Lightning Overvoltages in Copel's Compact Urban Transmission Lines

Modeling and comparison of compact and supercompact arrangements

SOUZA, Muryllo Amalio
Department of Substations and Transmission Lines
Companhia Paranaense de Energia - COPEL
Curitiba - Brazil
muryllo@copel.com

CHEMIN NETTO, Ulisses
Department of Electrical Engineering
Federal University of Technology - Parana
Curitiba - Brazil
ucnetto@utfpr.edu.br

Abstract— Knowledge about possible internal or external overvoltages in electrical power systems is critical to their proper design and reliable operation. In overhead AC transmission lines, such overvoltages will directly determine the type of insulation and phase-to-phase clearance. It is essential to analyze the effects of overvoltages caused by atmospheric discharges on compact AC overhead transmission lines in order to identify their behavior and propose strategies to prevent line outages, ultimately improving transmission line performance. This paper describes a study of possible transient overvoltages in Copel's compact and supercompact urban transmission lines, using ATPDraw software for modeling and simulations. Compact and supercompact overvoltages are found to differ from each other mainly due to the different levels of surge impedance in transmission lines. It can therefore be stated that, in this case, smaller phase-to-phase clearances are not a decisive factor in overvoltages caused by atmospheric discharges .

Keywords—overvoltages; compaction; urban transmission lines; ATPDraw.

I. INTRODUCTION

For more than 40 years, Copel, an electric utility company located in southern Brazil, has studied and developed a specific overhead transmission line arrangement for use in places where space is limited, such as highly populated urban areas. This arrangement, known as Urban Transmission Lines (UTL), is built using circular concrete poles, line post insulators, and overhead and underbuilt grounded cables [1,2]. In 2013, Copel analyzed the technical feasibility of reducing the typical phase-to-phase clearance in 138 kV UTLs from 1.7 m to 1.2 m, and this analysis resulted in the creation of a new arrangement called Supercompact Urban Transmission Lines (SCUTL).

Reducing the phase-to-phase clearance may cause variations in the transient overvoltage behavior of 138 kV transmission lines. This article analyzes overvoltage levels in compact and supercompact urban transmission lines to determine whether a reduction in phase-to-phase clearances would result in higher voltages. ATPDraw software is used here for modeling and simulation, a description is given of the modeling criteria, and comparisons are made based on an analysis of overvoltage curves.

II. COPEL'S URBAN TRANSMISSION LINES

Copel's urban compact transmission lines [2,3] are built with 22 to 28-meter-tall concrete pole structures, polymer line post insulators and grounding systems consisting of three copper clad steel rods (each 6 meters long). Phase conductors are ACSR 636 or 795 kcmil cables, and both overhead and underbuilt ground –cables are ACSR 4/0 type. These structures have a mean span of about 80 meters. Phase-to-phase clearances in the conventional arrangement are 1.2 meters for 69 kV and 1.7 meters for 138 kV. In contrast, the supercompact arrangement has a 1.2-meter phase-to-phase clearance for 138 kV [3]. This type of urban arrangement can be installed on sidewalks, since it requires little physical space.

The visual impact of transmission lines in urban areas is important. Therefore, circular concrete structures were chosen rather than metal lattice structures. Concrete structures are commonplace in Brazil, and people are accustomed to them because they are used for distribution and telecommunication systems.

The use of line post insulators in place of crossarms reduces the physical dimensions of the arrangement. Moreover, its visual impact is softened by using polymer line post insulators, which are lighter and thinner than ceramic ones. Phase conductors are electrically oversized (i.e., their ampacity is much higher than the current in the cable) because of the electric field surface. The proximity of the phases may cause a corona effect, but problems such as audible noise, visual corona, and radio interference can be prevented by using the chosen conductors. These conductors are also mechanically oversized, since they are strung by a tension of 500 kgf and have rated strengths of 11400 kgf (636 kcmil) and 14200 kgf (795 kcmil), giving these transmission lines high safety levels. This is another vital aspect of transmission lines in urban areas.

Underbuilt grounded cables also contribute to the system's safety by reducing fault current flowing to the ground, as well as step and touch voltages in nearby structures. These cables also contribute to electric field mitigation. Underground cables act as a physical barrier against accidental touches on phase cables. Moreover, these cables act as a safety device for protection against mechanical breakdowns of insulators or phase conductors.

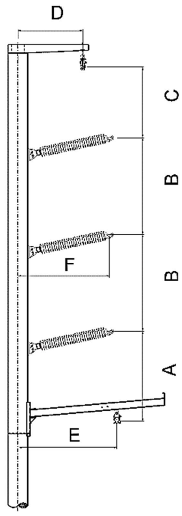

Fig. 1. Schematic diagram of a Copel urban transmission line

TABLE I. COMPACT AND SUPERCOMPACT UTL CLEARANCES

Arrangement	Clearance					
	A(m)	***B(m)***	***C (m)***	***D(m)***	***E (m)***	***F (m)***
Compact	1.5	1.7	1.2	1.1	1.7	1.6
Supercompact	1.3	1.2	1.0	0.7	1.0	1.1

Figure 1 and Table I describe the physical dimensions of 138-kV compact and supercompact transmission lines. This information is essential for ATPDraw modeling.

Table II describes the characteristics of the conductors and their positions in the structure. The resistance is given for direct current and for 75ºC. Midspan clearances were calculated considering an 80-meter span and cables strung for a 500 kfg tension.

TABLE II. CHARACTERISTICS AND CLEARANCES BETWEEN PHASE CONDUCTORS.

Conductor	Internal radius (cm)	External Radius (cm)	DC Resistance (ohm/km)	Conventional UTL			Supercompact UTL		
				Horizontal (m)	**Vertical Tower (m)**	**Vertical Midspan (m)**	**Horizontal (m)**	**Vertical Tower (m)**	**Vertical Midspan (m)**
Upper phase	0.4635	1.2575	0.1062	1.6	18	16	1.6	17	14
Mid phase	0.4635	1.2575	0.1062	1.6	16.3	14.3	1.6	15.8	13.8
Lower phase	0.4635	1.2575	0.1062	1.6	14.6	12.6	1.6	14.6	12.6
OHGW*	0.2385	0.7155	0.2676	1.1	19.2	17.6	1.1	18.3	15.3
UBGW**	0.2385	0.7155	0.2676	1.7	13.1	11.5	1.7	13.6	10.6

* Overhead ground wire.** Underbuilt ground wire.

III. ATPDRAW MODELING CRITERIA

This section explains the criteria used to model the two arrangements using ATPDraw software, as described in references [4] to [12].

A. Overhead Transmission Line

The overhead transmission lines were represented by the characteristics and clearances of the conductors, using the LCC component in ATPDraw. According to Assis et al. [4], overvoltages caused by lightning strikes are electrical fast transients that are influenced by waves traveling along the adjacent spans. Thus, overhead transmission lines can be modeled considering only 3 or 4 spans on each side of the point of impact. The LCC component was used to model each span, as well as the structure and grounding system.

The remaining length of the line was modeled using only the LCC component, considering a total length of 5 km. Urban transmission lines are typically 5 km long and have a span length of 80 m. When modeling the rest of the line, it is essential to avoid reflections, which affect overvoltage results. The JMarti model was therefore chosen, since this study focused on transient phenomena.

B. Structures

As mentioned earlier herein, Copel's urban transmission lines are built using concrete structures with steel reinforcing bars (rebar). When modeling transmission lines, the rebar is disregarded. The overhead ground wires are connected to the grounding system by Poppy conductors and copper clad steel 7X8 cable, all of them isolated from the rebar. Thus, the surge impedance of the structure is calculated considering only these connection cables.

When the conductor length is greater than its radius, the surge impedance is calculated using Equation (1) [5]. In both arrangements, the structure has a height H of 12 m and a radius "r" of 0.00489 m, resulting in a surge impedance Z equal to 408 ohms.

$$Z = 60.\left[ln\left(\frac{H}{r}\right) - 1\right] \qquad (1)$$

The impedance of Poppy and copper clad steel cables is calculated using the same method. These conductors are represented by the dimensions C+D, B and A+E in Figure 1. In addition, there are two Poppy conductors in parallel. The radius of Poppy cable is 0.00468 m, and that of copper clad steel cable is 0.004895 m. Figure 2 illustrates the spans of the two arrangements.

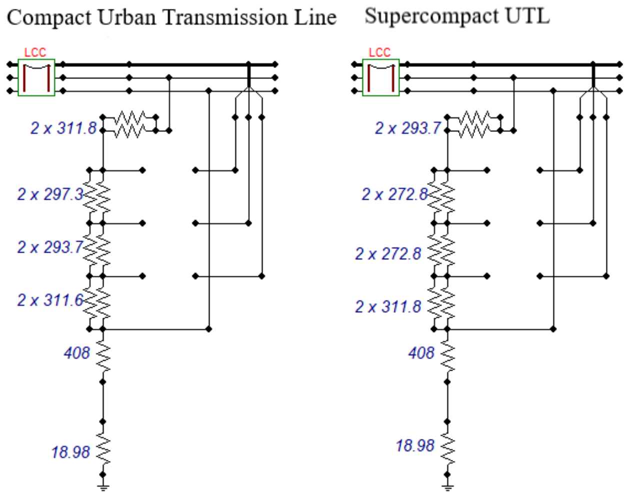

Fig. 2. Detailed modeling of the spans of Copel's compact (left) and supercompact (right) urban transmission lines .

C. Grounding system

The grounding system of Copel's urban transmission lines consists of three aligned copper clad steel rods, 6 m long, spaced 6 m apart. Their typical resistance is 20 Ω, while the resistivity of soil is 300 Ω.m. Alipio and Visacro [6] discuss a method to calculate surge impedance based on low-frequency grounding resistance. These authors state that surge impedance can be calculated as a function of low-frequency grounding, using a factor that multiplies the grounding resistance. This factor depends on the configuration of the grounding system.

This methodology was therefore used to calculate surge impedance in the grounding systems of compact and supercompact arrangements, which are the same. The result is 18.98 ohms, represented as a regular resistance element (see Fig. 2).

D. Insulators

To analyze the insulator's capacity to withstand flashover, the overvoltages were compared to the insulator volt-time curve, which was calculated using eq. (2) published in IEEE Transactions on Power Delivery [7]. This curve represents the time elapsed after a lightning strike and flashover voltage. In this case, we considered an elapsed time of 0.5 to 16 µs and an insulator length of 1.2 m.

$$V_{v-t} = K_1 + \frac{K_2}{t^{0.75}} \qquad (2)$$

K_1 = 410.L
K_2 = 710.L
V_{v-t} = Flashover voltage, kV
L = Insulator length, m
t = Time elapsed after lightning strike, in µs

E. Lightning surge source

Some types of surge sources are available in ATPDraw and can be set up according to user need. One of the types of surge source provided by ATP is the Heidler model. Assis et al. [8] state that the Heidler model is the suitable type of source to represent the interaction of lightning strikes with power systems. According to Chisholm [9], a lightning strike can be accurately represented by a curve where the front time is equal to 1 µs and the tail time is equal to 5 µs. This curve is used to analyze the effects of lightning strikes on insulators.

A peak current value of 31 kA was used, which is the peak value of current adjusted according to Heidler's current source. This is presumably the peak current that prevails in the region of Curitiba, state of Paraná, Brazil, where most of Copel's 69 and 138 kV urban transmission lines are located. This peak current is suggested by Chisholm et al. [10], and is also mentioned by Naccarato [11], who studied the peak values of lightning strikes in Brazil, as illustrated in Figure 3.

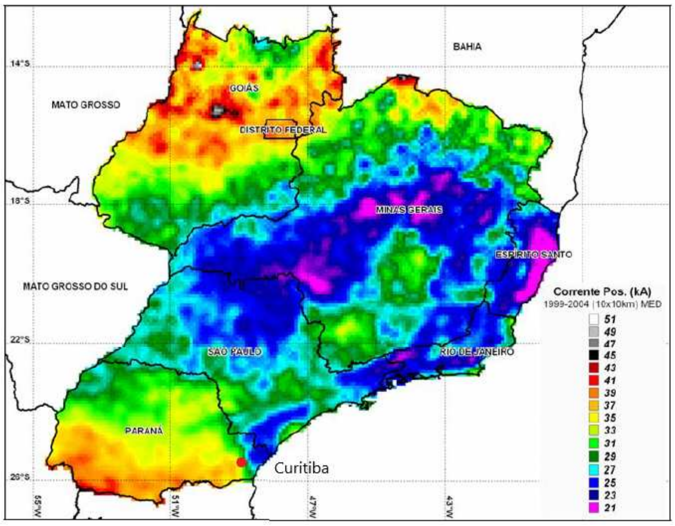

Fig. 3. Peak lightning strikes in part of Brazil [11].

Some studies recommend representing the impedance path of lightning as a resistance parallel to current source. The resistance value is taken to be 400 Ω, as proposed by Fekete et al.[12].

F. Overall model used in simulations

Figure 4 depicts the complete model of compact and supercompact urban transmission lines. Both transmission line arrangements are 5 km in length and 138 kV.

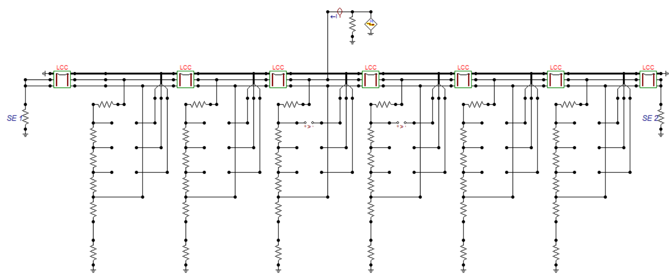

Fig. 4. Overall Model for simulating lightning overvoltages.

IV. RESULTS

Figures 5 and 6 illustrate the calculated lightning overvoltages in the mid-span and structure of compact and supercompact transmission lines.

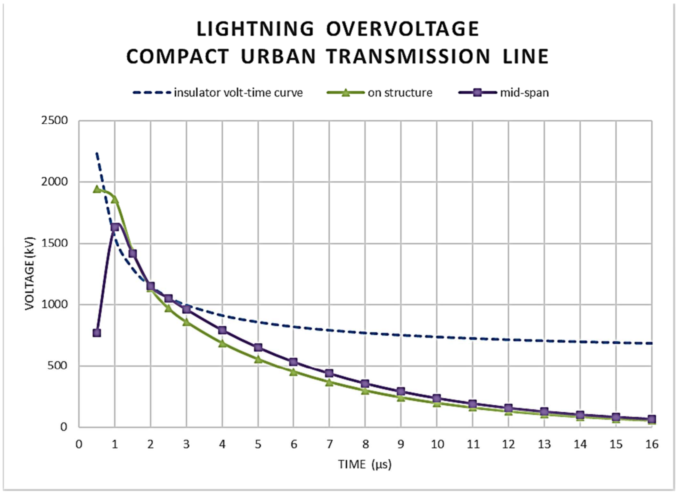

Fig. 5. Comparison of calculated overvoltages and insulator v-t curve of a compact urban transmission line.

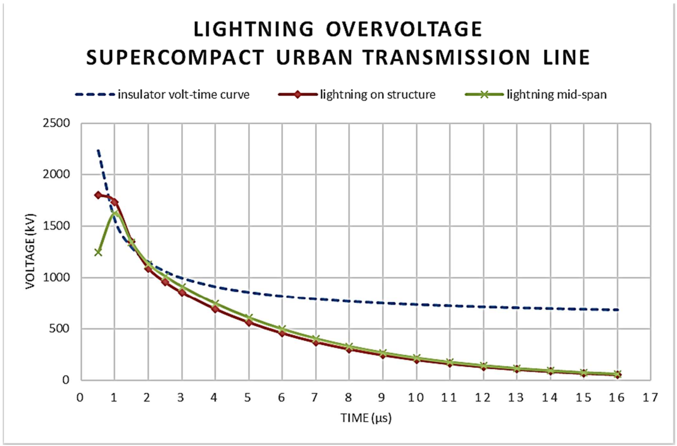

Fig. 6. Comparison of calculated overvoltages and insulator v-t curve of a supercompact urban transmission line.

As mentioned earlier, the compact and supercompact urban transmission lines were both modeled with a length of 5 km. The lightning strike was modeled assuming it hit the span and structure of the transmission line. In both cases, the transmission lines were struck by lightning precisely at mid-span. Figures 5 and 6 also show the insulator V-T curves.

In this scenario, the simulated results for both arrangements indicate that the overvoltages are very close to the insulator limit in a time of 1 µs. Table III lists the values calculated by ATP for lightning strikes at mid-span. Note the difference between the compact and supercompact arrangements. Because the phase-to-phase clearance of the supercompact structure is smaller than that of the compact structure, its impedance withstand capability is lower.

In this case, therefore, the decrease in phase-to-phase clearance from 1.7 m to 1.2 m has less impact on the magnitude of overvoltages. Table IV describes a scenario in which both compact and supercompact structures the same surge impedance.

TABLE III. COMPARISON OF OVERVOLTAGES IN COMPACT AND SUPERCOMPACT STRUCTURES CONSIDERING DIFFERENT SURGE IMPEDANCES.

Time (µs)	Compact Urban Transmission Line Overvoltage (kV)	Supercompact Urban Transmission Line Overvoltage (kV)	Diff.(%)
0.5	1941.91	1800.39	7.29%
1	1861.56	1732.22	6.95%
2	1135.56	1090.20	3.99%
3	857.84	855.51	0.27%
4	686.65	691.96	-0.77%
5	555.08	562.41	-1.32%
6	450.33	457.57	-1.61%
7	365.80	372.26	-1.77%
8	297.20	302.76	-1.87%
9	241.39	246.10	-1.95%
10	195.95	199.91	-2.02%
11	158.94	162.26	-2.09%
12	128.79	131.58	-2.17%
13	104.23	106.58	-2.25%
14	84.23	86.22	-2.36%
15	67.94	69.64	-2.49%
16	54.69	56.14	-2.65%

TABLE IV. COMPARISON OF OVERVOLTAGES IN COMPACT AND SUPERCOMPACT STRUCTURES CONSIDERING THE SAME SURGE IMPEDANCES.

Time (µs)	Compact Urban Transmission Line Overvoltage (kV)	Supercompact Urban Transmission Line Overvoltage (kV)	Diff.(%)
0.5	1227.9	1227.1	0.06%
1	1613.2	1602.4	0.67%
2	1126.4	1119.0	0.66%
3	905.2	903.4	0.20%
4	738.4	738.1	0.05%
5	602.7	602.4	0.05%
6	491.6	491.2	0.09%
7	400.7	400.1	0.14%
8	326.3	325.7	0.17%
9	265.5	264.9	0.20%
10	215.8	215.4	0.20%
11	175.3	174.9	0.20%
12	142.2	141.9	0.18%
13	115.2	115.0	0.14%
14	93.2	93.1	0.08%
15	75.3	75.3	0.00%
16	60.7	60.8	-0.10%

V. CONCLUSIONS

This study focused on modeling and simulating lightning-induced transient overvoltages in 138 kV compact and supercompact overhead urban transmission lines, using ATPDraw software. The results indicated that supercompact urban transmission lines would present lower overvoltages mainly due to their lower surge impedance. Moreover, it was found that 31 kA peak currents would exceed the insulator's capacity to withstand flashover in both compact and supercompact arrangements.

Thus, there is an urgent need for further studies to characterize peak values of lightning strikes and evaluate the probability of lightning striking transmission lines. Additional studies are also needed to analyze different lightning waveforms such as CIGRE, triangular and the association of six Heidler curves. The use of ZnO surge arresters and their impact on urban transmission line compaction should also be analyzed.

REFERENCES

[1] J. N. Hoffmann, R. W. Wiedmer, M. J. Bubniak, I. S. Moreira. "Urban overhead transmission lines of compact design for 69, 138 and 230 kV" (CIGRE Session, 2010). Paris, France.

[2] M.A. Souza, J.N. Hoffmann, F.L.R. Casagrande and U.C. Netto, "Compact Transmission". T&D Magazine. March 2019. pp-28-31 pp.

[3] M.A.Souza, J.N. Hoffmann, F.L.R. Casagrande and U.C. Netto, "Copel's experience on uprating a 69 kV Compact Urban Transmission Line into 138 kV (Supercompact Urban Transmission Line)". CIGRE SESSION 2018. Paris, France, 2018.

[4] S.C. Assis, W.C. Boaventura, J.O.S. Paulino and R.L. Markiewicz. "Lightning Performance of Transmission Line with and without surge arresters: comparison between a Monte Carlo method and field experience". Electric Power System Research 149, pp. 169-177. 2017.

[5] CIGRE, Technical Brochure 440. "Use of Surge Arresters for lightning protection of transmission Lines". Working Group C4.301. December 2010.

[6] R. Alipio and S. Visacro"Impulse efficiency of ground eletrodes: effect of frequency-dependent soil parameters" (IEEE Trans. Power Deliv. 29 (2) (2014). pp.716–723.

[7] IEEE. "Modeling guidelines for fast front transients." IEEE Transactions on Power Delivery, vol. 11, n. 1, January 1996.

[8] S.C. Assis, W.C. Boaventura and J.O.S. Paulino. "Lightning performance of transmission lines: Comparison IEEE Flash and Monte Carlo Method". IEEE Latin America Transactions, Vol. 15, n. 2, 2017.pp. 269-274.

[9] W.A. Chisholm, "New Challenges in Lightning Impulse Flashover Modeling of air gaps and insulators." IEEE Electrical Insulation Magazine. March/April. Vol. 26, n. 2. 2010.

[10] W.A. Chisholm, J.G. Anderson, A. Phillips and J. Chan "Lightning performance of compact lines". X SIPDA International Symposium on Lightning Protection. Curitiba. 2009.

[11] K.P. Naccarato, "Analysis of lightning characteristics in southeastern Brazil " - "Análise das Características dos relâmpagos na região sudeste do Brasil". São José dos Campos. Instituto Nacional de Pesquisas Espaciais (INPE). 362 p. São José dos Campos. Brazil, 2006.

[12] K. Fekete, S. Nikolovski, G. Knezevic, M. Stojkov, Z. Kovac.. "Simulation of lightning transients o 110 kV overhead-cable transmission line using ATP-EMTP". MELECON 2010 - 2010 15th IEEE Mediterranean Electrotechnical Conference. 2010.