Combined measures for improving the lightning performance of transmision lines

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***Abstract*— This work discusses the use of combined solutions for improving of the lightning performance of a real transmission line installed in an extremely unfavorable region, in terms of flash density and soil resistivity. It assesses impact on the line performance of the use of underbuilt wires combined with the reduction of tower-footing resistance and different arrangements of surge arresters. Notably, the range of efficient application of the solutions was determined as a function of tower-footing resistance, including the use of 2 and 4 surge arresters per tower.**

Keywords*— *Lightning performance of transmission lines; underbuilt wires; constraints on the use of surge-arresters; grounding resitance; tower-footing impedance.

I. INTRODUCTION

Backflashover is the main mechanism responsible for outages of high voltage transmission line (TL) below 500 kV installed over soils with moderated and high resistivity, subjected to direct lightning strikes [1,2].

There is a set of alternatives for improving TLs' lightning performance by reducing their backflashover rate. In most cases the more cost-effective measure consists of reducing the tower footing impulse impedance Zp (or the corresponding grounding resistance) [3,4]. In high resistivity soils, such reduction can be achieved using long counterpoise cables [5]. Reducing this impedance lowers the amplitude of lightning overvoltage across TL insulators, decreasing the probability of developing electric arcs across them, which would lead to backflashover. This subject is explored in details on references [4, 6]. Fig. 1 illustrates this aspect.

A second measure consists of installing surge-arrester devices (TLSAs) in parallel with the line insulators [7]. A TLSA has a VxI-curve characteristic that presents extremely high impedance for steady state voltages (it works similarly to an open switch for voltage levels below a determined threshold) and low impedance for voltages that exceed a given threshold. The operation of TLSAs limits the overvoltage between the phase and the tower structure, preventing it from exceeding the insulator withstanding, which would cause the occurrence of flashover across the insulator [7,9]. The use of TLSAs in all three phases is very effective for preventing the occurrence of backflashover at the tower.

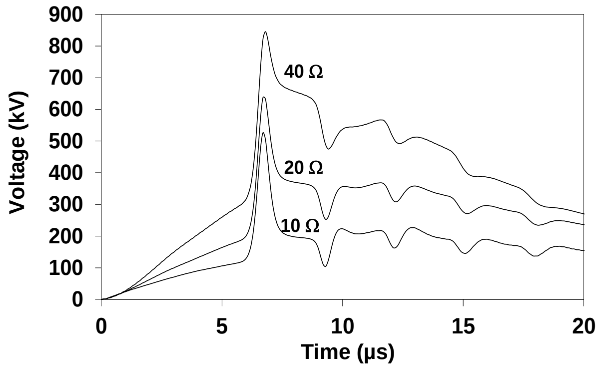

Fig. 1. Reduction of the amplitude of lightning overvoltage across the upper insulator string of a 138 kV TL, whose free-standing tower is submitted to a typical first return stroke current (cloud-to-ground), by decreasing the tower footing impedance. Adapted from [8].

However, the associated costs are usually high, not only by the acquisition cost, but also due to the costs associated to their installation and maintenance, as well. Furthermore, their proper operation still requires certain level of investing on grounding electrodes. In many cases, this makes unfeasible the application of this measure all along the line. Hence, it is a common practice to install the TLSAs just in a few critical towers and/or protect just one or two phases of the line with them. Depending on the tower footing impedance and the lightning current amplitude, protecting just part of the phases with TLSAs let the insulators of the unprotected phases still susceptible to the occurrence of backflashover.

Until recently, unbiased technical literature was relatively poor on the effectiveness and constraints of the different arrangements of TLSAs (specifically concerning the distribution the devices to protect the phases), as well as on the corresponding recommendations and guidelines. Mainly the manufacturers of TLSAs were responsible for providing corresponding information. Part of this scenario has been recently overcome with the publication of a set of works (e.g., [10-12]) that develop elaborated assessments on the TLs lightning performances of simple and double circuits, considering arrangements of TLSAs' installation under different conditions of tower-footing impedance. Fig. 2, adapted from [10], illustrates the reduction of the overvoltage across the insulator's string due to the use of TLSAs.

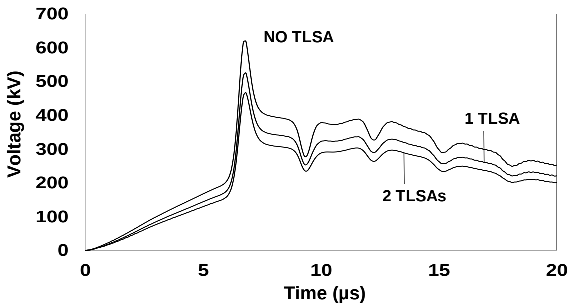

Fig. 2. Illustration of the overvoltage reduction across the insulator string by installing surge arrester devices at the tower of a 138 kV TL (Tower footing impedance Zp = 20 Ω). Adapted from [10].

A third protective measure to improve the lightning performance of TLs consists of using the so-called "underbuilt wires". These wires are installed along the spans that flank towers that show very high grounding impedance values, which exceed the value of impedance that ensures an acceptable number of outages for the TL. This alternative is discussed in details on reference [13]. Depending on the number of underbuilt wires employed and the value of tower footing impedance, the use of this alternative can yield a substantial reduction of the overvoltage across TL insulators, decreasing the probability of the outages. In certain cases, the reduction is comparable to that resulting from decreasing the tower grounding impedance to the half value.

Naturally, combined solutions are usual. Defining the best alternative to adopt requires considering technical and economic issues associated with the TL characteristics and surrounding environment.

In particular, this work discusses the improvement of the lightning performance of a real TL, installed in a region with very high flash density and extremely high soil resistivity (from 6000 to 60,000 Ωm). In spite of bulky investments for improving the quality of tower-footing resistance and for installing TLSAs, the performance of this line remains worse than required. The developments of this work focuses on the impact of installing underbuilt wires along a 100-km length along the TL, considering its real condition, in terms of tower-footing impedance and of installed TLSAs. Although it corresponds to a case study, the very critical conditions of this line ensures a certain level of generality for the solutions provided for lightning performance improvement of the TL that can be extended to other situations.

II. Transmission Line Characteristics, Methodology and Developments

The 230-kV double circuit transmission line Jauru-Vilhena has an extension of 345 km, most of them in Mato Grosso State, Brazil. The line has 766 towers and an average 450 m span. The right of way is 45 m wide. About 90% of the line structures are guyed-towers, with a typical height of 41 m. Fig. 3 exhibits a view of one of such towers.

Part of the towers are provided with 2 and 4 surge arresters and after the first interventions for improvements of the tower-footing impedance, the ground resistance of all towers have been measured by using 25-kHz instrument, that prevents the need to disconnect shield wires from the tower. Table I shows the ranges of distribution of the measured tower-footing resistances.

Fig. 3. View of a typical guyed-tower of the 230 kV double circuit transmission line Jauru-Vilhena.

TABLE I. Distribution of measured of tower-footing resistance in R_{25kHz} different ranges.

Range of R_{25kHz} (Ω)	Samples	Percentage	Backflashover probability
R<10	114	17.2%	Extremely small
10-15	111	16.8%	Very small
15-17	52	7.9%	Acceptable
17-20	74	11.2%	Significant
20-30	268	40.5%	Large
30-40	40	6.1%	Very large
R>40	2	0.3%	Extremely large

The assessment of the impact of the alternative for improvement of the TL performance followed a standard procedure based on computational simulations.

According to this procedure, the overvoltage across the insulators strings resulting from a direct lightning strike to the tower top was simulated by using the Hybrid Electromagnetic Model (HEM) [14] and assuming the representative double-peaked waveform for the first return stroke current, as indicated in [15]. This waveform reproduces all median parameters of amplitude (first and second peaks) and of time (rise time Td30/Td10 and time to half-peak) in addition to the maximum derivative, from Berger's first return stroke currents [16].

The tower-footing was represented by means of the first-return-stroke impulse grounding impedance Z_P ($Z_P = V_{P/} I_P$) in the range of 10 to 80 Ω. As reference [4] demonstrates, the TL performance calculated under this representation is practically the same obtained under the physical representation of the electrodes. The presence of 2 and 4 surge-arrester devices at the towers was simulated, according to their VxI curve [10-12]. In all cases, the absence and the presence of 2 underbuilt wires, installed 30 m above ground level, were considered.

The DE Method (Disruptive Effect) [17] was used for determining the critical current (threshold peak of first return stroke current that leads the insulator to flashover) in each simulated condition. The percentage of lightning currents whose peak exceeds this threshold was determined in the IEEE's cumulative peak current distribution [18]. This percentage corresponds to the backflashover probability of the stricken tower. The expected number of outages for that tower was determined by multiplying this percentage by the expected number of lightning strikes to the line with the span (1/2 span to each side) , applying a multiplicative factor of 0.6, to take into account that strikes distributed along the span are less severe than direct strikes to the tower [18]. Reference [6] presents a detailed description of this procedure for determining the outage rate of TLs.

A flash density of 8 flashes/km²/year was estimated based on a piece of satellite information about the distribution of flash density along the line. This density is consistent with the number determined using a reversal engineering approach based on the number of outages of the TL. This density led to expectation of an average number of 220 strikes/100-km/year [18].

This procedure was applied considering the different conditions the tower-footing grounding resistance and TLSAs installation, assuming the presence and absence of two underbuilt wires installed at each side of the central tower mast, as indicated in Fig. 4.

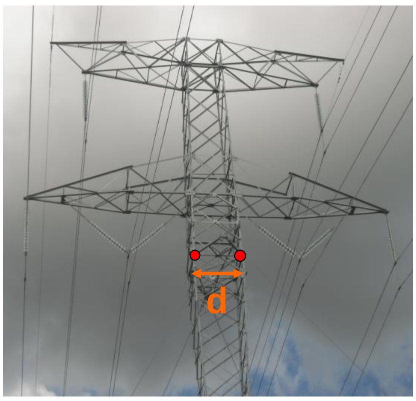

Fig. 4. Illustration of the position of of the two underbuilt wires at the guyed towers of the TL. Adapted from [19].

III. Results

The developments of this work are intended to indicate the guidelines for achieving a backflashover rate of 2 outages/100-km/year for the 230 kV line, as recommended by Brazilian regulations.

Applying the methodology indicated in Section II, the results, organized in the form of the curves of Fig. 5, were obtained and were presented along with the horizontal line that indicates the maximum acceptable backflashover rate of the line. In fact, what the curves translate is the limiting condition of each tower, required for ensuring that its contribution to the outage rate of the TL respects a threshold (under the assumption of a uniform distribution of the contributions of all towers). Of course, under a probabilistic approach, some towers exceeding this threshold would be acceptable if their contributions were compensated for by contributions lower than the threshold of other towers.

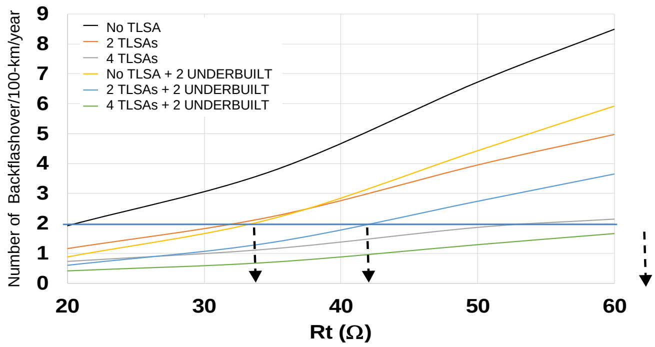

Fig. 5. Expected lightning performance of the TL for different arrangements of TLSAs as a function of tower-footing resistance, with the inclusion of the underbuilt wires. Adapted from [19].

In general, for all conditions, the curves shows the increase of the outage rate with increasing tower-footing resistance.

The superior curve shows the estimated outage rate of the line as a function of tower-footing resistance without any improvement. It indicates how the outage rate increases as tower-footing resistance becomes larger. The most important, is that it reveals a maximum acceptable tower-footing resistance of 21 Ω for ensuring a number below 2 outages/100-km/year.

In particular, the simple use of 2 (one in each circuit) and 4 (2 in each circuit) surge arresters allows increasing the acceptable tower-footing resistance from 21 Ω to 32 and 54 Ω, respectively.

On the other hand, the presence of two underbuilt wires, with no TLSAs installed, produces a performance improvement similar to that obtained by installing two surge arresters: the acceptable tower-footing resistance increases to about 33.5 Ω.

Notably, it is observed that the effect of installing underbuilt wires promote a significant improvement on the TL performance in all cases. The limits of 21, 32 and 54 Ω for the acceptable tower-footing resistance that ensures a performance of a maximum of 2 outages of the TL for the conditions of tower without TLSAs, with 2 TLSAs and with 4 TLSAs are shifted to greater values, 33.5, 42 and 66 Ω, respectively.

From the graph of Fig. 5, considering the tower-footing resistance measured for each tower and its respective condition, in terms of installed TLSAs, one can estimate the lightning performance of the whole or of any length of the line by integrating contribution of each tower to the outage rate.

In the developments of this work, dedicated to pilot experimental project, taking into account the limited availability of resources, we defined installing underbuilt wires along two sections of the line: from the towers 7 to 171 and from towers 401 to 464, reaching a total length of 100 km. These sections were chosen because of their different configurations and because of the possibility of better checking experimentally the efficiency of the underbuilt wire employment as a procedure for improving the TL performance. The first section has no surge arresters installed. This allows observing better the effect of their installation. The second section has a worse performance and has TLSAs installed in a considerable number of towers (62 towers: 53 towers with 2 TLSAs and 9 towers with 4 TLSAs).

Using the data from Fig. 5 and integrating the corresponding contributions for the performance of the 100-km length, an improvement of 53% was estimated in the performance of this part of the TL due to the installation of the underbuilt wires. This corresponds to the same reduction in the number of outages.

IV. Final Remarks

Though the use of underbuilt wires had already been suggested (e.g., in [13]), as an efficient alternative for the improvement of the lightning performance of critical sections of the TLs, to the better of the authors knowledge, this work is developing the first continuous installation of them along a 100 -km length of line (230-kV double-circuit TL Jauru-Vilhena).

This application was recommended due to the critical conditions of soil resistivity, which turned additional investments in the reduction of tower-footing resistance and in the installation of TLSAs inefficient for achieving the desired performance of the TL. The results of the paper indicate that this practice consists of an impactful preliminary measure, able to improve the lightning performance of the 100-km length in about 53%.

It is worth remarking the need of assessing the additional mechanical stresses resulting from installing underbuilt wires in the towers and their foundations, including the ones associated with the effect of wind. The assessments developed in this work indicated the feasibility of the practice and, in a few cases, recommended adopting additional cares, such as installing complementary guyed wires in certain towers.

After a period for experimental assessment of the results, this alternative should be extended to the whole TL length, eventually combined with other complementary alternatives.

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