Lightning performance of a critical path from a 230-kV transmission line with grounding composed by deep vertical electrodes

R. Batista, P. E. B. B. Louro, J. O. S. Paulino

Abstract - **This work presents the impacts related to the addition of deep vertical electrodes on grounding meshes to transmission line performance. For soils with electric resistivity value lower at below layers, to use deep vertical electrodes can be a very interesting procedure to improve the grounding resistance and impedance characteristics for fast transients. A proposed installation procedure is presented as well as a brief cost comparison to the commonly use of surge arresters. A critical path from a 230-kV transmission line is evaluated for the direct incidence at the top of structures and mid span of first and subsequent lightning strokes. The results suggest a remarkable improvement of TL performance due to the use of deep vertical electrodes, particularly for first strokes, and the possibility of being added with other techniques, as underbuilt wires.**

Keywords: **Backflashover, Grounding, Lightning, Multilayer soils, Vertical electrodes.**

I. INTRODUCTION

IN order to improve the lightning performance of transmission lines (TL), different techniques can be adopt as the installation of surge arresters (SA), to increase the numbers of disks in the insulator chain (IC), shielding improvement by the use of ground wires (GW) and to decrease the grounding impedance of TL towers [1-5]. The common choice is to improve the grounding and, if it still not enough for the desired TL performance, to use SA in parallel to the IC of each circuit phase. It is well known that SA are expensive for high-voltage TL and can fail for varied reasons [6], requiring permanent supervision for the device. This behavior is undesirable and is not observed for the grounding improvement procedure.

If the soil is approximated by a two-layer stratified medium, with a lower electric resistivity of the second-layer, a recent work shows that deep vertical electrodes (DVE) can be a solution to reach considerably lower grounding impedances [7]. Although the simulations shown promising results, a technical analysis concerning costs and a procedure to its installation is desired to conclude if the technique is feasible. Being Brazil a place of many reports of TL lightning strikes [8], the viability of the technique supports its study as a solution or complement to improve the grounding of TL towers.

This work presents a case study of 230-kV TL, particularly on a critical path composed by three towers, englobing its lightning performance due to strikes on the top of structures and mid span. The original grounding meshes are compared to the addition of DVE and the installation of an underbuilt wire (UW) besides to a cost comparison between DVE and SA. Furthermore, the machinery required to install DVE is shown. All time-domain simulations are performed by Alternative Transients Program (ATP), while the impulse grounding behavior is computed by a rigorous electromagnetic (EM) technique [9], [10]: the HFSS software.

II. CONSIDERATIONS ON ELECTRIC CHARACTERISTICS AND INSTALLATION OF DVE

As proposed in [7], DVE can be a good alternative to the conventional grounding from TL towers, that are composed by counterpoise wires (CW), for conditions with lower electric resistivity at deeper layers of the soil. The main advantage of DVE is to reach the lower resistivity of the second-layer of the soil, which decrease the low-frequency grounding resistance R_{LF} and impulse impedance Z_P, which is defined by [11] as:

$$Z_P = \max(\mathrm{GPR})/\max(I) \tag{1}$$

where GPR is the ground potential rise developed due to the current wave I.

Consequently, the towers that implement DVE will increase its insulation robustness against lightning strikes and other kind of transients. It is clearly too that, if soil does not present this stratified behavior, the main justification to study DVE is vanished [7].

A way to install DVE on existing grounding meshes or as a unique configuration is illustrated in Fig. 1. A drill opens a hole on soil, with a certain length l and radius a, and the DVE is installed with connections to the tower feet. If desired, concrete or a similar material is used to fill the hole, improving the protection of the electrode as well as the grounding performance – concrete is a ground enhancing compound [12].

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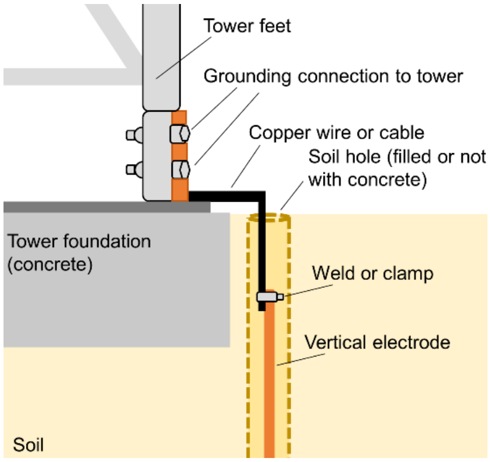


Fig. 1. Diagram of the proposed procedure to install DVE on TL towers – adapted from [13].

To drilling process involves a rotating probe drill rig, which allows holes with a $l > 100$ m and a in a range of 2.3 to 4.5 cm. Even rocks immersed in soil can be surpassed by this compact device, widely used in geotechnical studies. In Brazil, the drilling has a cost of R$ 50.00/m or, assuming US$ 1.00 = R$ 5.50, US$ 9.09 per m of l, including the soil evaluation that is unnecessary for our goal. The volume of concrete is estimated in R$ 285.60/m³ or US$ 51.00/m³ - since it does not have structural aim, it can be replaced by mortar inside the soil hole and maintain the same desired electrical properties. Furthermore, grounding wire conductor has a mean cost of US$ 4.00 up to US$ 5.00/m.

From the data reported by the Brazilian Energy Research Company or EPE [14], SA have their prices related to the nominal TL voltage. As example, a single device for 230 and 345 kV is valued, respectively, in US$ 6,290.00 and US$ 9,324.00. For the installation, a 20% price increase is expected.

Fig. 2 shows the differences between a conventional grounding and DVE option for TL towers. A compact mesh is reached by the vertical grounding configuration, which is desirable for places with significative people movement, as urban areas that can be crossed by TL towers. The robustness against stealing of conductors or sabotage is also improved by using DVE.

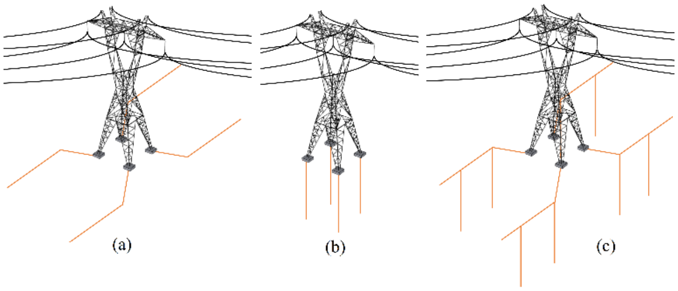


Fig. 2. Usual grounding meshes for TL towers: (a) conventional CW, (b) DVE alternative and (c) hybrid configuration – CW+DVE.

III. NUMERICAL ANALYSIS

A. 230-kV Irapé-Araçuaí 2 TL

This TL is composed by the conductors shown in Table I, cable-stayed towers with a typical height h_t = 35.85 m, 12 glass disks for the IC with a conventional BIL (basic insulation level) of 995 kV per phase [15] and a span of 420 m between towers. Its single circuit involves one conductor per phase as well as a single aerial GW. As presented in Table I, a single UW [16] is supposed to be installed for the posterior simulations of this work, where a_{int} is the internal radius of the conductor, a_{ext} is its external radius, R' is the longitudinal resistance per km for the cables at a fixed temperature (70° C for phase conductors, 40° C for GW and UW), x_{pos} is the horizontal position, h_{tower} and h_{mid} are, respectively, the vertical positions for the conductors at the tower and at mid span.

TABLE I
CONDUCTORS APPLIED TO THE 230-KV TL IRAPÉ-ARAÇUAÍ 2 [17]

Phases	a_{int} **(mm)**	a_{ext} **(mm)**	R' **(Ω/km)**	x_{pos} **(m)**	h_{tower} **(m)**	h_{mid} **(m)**
Phase cables: CAA TERN – 795 MCM (1 conductor/phase)						
A	3.38	13.52	0,088	3.43	31.3	19.49
B	3.38	13.52	0,088	-3.43	25.5	13.69
C	3.38	13.52	0,088	3.43	25.5	13.69
GW and UW: 3/8” EHS (1 conductor)						
GW	---	4.76	4.153	1.6	35.5	25.46
UW	---	4.76	4.153	0	21.2	11.19

Each tower is approximated by a single-phase line with a surge impedance and travel time in ATP. A direct lightning strike at the top of the structures derives in a vertical path for the current wave, while at mid span approaches horizontally to the towers [18]. Thus, following the division presented in Fig. 3, the cylindrical tower with h_t = 35.85 m and radius r_t = 3.43 m is computed to the vertical path as:

$$Z_s = 60\left(-1+\ln\left(\frac{2\sqrt{2}h}{r}\right)\right) \tag{2}$$

and, for the horizontal path of the lightning current, as [19]:

$$Z_s = 60\left(-1+\ln\left(\cot\left(\tan^{-1}\left(\frac{r}{h}\right)\Big/2\right)\right)\right) \tag{3}$$

where Z_s is the surge impedance of the entire tower.

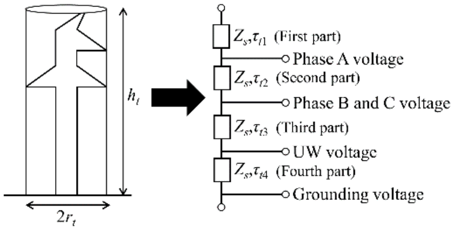


Fig. 3. Representation of the towers by their surge impedance.

The surge tower impedances have their values present in Table II, where τ is the travel time. The structure divisions from Fig. 3 are used to turn possible the voltage estimative for the points associated to the cross-arms and UW due to the lightning strike. The wave propagation along the towers is admitted to be 85% of the speed of light [18].

B. Grounding meshes

The three-towers' path has conventional grounding meshes installed in each metallic structure, as that from Fig. 2 (a), with

TABLE II

SURGE IMPEDANCE AND TRAVEL TIME FOR THE TOWERS

Structure	Z_s by Eq. (2) (Ω)	Z_s by Eq. (3) (Ω)	τ (ns)
First part	143.28	122.62	7.1
Second part	143.28	122.62	22.8
Third part	143.28	122.62	27.5
Fourth part	143.28	122.62	83.3
Entire tower	143.28	122.62	140.7

l = 90 m, 50 cm deep, right-of-way of 36 m and a = 5 mm. The soil referred to the structures are shown in Table III, with the electric resistivity for the conductors' span evaluated in 5956 Ωm, which is an extremely high value. The first- and second-layer electric resistivity, respectively, are denoted by ρ_1 and ρ_2, while h_1 is the first-layer thickness of the soil.

TABLE III

SOIL RELATED TO EACH TOWER FROM THE TL CRITICAL PATH [17]

Structure	ρ_1 (Ωm)	h_1 (m)	ρ_2 (Ωm)
Left tower (LT)	8417	7.2	5415
Central tower (CT)	8806	3.8	5379
Right tower (RT)	8679	2.7	6293

Assuming the addition of DVE to the original grounding mesh, as illustrated in Fig. 4, a total of eight rods or two vertical electrodes per diagonal path from CW is admitted, arranged every 30 m from each other – in this work, this grounding mesh is denoted as hybrid configuration. Each DVE is 100 m long and has an equivalent radius of 25 mm – 5 mm from the conductors and 20 mm from concrete. To consider a 25 mm radius is a consistent procedure due to the much greater soil resistivity around the grounding [20].

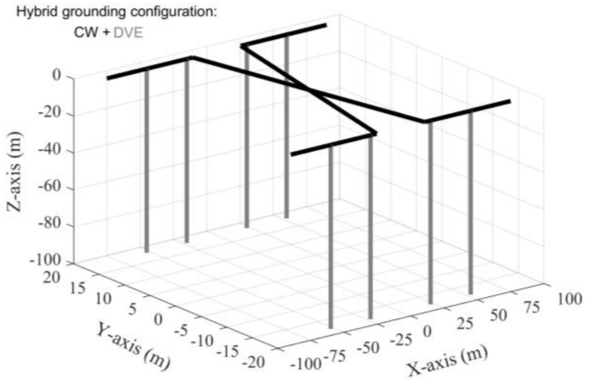


Fig. 4. Hybrid grounding configuration as an alternative for the TL towers.

The commercial software HFSS, which solves the full-wave Maxwell's equations using Finite Element Method, is considered to perform the grounding simulations. Implemented in a similar way than that presented in [21], the grounding problem considers each layer of the soil with frequency-dependent electric resistivity and permittivity, i.e., $\rho(f)$ and $\varepsilon(f)$ described by the mean values of [22]. Analytical proof and details to this procedure for multilayer soils are shown in [23]. Grounding harmonic impedance is estimated by HFSS software and its time-response for a certain current waveform is simplified to a resistance with the same Z_P value in ATP.

Table IV shows the computed R_{LF} and the impulse impedance Z_P referred to first and subsequent strokes, defined as Z_{PFST} and Z_{PSUB}, from representative current waves of Morro do Cachimbo Station (MCS). The double-peak first stroke MCS_FST#2 and subsequent current wave MCS_SUB, as denoted in [24], are considered with their median peak-values I_P.

TABLE IV

IMPULSE IMPEDANCE FOR EACH TOWER AND GROUNDING MESH RELATED TO THE TL TOWERS PROVIDED BY HFSS SOFTWARE

Tower	LT		CT		RT	
Grounding mesh	**CW**	**Hybrid**	**CW**	**Hybrid**	**CW**	**Hybrid**
R_{LF} (Ω)	57.33	17.57	56.84	17.35	59.46	20.02
Decrease of	- 69.3%		- 69.5%		- 66.3%	
Z_{PFST} (Ω)	42.52	13.48	42.17	13.33	43.88	15.03
Decrease of	- 68.3%		- 68.4%		- 65.7%	
Z_{PSUB} (Ω)	37.27	18.49	36.96	18.31	38.21	19.57
Decrease of	- 50.4%		- 50.5%		- 48.8%	

Considering the initial grounding configuration, a mean decrease of 68.4% is linked to R_{LF}, 67.5% to Z_{PFST} and 49.9% to Z_{PSUB} is achieved by the addition of DVE – these remarkable results are mainly due to $\rho_2 < \rho_1$. To obtain similar decrease uniquely by the use of horizontal conductors is a very complex task, since CW has its electric behavior defined mainly by the soil layer in which it is installed, i.e., ρ_1.

For the case shown in Table IV, the DVE demands a drilling of 800 m or U$S 7,273.00. Using a conductor with a = 5 mm filled by 20 cm of concrete, derives in 1 m³ of material and US$ 51.00. Thus, a final price of US$ 7,323.00 is calculated and, assuming the 800 m length of conductors and the electric connection to the metallic structure, a cost lower than US$ 11,000.00 is considered feasible for each tower or U$ 33,000.00 for the entire TL path.

To install a SA for each phase of a tower, considering a 230-kV TL, derives in US$ 18,870.00, but the ideal is to use the device also for the adjacent structures. Thus, US$ 56,610.00 needs to be added to 20% for the installation service, which implies to a final cost of US$ 67,932.00. This price is more than two times greater than the DVE option, which does not need to be monitoring with the same rigorous criteria of SA to prevent fails. The percentage of lightning strikes that SA can be required to actuate is proportional to the maximum current peak supported by the grounding, which is, as will be seen in the next Sections, lower for CW compared to DVE alternative. Consequently, the fail chances for SA are increased in such case.

C. ATP simulation

The TL path, composed by three towers with two conductor's sag of 420 m, is implemented in ATP for two conditions: a direct lightning strike at the top of CT and at mid span between CT and RT. First and subsequent lightning strokes are assumed changing I_P value, until the voltage between the IC reach the conventional BIL of 995 kV.

As presented in Fig. 5, the line cables modelled by JMarti model in ATP can include a UW as an additional conductor for the TL. If UW is omitted, its conductor is removed from the line model and also its connection to the adjacent towers – Fig. 6 shows the defined parameters for JMarti model in simulations.

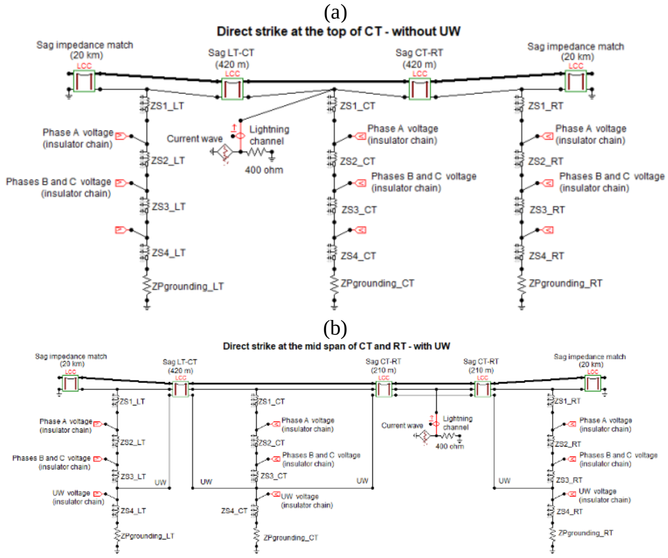
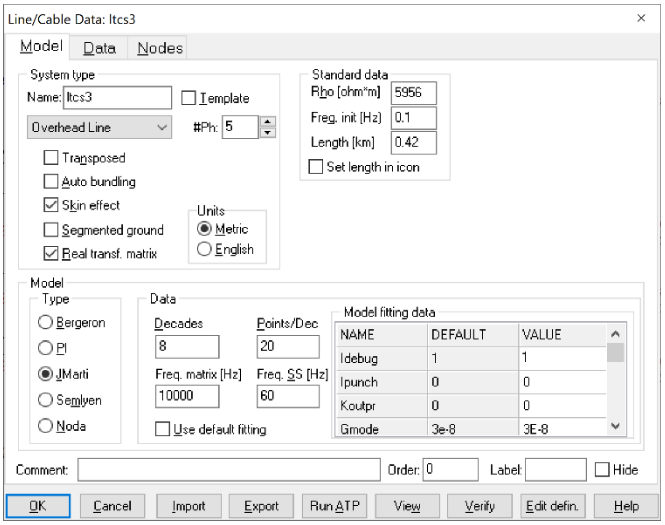


Fig. 5. Circuit implemented in ATP referred to: (a) a direct incidence at the top of CT, without UW, and (b) at mid span between CT and RT, including UW.



System type

Name: ltcs3 ☐ Template

Overhead Line #Ph: 5

☐ Transposed

☐ Auto bundling

☑ Skin effect

☐ Segmented ground

☑ Real transf. matrix

Units: ● Metric ○ English

Standard data

Rho [ohm*m]: 5956

Freq. init [Hz]: 0.1

Length [km]: 0.42

☐ Set length in icon

Model

Type: ○ Bergeron ○ PI ● JMarti ○ Semlyen ○ Noda

Data

Decades: 8

Points/Dec: 20

Freq. matrix [Hz]: 10000

Freq. SS [Hz]: 60

☐ Use default fitting

Model fitting data

NAME	DEFAULT	VALUE
Idebug	1	1
Ipunch	0	0
Koutpr	0	0
Gmode	3e-8	3E-8

Comment:

Order: 0

Label:

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Fig. 6. Data related to JMarti model in ATP.

To include the circuit voltages, fluctuations of 5% are considered acceptable to the line, which derives in an amplitude V_{ph} for the phase voltage equals to:

$$V_{ph} = \frac{230 \cdot 1.05 \cdot \sqrt{2}}{\sqrt{3}} = 197,2 \text{ kV} \tag{4}$$

The phases conductors can present this value at the time instant that the lightning strikes the TL and can be considered to the peak values associated to the transient. To achieve this behavior, the conventional BIL is decreased by 197.2 kV, deriving in 797.8 kV as the new limit for electric potential between the terminals of the IC. This procedure is very pessimist due to the lower chances to happen in practice, but assures the robustness of the solutions due to a possible backflashover occurrence from tower to the phase cables.

Furthermore, coupling between grounding, towers and TL cables systems in ATP are omitted for simplicity purposes.

IV. RESULTS

All simulations performed with ATP have the main objective to identify the maximum value of I_P that maintains the electric potential between the IC below to the limit acceptable value of 797.8 kV. Although first and subsequent strokes can have their front time modified linked to the increase of I_P, their median values were supposed to be constant. Consequently, only the peak value from the current waves evaluated were modified in ATP.

To exemplify the curves obtained, Fig. 7 presents the electric potential between IC for the phases of each structure assuming the current wave MCS_FST#2 with median peak values, as originally shown in [24]. The condition is associated to the lightning strike at the top of CT with CW and hybrid grounding configurations.

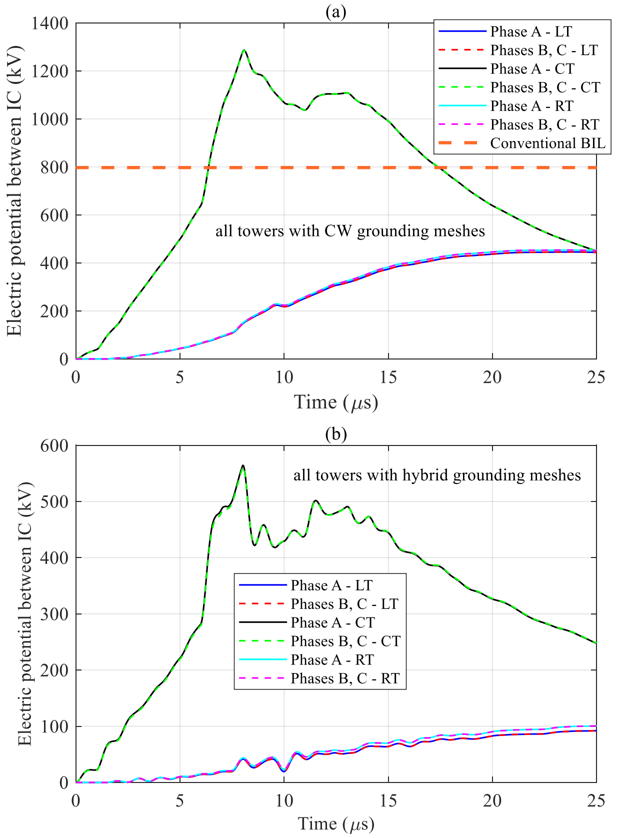

Fig. 7. Curves of electric potential between IC for the towers with (a) CW grounding configuration and (b) hybrid grounding mesh.

A. Lightning incidence at the top of CT

The maximum I_P values of lightning current waves that do not promote backflashover at the towers are shown in Table V. The critical electric potential values for this condition correspond to the IC of phase A from CT. An additional information is the percentage of lightning strokes that surpass I_P [25], which provides the lightning performance achieved by the TL with the use of each procedure.

The results indicate that the original grounding configuration, composed by CW, provides a poor lightning protection to backflashover occurrence at IC. For first strokes, a peak of 28 kA is supported, which has an amplitude greater than only 15% of the statistical currents reported by [25].

TABLE V

MAXIMUM I_P VALUES FOR DIRECT LIGHTNING STRIKES AT THE TOP OF CT

Parameter	**CW**	**Hybrid**	**CW + 1 UW**	**Hybrid + 1 UW**
Maximum I_P – first stroke (kA)	28	64	33	71
Currents with greater I_P	85%	22%	75%	16%
Maximum I_P – subsequent stroke (kA)	20	23	24	27
Currents with greater I_P	40%	30%	27%	20%

The subsequent stroke condition is better, but 40% of the possible current wave still can surpass the I_P value of 20 kA. To add DVE seems to be very effective for first strokes, with the maximum I_P going to 64 kA and only 22% of current wave tends to have greater peak values, which corresponds to an improvement of almost 400% compared to CW option. However, the subsequent stroke transient is less affected by the decrease of the impulse impedance, with 23 kA. Currents that surpass this I_P value is estimated in 30%, a better result than that 40% from CW alternative, but the upgrading is considerably lower than the first stroke incidence. This behavior can be justified by the propagation effect of the faster transient compared to the first stroke incidence.

Subsequent strokes present current components with higher frequencies, which can be completely attenuated and deformed along the propagation on sag conductors. As a result, it is much more complex to decrease the voltage levels linked to faster transients with only the reduction of grounding impedance. To include a UW, as seen in Table V, tends to be a better alternative because it works, in a simplistic and general view, decreasing the characteristic impedance of the line conductors by the capacitive coupling with the ground wires at towers. This characteristic is commonly not very well represented by ATP, since this kind of coupling demands EM methods to be precisely computed, as HFSS and HEM [26]. Thus, we expect that the improvement using UW is underestimated by ATP.

To add one UW to the CW option slightly modifies the TL performance, notably for first strokes, being much worse than DVE procedure, but better for subsequent currents. For this specific case, 27% of lightning currents are expected to have greater peak values by the addition of a UW. If the improvement is insufficient, DVE and UW can be added to the basic CW grounding, which mix the best features of each technique. The maximum I_P value for first strokes is updated to 71 kA, while for subsequent currents is changed to 27 kA. This corresponds to a robustness of 84% for first and 80% for subsequent strokes, a remarkable result for a soil with a substantial high resistivity value.

B. Lightning incidence at mid span of CT and RT

The lightning incidence at mid span of CT and RT is not so critical as the last analysis, as seen in Table IV, but indicates that DVE seems to be a better option than UW in all conditions evaluated. The current waves, even for subsequent strokes, have a path to the structures that is the half-length of the first analysis. This characteristic turns the improvement of the grounding more efficient to decrease the voltage levels at IC.

Table VI shows that 44% of the first stroke currents are able to maintain the normal TL operation for the original configuration, while a single UW improves this behaviour to 48%. To install DVE virtually nullifies the possibilities of a backflashover on IC almost tripling the maximum I_P value. For subsequent strokes, DVE doubles the performance from CW option for the chances of greater peak value currents and is better than a single UW added to the original path. The arrange composed by DVE and UW does not promote justified results to be opted for mid span lightning incidences, being slightly better than DVE installed with CW grounding.

TABLE VI

MAXIMUM I_P VALUES FOR DIRECT LIGHTNING STRIKES AT MID SPAN OF CT-RT

Parameter	**CW**	**Hybrid**	**CW + 1 UW**	**Hybrid + 1 UW**
Maximum I_P – first stroke (kA)	42	112	44	113
Currents with greater I_P	56%	2%	52%	2%
Maximum I_P – subsequent stroke (kA)	35	42	37	45
Currents with greater I_P	9%	4.6%	7.5%	3.5%

V. CONCLUSIONS

This work presented a study on the influence of DVE installed on grounding meshes to the TL performance related to direct incidence of first and subsequent strokes. Considering a 230-kV TL, the performance for its critical path is evaluated with the original configurations and the addition of DVE and/or UW. A comparison cost and a procedure to its installation in TL was presented, being, for the critical path, at least two times cheaper than the usual option for SA.

The results support the feasibility of using DVE in soils with $\rho_2 < \rho_1$, achieving remarkable improvements on TL performance, notably first strokes. For the soil analyzed with significant high resistivity value, to change the electric properties from the TL conductors by the use of UW seems to be a better option – TL towers require mechanical studies to know if UW are feasible to be installed as well as future repowering of lines. Cases with lower soil resistivities will be studied in future works in addition to TL with greater nominal voltages, that seems to be even better for DVE utilization compared to SA – while SA price increases for greater nominal voltages, DVE maintains their related costs. Procedures to coupling all equipment that compose TL are also aimed in future works.

VI. REFERENCES

[1] *IEEE Guide for Improving the Lightning Performance of Transmission Lines*, IEEE Standard 1243-1997, Dec. 1995.

[2] M. S. Banjanin, M. S. Savic and Z. M. Stojkovic, "Lightning protection of overhead transmission lines using external ground wires", *Electric Power Systems Research*, vol. 127, pp. 206-212, Oct. 2015.

[3] M. Asadpourahmadchali, M. Niasati and Y. Alinejad-Beromiand, "Improving tower grounding vs. insulation level to obtain the desired back-flashover rate for HV transmission lines," *International Journal of Electrical Power & Energy Systems*, vol. 123, pp. 1-10, Dec. 2020.

[4] P. Sarajcev, D. Jakus and J. Vasilj, " Introducing novel risk-based indicator for determining transmission line tower's backflashover performance", *Electric Power Systems Research*, vol. 160, pp. 337-347, July 2018.

[5] R. M. A. Velásquez and J. V. M. Lara, "Model for failure analysis for overhead lines with distributed parameters associated to atmospheric

discharges," *Engineering Failure Analysis*, vol. 100, pp. 406-427, June 2019.

[6] M. Gumede, and G. F. D'Almaine, “Surge arrester faults and their causes at eThekwini electricity,” *International Journal of Electrical Energy*, vol. 2, pp. 39-44, 2014.

[7] R. Batista, C. E. F. Caetano, J. O. S. Paulino, W. C. Boaventura, I. J. S. Lopes, E. N. Cardoso, "A study of grounding arrangements composed by vertical electrodes for two-layered stratified soil models," *Electric Power Systems Research*, vol. 180, pp. 1-9, Mar. 2020.

[8] S. Visacro, R. N. Dias, C. R. Mesquita, P. Resende, A. Cazetta, “Metodologia para aplicação de sistemas de detecção e localização de descargas atmosféricas nas etapas de projeto e manutenção do sistema elétrico,” in *2005 CITENEL*, pp. 1-5.

[9] J. P. Plumey, D. Roubertou, J. Fontaine, and P. Kouteynikoff, “High frequency harmonic input impedance of an antenna embedded in a conducting half-space,” in *1983 Proc. Int. Zurich Symp. Electromagnetic Compatibility*, pp. 45–50.

[10] L. Grcev and M. Popov, “On high-frequency circuit equivalents of a vertical ground rod,” *IEEE Trans. Power Del.*, vol. 20, no. 2, pp.1598-1603, Apr. 2005.

[11] A. L. Vainer, “Impulse characteristics of complex earth grids,” *Elektrichestvo*, vol. 3, pp. 107–117, 1965.

[12] V. P. Androvitsaneas, I. F. Gonos, and I. A. Stathopulos, “Research and applications of ground enhancing compounds in grounding systems,” *IET Gener. Transm. Distrib.*, vol. 11, no. 13, pp. 3195-3201, Oct. 2017.

[13] D. G. Fink, and H. W. Beaty (Org.), *Standard handbook for electrical engineers*, 14 ed. New York: McGraw-Hill, 2000.

[14] *Banco de Preços de Referência da ANEEL: Atualização dos Valores para a Data-Base Junho de 2020*, EPE-DEE-IT-066/2020, 2020.

[15] *IEEE Standard for Insulation Coordination--Definitions, Principles, and Rules*, IEEE Std C62.82.1-2010, April 2011.

[16] S. Visacro, F. H. Silveira, and A. De Conti, "The Use of Underbuilt Wires to Improve the Lightning Performance of Transmission Lines," *IEEE Transactions on Power Delivery*, vol. 27, no. 1, pp. 205-213, Jan. 2012.

[17] Transmineira, “Estudos de desempenho de linha de transmissão quanto a surtos atmosféricos e avaliação de risco à 60 Hz, LT 230-kV Irapé-Araçuaí 2,”, Cia Transmineira, Tech. Rep. ES-363-001, 2007.

[18] J. A. Martinez-Velasco, *Power System Transients: Parameter Determination*, 1st ed. Boca Raton: CRC Press, 2009.

[19] W. Chisholm, Y. L. Chow, and K. D. Srivastava, “Lightning surge response of transmission towers,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-102, no. 9, pp. 3232–3242, Sep. 1983.

[20] A. B. Lima, J. O. S. Paulino, W. C. Boaventura, and M. F. Guimarães, “Transient ground impedance measurement using a very short current lead,” in *2013 International Symposium on Lightning Protection (XII SIPDA)*, pp. 177-183.

[21] B. Salarieh, J. De Silva, and B. Kordi, “Wideband EMT-compatible model for grounding electrodes buried in frequency dependent soil,” in *2019 International Conference on Power Systems Transients (IPST)*, pp. 1-6.

[22] R. Alipio and S. Visacro, "Modeling the Frequency Dependence of Electrical Parameters of Soil," *IEEE Transactions on Electromagnetic Compatibility*, vol. 56, no. 5, pp. 1163-1171, Oct. 2014.

[23] R. Batista, "Analysis of grounding meshes composed by deep vertical electrodes in transmission line towers," (in Portuguese) Ph.D. dissertation, Dept. Elect. Eng., UFMG, Belo Horizonte, 2020.

[24] A. De Conti and S. Visacro, "Analytical Representation of Single- and Double-Peaked Lightning Current Waveforms," *IEEE Transactions on Electromagnetic Compatibility*, vol. 49, no. 2, pp. 448-451, May 2007.

[25] S. Visacro, C. R. Mesquita, A. De Conti, and F. H. Silveira, "Updated statistics of lightning currents measured at Morro do Cachimbo Station," *Atmospheric Research*, vol. 117, pp. 55-63, Nov. 2012.

[26] S. Visacro and A. Soares, "HEM: a model for simulation of lightning-related engineering problems," *IEEE Transactions on Power Delivery*, vol. 20, no. 2, pp. 1206-1208, April 2005.