Lightning Overvoltages in HV-EHV "Mixed" Overhead-Cable Lines

L. Colla, F. M. Gatta, A. Geri, S. Lauria

Abstract-- In this paper the authors analyze the lightning behaviour of extra-high voltage unconventional transmission lines, named mixed-lines, consisting of a XLPE-insulated cable line (CL) solidly series-connected to conventional overhead line (OHL). ATP-EMTP time-domain simulations have been carried out to analyze overvoltage levels achieved in a 380 kV-50Hz mixed-line in Europe varying the CL length. Attention is focused on the effects both of shielding failure and of direct lightning strokes to OHL sections, in particular to cable-overhead transition tower. The ATP-EMTP model of the affected portion of mixed line includes frequency dependent modeling both of CL and of OHL, a CIGRE leader progression model (LPM) of line insulation, and a detailed circuit-based model of tower grounding system, taking into account soil ionization. Numerical results show a good lightning performance of the line under study: shielding failures do not endanger the main CL insulation, probability of backflashover is extremely low and stresses on outer sheath insulation are effectively contained.

Keywords: backflashover, extra-high voltage lines, lightning, mixed-lines, overvoltages, shielding failure.

I. Introduction

In the last decade, several extra-high voltage (EHV) AC (380 kV-50Hz in Europe) underground cable links have undergone installation or planning. Besides their suitability to specific installation requirements (e.g. in congested urban areas) EHV cable lines (CLs) are often the only alternative that is accepted by a public that strongly opposes the construction of conventional overhead line (OHL) stretches in sensitive locations. The result is a "mixed" line [1], [2], with intermingled CL and OHL sections.

The paper addresses the simulation of lightning response of a 380 kV-50 Hz mixed line (Fig. 1), presenting modelling improvements with respect to previous work by the authors in [3] and [4]. Direct lightning strokes to OHL towers as well to phase conductors were simulated, near the OHL-CL transitions.

II. System description

A. Overhead line

The single circuit 380kV-50Hz OHL, on lattice suspension towers, with horizontally arranged phase conductors, V insulator strings, two shield wires and line spans up to 400 m (Fig. 1a), is a typical European design [5]. The overall simulated tower height is 36 m; phase to phase horizontal distance is 7.40 m with 15 m maximum phase conductor sag and 14 m minimum ground clearance. Each phase is equipped with a triplet bundle of ACSR conductors (Ø = 31.5 mm), in a symmetrical triangular configuration with 40 cm spacing. Galvanized steel shield wires (Ø = 11.5 mm) are conservatively simulated, instead of recently adopted, larger ACSR OPGWs. Outer phase "V" strings are made of 21 standard 5 1/4" insulators; the inner one has an additional insulator. However, arc control devices dictate the minimum gap to the horizontal truss, which is 3 m.

The tower grounding system, shown in Fig. 3, is devised by an important European TSO for use in medium resistivity soils (ρ_t=300-600 Ωm), referred to as "Type 1" in [5].

B. Cable line

The single circuit CL is made of three single-core, 2500 mm^2 Cu, 380 kV XLPE-insulated cables, with overall laying configuration adopted in [3] and [5]: horizontal flat configuration with 0.35 m spacing and direct buried at 1.5 m. Table I reports the main cable geometrical-physical parameters; cable cross-section and laying are shown in Fig. 2.

Following the long-established practice for long underground cables, the CL has been considered transposed along the line route, with sectionalized sheath cross-bonding. Minor transposition sections are 830 m long (i.e. the length of a cable drum), so a major cross bonding section is 2.5 km long.

III. System Modeling

A. Overhead line towers

OHL towers have been simulated as lossless, single phase transmission lines with $c \cong 3\cdot10^8$ ms^{-1} and Z_t=180 Ω [11].

TABLE I
GEOMETRICAL AND PHYSICAL CHARACTERISTICS OF 2500 MM^2 CABLE

r_2	32.5 mm
r_3	64.2 mm
r_4	65.5 mm
r_5	71.3 mm
ε_{r1}	2.4
ε_{r2}	2.0
ρ_c	$1.724\cdot10^{-8}$ Ωm
ρ_s	$2.84\cdot10^{-8}$ Ωm

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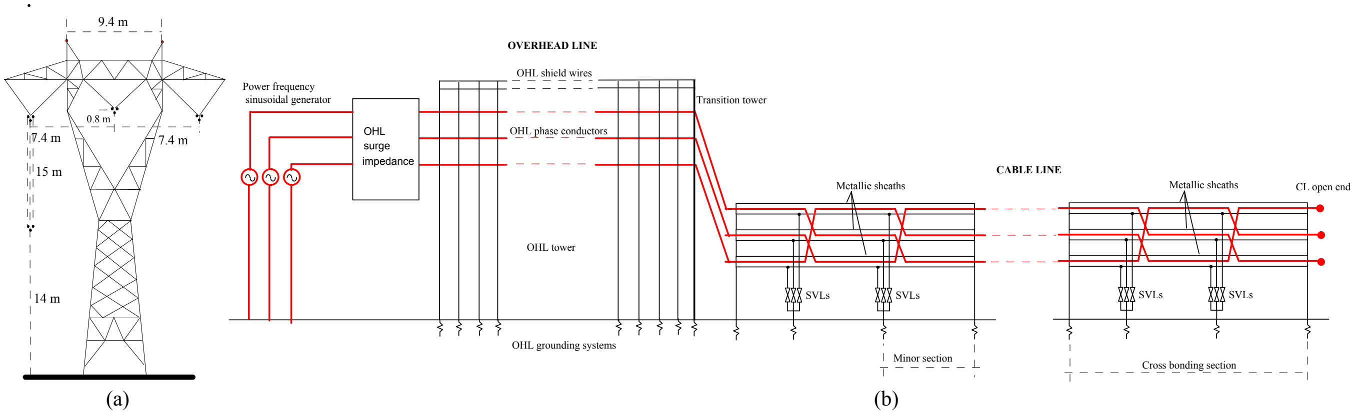

Fig. 1. (a) Outline of the simulated 380 kV OHL tower (not to scale); (b) model of the 380 kV line simulated for lightning response analysis.

All towers except the struck one are grounded via the grounding system 50 Hz calculated resistance (14.4 Ω). At the struck tower, the grounding system depicted in Fig. 3 has been modeled in greater detail.

B. Grounding system of the struck tower

The grounding system model has been proposed and validated in previous papers [6]-[9], [13]-[14].

The grounding system model is based on a circuit approach. All ground electrodes are represented by a discrete number of lumped π-networks (having serial resistive-inductive longitudinal parameters and parallel capacitive-conductive transversal parameters) each of which is full coupled with the others by inductive, resistive and capacitive coupling.

The model has been validated by comparing the numerical results both with experimental tests [6]-[7] and with more sophisticated simulation models [8]-[9].

The model allows to simulate both simple [6]-[7] and very complex grounding systems [8]-[9]. There are no inherent limitations about shape and position of grounding electrodes.

In addition, the model is able to account for non-linear soil ionization phenomena that take place when high lightning current are drained to earth. These phenomena are simulated by transversal current-dependent shunt conductances [7], that are governed by the constraint $E < E_{cr} = 350$ kV/m (E_{cr} is the soil critical value) imposed on the electrical field, E, at the "apparent" lateral surfaces of every electrode [7].

A pre-processor [5], [10] generates the ATP-EMTP simulation data for the grounding system (see Fig. 3), and includes into the whole system model.

C. Overhead line

The 10 km of OHL adjoining the cable have been simulated in ATP-EMTP as 25 line spans, each 400 m long, by means of the "JMARTI" frequency-dependent model [3], [11]. The models of OHL spans have been obtained around a main frequency of 100 kHz for backflashover-oriented simulation, 500 kHz for shielding failures, with 500 Ωm earth resistivity. At the opposite end from the cable, the OHL model is "connected" to the line surge impedances; phase conductors are then terminated on a symmetrical three-phase 380 kV-50 Hz voltage system, while shield wires are solidly grounded. Shield wires are connected to tower peaks at each tower.

The physical connection between OHL and CL (downleads) is simulated by means of short, uncoupled TLs.

OHL insulation breakdown has been simulated with the CIGRE Leader Progression Model (LPM), implemented with ATP-EMTP by means of the "MODELS" programming andsimulation language [5]. Line corona has been disregarded.

D. Cable line

The 400 kV underground CL has also been simulated by means of a JMarti frequency-dependent model.

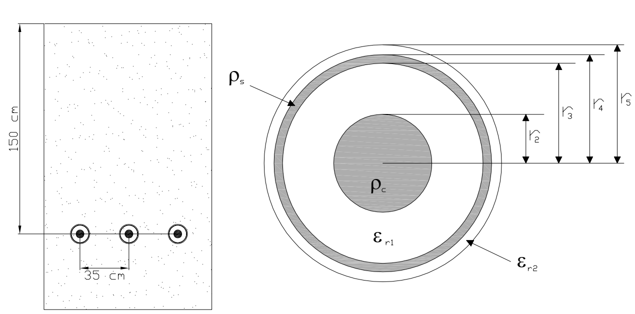

Fig. 2. a) Cable laying arrangement; b) cable cross section

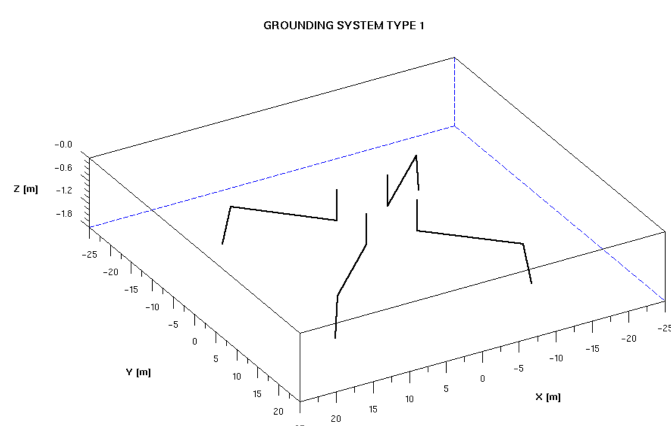

Fig. 3. Sketch of simulated grounding system [5]

A good fitting of the cable model has been achieved for the frequency range of interest, as reported in [3]-[4], by means of a slight loss reduction of both cable core and sheath (i.e. a straightforward decrease of series resistance).

The accuracy of the fitting was satisfactorily checked by means of the dedicated ATP-EMTP 'Xverify' subroutine.

Simulations have been carried out for several different values of CL length: 2.5 km, 5 km, 7.5 km and 10 km. In order to assess worst-case conditions, the CL is kept open at the receiving end and without phase-connected SAs at either end.

Indiviual CL stretches coincide with 830 m long cross-bonding minor sections; cable transposition and sheath sectionalized cross-bonding are taken into account. Bonding leads have been simulated as lumped R-L elements, with two different inductance values l_{BL}, namely 0.15 μH/m and 1.2 μH/m; total lead length is 10 m. At minor cross-bonding sections, sheaths are connected to the local ground via sheath voltage limiters (SVLs), i.e. metal oxide surge arresters which have been simulated for two different ratings (U_r=9 kV or 12 kV). SVL characteristics are reported in the Appendix. Two earthing resistance values have been simulated for local grounds at sheath sectionalizing and bonding locations, namely 25 Ω and 50 Ω.

E. Lightning current

The “Heidler” impulse current source available in ATP-EMTP has been used in all simulations.

IV. Shielding failure simulations

Shielding failures have been simulated at the transition tower, and, for the sake of comparison, at immediately adjacent towers. For the considered 380 kV OHL, the maximum shielding failure current according to Young [15] is around 7.5-9 kA. Simulations have been conservatively performed with 10 kA, 0.5/50 μs lightning current. This value, practically matching insulation critical current, is withstood by the OHL insulation for all operation voltages, as shown in [5].

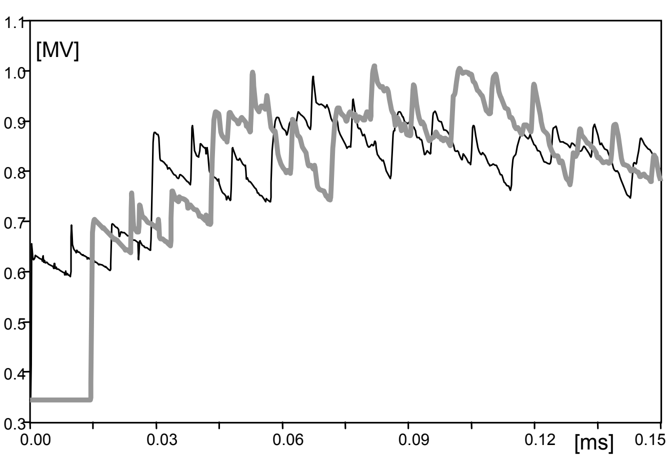

Fig. 4. Shielding failure at the transition tower (2.5 km cable, 12 kV SVLs); voltages of struck phase, vs. time. Black curve: CL entrance; light curve: open CL end.

TABLE II
PEAK VOLTAGES AT CL TERMINALS (SHIELDING FAILURE AT TRANS. TOWER)

	l_{BL} [μH/m]	0.15		1.2	
CL length [km]	$U_{r\text{-}SVL}$ [kV]	Send [kV]	Rec [kV]	Send [kV]	Rec [kV]
2.5 km	9	988	1019	1006	1011
	12	988	1010	1006	1010
5.0 km	9	691	800	745	783
	12	701	796	746	779
7.5 km	9	690	718	746	729
	12	695	738	747	748
10.0 km	9	690	705	746	639
	12	696	720	747	651

With the worst-case power frequency voltages, the initial peak at cable entrance ranges between 650 and 730 kV (due to the relatively low CL surge impedance), with the lower values associated to smaller bonding lead inductances. The initial overvoltage affecting the CL is little affected by the model adopted for downleads; the latter mostly influence the initial overvoltage peak on the struck OHL.

Shielding failures simulated at nearby towers, while slightly less challenging to cable insulation, are significantly more stressful to local OHL insulation.

Fig. 4 shows the struck phase voltages at the cable terminals for the 2.5 km CL. The maximum overvoltage calculated at cable entrance, occurring after a couple of reflections from the open end, is 990 kV phase-to-ground. The open-end peak voltage is only slightly higher, up to 1010 kV, on account of attenuation along the CL. For the 2.5 km cable, such maxima are practically unaffected by bonding leads inductance and by sheath/SVL grounding resistance values (despite the significant influence of the former on voltage waveshapes).

Shielding failure simulation results are summarized in Table II. The overall behaviour follows the pattern of the 2.5 km CL; maximum calculated receiving end voltages do not exceed sending-end voltages by more than 15%.

However, Table II shows that for longer cables grounding resistances practically do not affect maximum phase-to-ground voltages, while bonding lead inductances have an effect, albeit small: an increase in the value of l_{BL} tends to raise peak voltage at cable entrance and reduce it at the open end, especially for the 10 km case.

Receiving-end overvoltages are affected by SVL rated voltage (9 kV or 12 kV) only for the 10 km case, and then only by about 5%. For the sake of comparison, simulations have also been performed without any SVL (as in [3] and [4]). Maximum receiving-end overvoltages increase less than 10% compared to cases with U_r=12 kV.

Results thus obtained are obviously model-dependent. As an example, to check the relatively small voltage increase at the open receiving end of the CL, shielding failure simulations were also performed with the simpler constant-parameter model (calculated at 5 kHz). Such simulations yielded up to

20% higher overvoltages at both cable ends.

In conclusion, for all simulated cable lengths maximum calculated overvoltages along the cable are practically well under 1000 kV, provided that SVLs are taken into account. This is quite reassuring, given the 1425 kV LIWL currently specified for 380 kV cables. Under this regard, the worst fast-front overvoltage, mandatorily requiring SAs at the cable entrance, would be due to a nearby OHL backflashover; for the simulated configuration, however, critical backflashover currents should be well over 200 kA [4].

Practically speaking, the CL would always be fitted with SAs at the CL-OHL transitions; however, the above results show that for the simulated configuration the main cable insulation can safely withstand shielding failures with 10 kA lightning current with a reasonable margin.

V. Simulation of strokes to transition tower

For the simulated OHL, backflashover following a lightning stroke to a tower peak is highly unlikely, due to the combination of 380 kV line insulation, two shield wires and low tower grounding resistance. Fig. 5 shows the u(t)/i(t) ratio at the transition tower foot, clearly showing the effect of ionization. For strokes at the transition tower or adjacent ones, the lightning response of the mixed line under examination is even better than that of the OHL, due to the effect of cable sheaths connected to the tower foot (see f.i. the large critical backflashover currents calculated in [4]).

For the above reason, simulations of lightning strokes to transition tower were mainly aimed at assessing the dielectric stresses on the outer cable insulation (i.e. between metallic sheaths and ground). A 100 kA, 7/350 μs lightning stroke to the peak of the transition tower has been considered.

Fig. 6 reports sheath voltages (measured toward local ground) at the end of the first minor cross-bonding section of the 2.5 km CL (i.e. 830 m from the struck tower), as well as energy dissipated in SVLs at the same location. Results for different combinations of l_{BL} (0.15 μH/m or 1.2 μH/m) and earthing resistance (25 Ω or 50 Ω) are depicted, with 12 kV SVLs in both cases.

Plots in Fig. 6a show that larger inductances and grounding resistances only worsen the initial peak (up to a 33%-50% increase) of the sheath voltage with respect to local ground. Voltage rise toward the remote earth is 350-420 kV depending on cable model, l_{BL} and earthing resistances. Fig. 6b shows that a slightly higher "tail", however, can bring relatively large differences in energy absorption by SVLs. For the "reference" 100 kA stroke to the transition tower and 12 kV SVLs, the worst case energy value (black curve in fig. 6b) is 43 kJ (reached in 1 ms), that is, 3.6 kJ/kVrated. Note that with 9 kV SVLs, energy stresses are comparable (32 kJ). Such values should still be compatible with commonly available SVLs.

An interesting object of investigation, however, is the voltage stress of the outer sheath along the first minor section, i.e., at intermediate points, sufficiently distant from ground electrodes. This could probably be excessive.

Results in term of sheath voltages to ground (both local and remote) as well as SVL energy are given in Table III below.

In comparison with the JMARTI modeling used here, the constant-parameter model invariably yields higher initial voltages (i.e. a large voltage "spike", especially for the higher l_{BL}), up to a 130-150% increase of the peak voltage (to local ground). The behaviour on the "tail" of voltage surges reverses, with the constant parameter model yielding lower voltages and, most notably, SVL energy absorption.

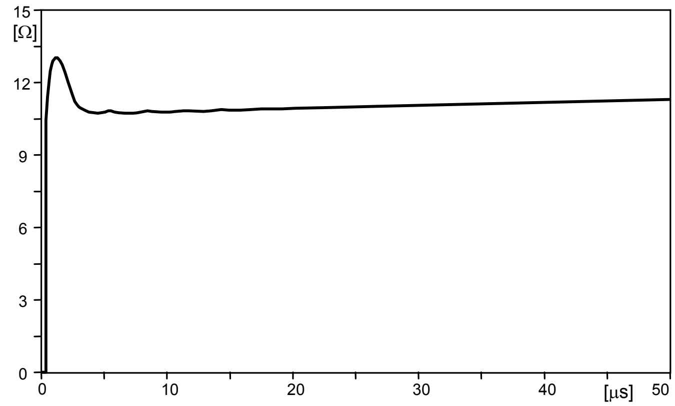

Fig. 5. Tower foot u(t)/i(t) ratio of transition tower grounding system, vs. time, following 100 kA, 7/350 μs stroke to tower peak (50 Hz calculated resistance is 14.4 Ω)

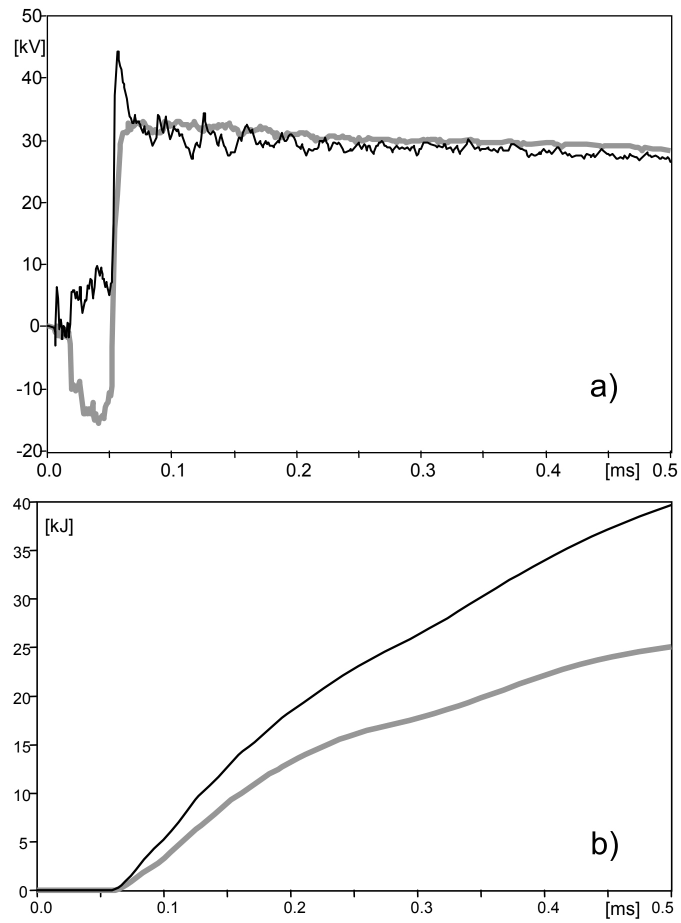

Fig. 6. Stroke to transition tower peak (100 kA, 7/350 μs). a) Sheath voltages to local ground, 25 Ω grounding resistance. b) Energy absorption in SVLs, 50 Ω grounding resistance. Light curves: l_{BL}=0,15 μH/m; black curves l_{BL}=1,2 μH/m.

TABLE III
SHEATH VOLTAGE AND SVL ENERGY ABSORPTION AT FIRST CROSS-BONDING SECTION (100 KA STROKE ON TRANSITION TOWER)

	l_{BL} [μH/m]	0.15						1.2					
CL length [km]		U_{Remote} [kV]		U_{Local} [kV]		Energy [kJ]		U_{Remote} [kV]		U_{Local} [kV]		Energy [kJ]	
	$R_{grounding}$ [Ω]	25	50	25	50	25	50	25	50	25	50	25	50
	$U_{r\text{-}SVL}$ [kV]												
2.5 km	9	354	406	25	24	29	21	356	356	37	37	28	32
	12	356	407	33	32	35	25	358	358	44	44	34	43
5.0 km	9	354	405	25	24	25	18	354	354	32	37	25	27
	12	356	407	33	31	32	21	356	356	39	44	31	34
7.5 km	9	354	406	25	24	26	18	355	355	37	37	25	27
	12	356	407	33	32	32	21	357	357	44	44	31	34
10.0 km	9	354	406	25	24	26	18	355	355	37	37	25	27
	12	356	407	33	32	32	21	357	357	44	44	31	34

VI. CONCLUSIONS

The paper analyzed the lightning behaviour of EHV mixed lines consisting of a XLPE-insulated cable line (CL) solidly series-connected to a conventional overhead line (OHL). Detailed ATP-EMTP time-domain simulations of a 380 kV-50Hz mixed-line with CL lengths varying between 2.5 and 10 km have been performed, in order to evaluate overvoltages due to lightning strokes at CL-OHL junction, either on phase conductors or on the transition tower.

Shielding failures do not pose a danger to the studied line, even for the shortest simulated CL. Taking into account SVLs protecting outer sheath insulation, overvoltages due to a 10-kA shielding failure current are barely over 1000 kV.

In case of strokes to the transition tower or adjacent ones, the lightning response of the mixed line under examination is better than that of the OHL, due to the effect of cable sheaths connected to the tower foot. Simulations show that at cross-bonding sections, transient voltages between metallic sheaths and local ground reaches 45 kV for a 100 kA stroke, while energy absorption by SVLs approaches the rated capabilities of commercially available devices.

VII. APPENDIX

The SVLs characteristics were derived from data in [12]:

TABLE IV
I-V CHARACTERISTICS OF SIMULATED SVLs

i [A]	v [kV]	
	(U_r = 9 kV)	(U_r = 12 kV)
.001	15.0	20.0
.01	16.5	22.0
.1	18.0	24.0
1.	18.75	25.0
10.	19.05	25.4
100.	19.5	26.0
1000.	21.75	29.0
10000.	27.75	37.0
100000.	41.25	55.0

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IX. Biographies

Luigi Colla was born in Marino (Italy) in 1980. He received the doctor degree in Electrical Engineering from the University of Rome "La Sapienza" in 2004. In 2005 he joined the Planning and Grid Development Department of Terna, Italian TSO and transmission grid owner. His main research interests are in power systems analysis, HVAC and HVDC transmission, electromagnetic transients and long distance transmission.

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