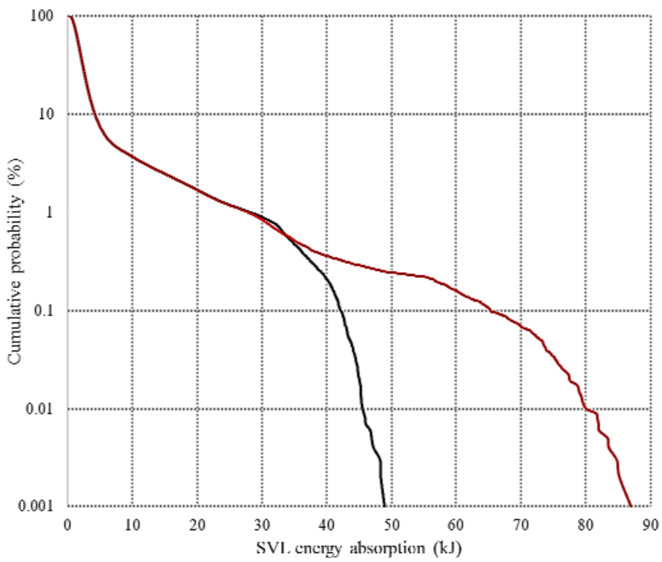

Figure 7. Strokes to transition tower: calculated cumulative probability of maximum SVL energy absorption (black: with cable-entry MOSAs, red: no MOSAs).

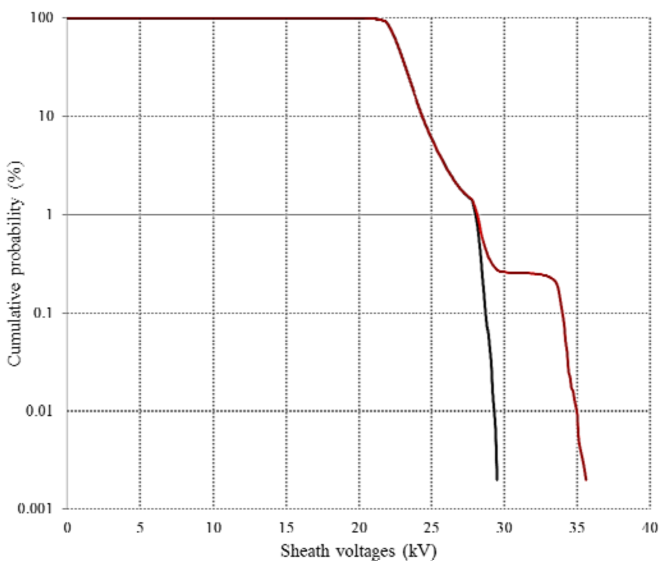

Figure 8. Strokes to transition tower: calculated cumulative probability of maximum sheath voltage (black: with cable-entry MOSAs, red: no MOSAs).

VI. CONCLUSIONS

The authors' ATP-EMTP-based Monte Carlo procedure, originally aimed at the evaluation of overhead lines' backflashover rate, has been applied to evaluate the lightning performance of a mixed HV overhead-cable line. In the context of an extensive statistical backflashover study, attention was also focused on the evaluation of stresses affecting some line components, either energy-constrained (cable-entry surge arresters, sheath voltage limiters) or voltage constrained (oversheath insulation). Main findings can be summarized as follows:

- if the overhead-cable transition tower is neglected, the backflashover response of the overhead portion of the mixed line is indistinguishable from an all-overhead line;
- the transition tower (confirmed to be much less exposed to backflashovers than the rest of the towers) benefits only marginally of the presence of cable-entry surge arresters installed at ground level;
- in case of strokes to the transition tower, cable-entry surge arresters (with U_r=168 kV, 5 kJ/kV) are endangered in less than 0.01 % of occurrences;
- the probability of damage to sheath voltage limiters (U_r=9 kV, 3.6 kJ/kV) installed at the first minor cross-bonding section is relatively higher, up to 0.7 % of all transition tower strokes;
- lastly, calculated sheath overvoltages at cable entry are never of concern.

The above results refer to lightning strokes to towers or shield wires: further developments will include the extension of the study to direct strokes to phase conductors, i.e. shielding failures, affecting the overhead portion of the mixed line.

REFERENCES

[1] CIGRE Working Group 01 of SC 33, "Guide to Procedures for Estimating the Lightning Performance of Transmission Lines," CIGRE Brochure n° 63, October 1991.

[2] Alternative Transients Program (ATP) Rule Book, Canadian/American EMTP User Group, 1995.

[3] F. M. Gatta, A. Geri, S. Lauria, and M. Maccioni, "Equivalent lumped parameter π-network of typical tower grounding systems for linear and non-linear transient analyses," in Proc. IEEE PowerTech Conf., Bucharest, Romania, June 28th–July 2nd, 2009.

[4] F. M. Gatta, A. Geri, S. Lauria, and M. Maccioni, "Simplified HV tower grounding system model for backflashover simulation," Electric power Systems Research, vol. 85, pp. 16-23, 2012.

[5] F. M. Gatta, A. Geri, S. Lauria, and M. Maccioni, "Generalized pi-circuit tower grounding model for direct lightning response simulation," Electric power Systems Research, vol. 116, pp. 330-337, 2014.

[6] A. Geri, "Behavior of grounding systems excited by high impulse currents: the model and its validation," IEEE Trans. Power Del., vol. 14, no. 3, pp. 1008-1017, July1999.

[7] R. Araneo, M. Maccioni, S. Lauria, A. Geri, F. M. Gatta, and S. Celozzi, "Hybrid and pi-circuit approaches for grounding system lightning response," in Proc. IEEE PowerTech Conf., Eindhoven, Netherlands, June 29th–July 2nd, 2015.

[8] A. Geri, F. M. Gatta, S. Lauria, and L. Colla, "Lightning performance of long mixed overhead-cable EHV lines", in Proc. of the 28th International Conference on Lightning Protection (ICLP 2006), Kanazawa, Japan, Sep. 2006.

[9] F. M. Gatta, A. Geri, and S. Lauria, "Simulation of lightning response of a long mixed overhead-cable EHV line", in Proc. of the International Conference on Grounding and Earthing (GROUND 2006), Maceiò, Brazil, 2006.

[10] S. Lauria, F. M. Gatta, A. Geri, and L. Colla, "Direct lightning strokes to mixed overhead-cable 132-150 kV subtransmission lines", in Proc. of the 29th International Conference on Lightning Protection (ICLP 2008), Uppsala, Sweden, June 2008.

[11] F. M. Gatta, A. Geri, S. Lauria, M. Maccioni, and A. Santarpia, "An ATP-EMTP Monte Carlo procedure for backflashover rate evaluation," in Proc. of the 31st International Conference on Lightning Protection (ICLP 2012), Vienna, Austria, 2012.

[12] F. M. Gatta, A. Geri, S. Lauria, M. Maccioni, and A. Santarpia, "An ATP-EMTP Monte Carlo procedure for backflashover rate evaluation: a comparison with the CIGRE method," Electric Power System Research, vol. 113, pp. 134-140, Aug. 2014.

[13] F. M. Gatta, A. Geri, S. Lauria, M. Maccioni, and F. Palone, "Tower grounding improvement vs. line surge arresters: comparison of remedial measures for high-BFOR subtransmission lines," IEEE Trans. Ind. Appl., vol. 51, pp. 4952-4960, Nov./Dec. 2015.

[14] A. J. Eriksson, "An improved electrogeometric model for transmission line shielding analysis," IEEE Trans. Power Del., vol. 2, pp. 871-886, July 1987.

[15] A. R. Hileman, Insulation Coordination for Power Systems, New York: Marcel Dekker Inc., 1999.

[16] Lightning Insulator Subcommittee of the T&D Committee, "Parameters of light-ning strokes: a review," IEEE Trans. Power Del., vol. 20, pp. 346-358, Jan. 2005.

[17] A. Xemard and E. Dorison, "Study of the protection of screen interruption joints against fast-front over-voltages", in Proc. of the International Conference on Power Systems Transients (IPST'05), paper no. IPST05-065, 2005.

[18] IEC 60229 ed. 3.0, "Electric cables - Tests on extruded oversheaths with a special protective function", Oct. 2007.