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Improving the Lightning Performance of Distribution Lines using High CFO Structures

Evolution of the theoretical assessment and comparison with field data

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***Abstract*— This paper analyzes the improvement on the lightning performance of distribution lines due to the increase in the line critical flashover voltage (CFO) from 95 kV to 170 kV. The paper briefly describes a research project on lightning protection carried out in the 1980's and the proposed modifications on the distribution line structures in order to increase their CFO. The paper describes the methodology for the lightning flashover rate assessment and exemplifies its application on the lines constructed with the proposed high CFO structures. The paper also considers the field data on the lightning performance from two rural distribution feeders, one with 95 kV CFO and the other with 170 kV CFO. The feeders are installed in the same region and their lightning performance refer to four years of operation and 3800 sustained power outages. The field data are compared with the predictions from the theoretical assessment carried out with the modern methodology and with the methodology used in the 1980's, and the results are discussed.**

Keywords—lightning; electric field; induced voltages;

I. INTRODUCTION

Lightning is a major factor affecting the reliability of the power delivered by CEMIG, the electric power utility operating at Minas Gerais State, Brazil. Back in 1980's, data from the utility showed that lightning was responsible for about 80% of the power failures due to natural causes, which amounted to 40% of the total sustained failures of the utility's distribution system. These failures represented 25% of the equivalent power outage per customer, which means nearly 1 hour and 50 minutes of power outage per consumer per year [1].

In order to reduce the lightning impact on the reliability of the power delivered by CEMIG, the utility carried out a research project in partnership with the team of the Extra- High-Voltage Laboratory (LEAT) of the Federal University of Minas Gerais (UFMG), Brazil. The results of the research project recommended some modifications on the structure used by the utility in order to increase its critical flashover voltage (CFO) from 95 kV to 170 kV. The theoretical studies indicated a reduction of nearly 50% on the power failures due to lightning, and this improvement would be largely obtained by reducing the line flashover due to indirect lightning flashes [2].

The high-CFO structure was progressively adopted by CEMIG and provided significant improvement of the lightning performance of its distribution lines. A detailed study to assess this improvement was carried out in 2005 by Ávila [3], which showed a reduction of about 45% on the power failures due to lightning in 170 kV distribution feeders when compared with 95 kV distribution feeders installed in the same region. This field data agreed very well with the theoretical assessment made in the middle 1980's.

Despite the good agreement between the field data and the theoretical assessment, the team of the original research project was not comfortable this result. The main reason is because, by middle 2000's, it was clear that finite ground conductivity plays an important role on the lightning induced voltages (LIVs) [4]-[5], whereas the theoretical assessment had considered perfect ground. Indeed, when the high-resistivity ground of Minas Gerais State was included in the model, the theoretical flashover rates increased significantly and became much higher than those encountered in practice.

The solution to this apparent paradox appeared when the effect of the multi-grounded neutral was included in the theoretical model. Simulation results showed that the mitigation effect of the multi-grounded neutral on the LIVs counteracted the enhancement of the LIVs due to lossy ground. Therefore, although the proposed high-CFO structure showed itself very effective in improving the lightning performance of CEMIG's distribution lines, its protective effect could be better assessed by considering the effects of the neutral conductor and the ground resistivity.

The aim of this paper is to describe the improvements on the assessment of the lightning performance of distribution lines since the original project and how the results compare with the field data. The paper is organized as follows. Section II describes the 1980's research project, including the proposed high-CFO structures and the original flashover rate assessment. Section III presents results using the modern flashover rate assessment method, which considers the neutral conductor and the effect of lossy ground. Section IV assesses the flashover rate of typical CEMIG's lines and compares the results with field data for 95 kV and 170 kV distribution feeders. Section VI discusses

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the effect of considering perfect ground and single conductor on the flashover rate assessment. Finally, Section VII draws the main conclusions.

II. THE 1980'S RESEARCH PROJECT

A. Minas Gerais State Environment

Minas Gerais State comprises an area of 586,5 km^2 in the Brazilian highlands. CEMIG is responsible to deliver electric power to about 96% of the state market, represented by 12 million consumers distributed in 805 municipalities. To cover such large area, it is common to have feeders with 600 km of aerial medium-voltage lines, operating mostly at 13.8 kV.

The median apparent ground resistivity value is 1700 Ω·m and 10% of the soils has apparent resistivity value above 5000 Ω·m. Fig. 1 shows the distribution of the apparent ground resistivity values in the state [6]. The rate of cloud-to-ground flashes in the state is relatively high, with average values around 5 flashes / km^2 / year and maximum values of 17 flashes / km^2 / year.

The joint effect of large territorial extension (which requires long rural feeders), high ground resistivity values, and high ground flash density values justifies the concerns of CEMIG with the protection against lightning. These concerns resulted in a research project carried out by CEMIG engineers and the team of the Extra- High-Voltage Laboratory (LEAT) of the Federal University of Minas Gerais (UFMG).

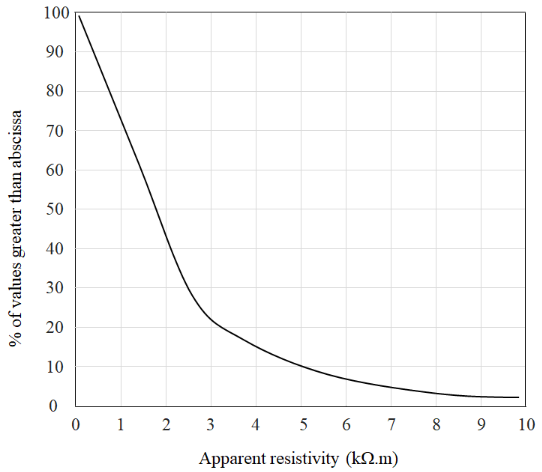

Fig. 1. Apparent soil resistivity in Minas Gerais State. Adapted from [6].

B. Brief Description of the Project

The research project had large experimental work, whereas several distribution structures used by CEMIG were installed inside the high-voltage laboratory and tested with standard lightning impulses (1.2/50 µs) in order to characterize their CFO values. This experimental work covered all structures used in the 13.8 kV feeders, including several modified structures with higher CFO [7]. It is worth to mention that most of the structures used by CEMIG were made of steel-reinforced concrete poles with wood crossarms and ceramic insulators.

The experimental investigation also covered the behavior of wood crossarms under impulsive voltages. This investigation evaluated the effective CFO value provided by different combinations of wood and ceramic insulators. Moreover, some efforts addressed the residual voltage due to an electric arc over a wood crossarm, which could eventually quench the arc and prevent the power-follow current [8].

The theoretical investigation was influenced by the studies carried out by Eriksson *et al.* [9], which were based on the models developed by Rusck [10] considering a single wire above perfect ground. It is worth to mention that lately the 2004 version of the IEEE Guide also used the same approach [11].

Several simulations were carried out with this methodology and the results showed that increasing the line CFO up to 170 kV would decrease significantly the number of line flashovers due to the LIVs. When direct and indirect lightning flashes were considered, the overall flashover rate was reduced to about half, when compared with the results of the standard 95 kV CFO line. As a result, several 170 kV and 300 kV structures were proposed and tested, considering a minimum increase in the cost of the existing structures. Some of the 170 kV structures are presented in the following.

C. High-CFO Structures

The new structures were developed considering the existing structures. Fig. 1 shows a typical three-phase 95 kV CFO structure used by CEMIG. As the pole is made of steel-reinforced concrete, it acts as a conductor for the assessment of the line insulation. Moreover, the crossarm brace are metallic, which makes the CFO of the inner phase to be determined exclusively by the pin insulator (95 kV). The CFO of the outer phases are 300 kV, due to the contribution of the wood crossarm. The neutral conductor is attached to the pole through a 1 kV insulator (CFO of 35 kV).

Fig. 3 shows the modified three-phase structure. The modification was limited to removing the metallic crossarm brace that was attached close to Phase B insulator and reinforcing the remaining crossarm. This modification increased the line CFB to 170 kV, given by Phase B insulation (flashover between the Phase B and the top of the pole).

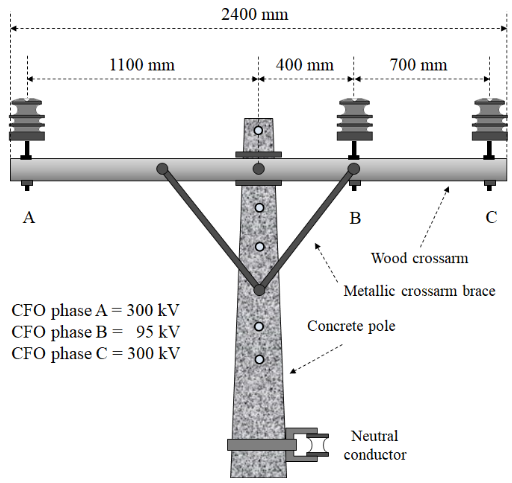

Fig. 2. Original three-phase 95 kV CFO structure.

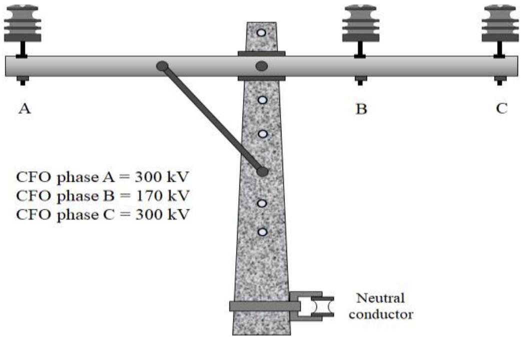

Fig. 3. Modified three-phase 170 kV structure.

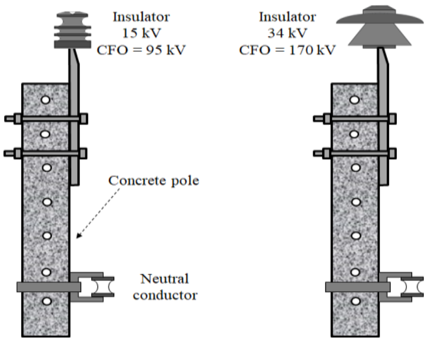

Fig. 4. Single-phase structures. Left: Original 95 kV structure; Right: Modified 170 kV structure.

Fig. 4 shows the original single-phase structure, where the 95 kV CFO is given by the ceramic insulator. The same figure shows the modified single-phase structure, whereas the higher CFO (170 kV) was obtained by using a bigger pin insulator (normally used in 34.5 kV lines). Nowadays, the high-CFO standard is applied in 85% of the State of Minas Gerais. The 95 kV CFO structures is applied only in areas with low ground flash density.

Different higher CFO structures were developed, both by CEMIG and by other utilities. For instance, Fig. 5 shows a three-phase 150 kV CFO structure that uses metallic crossarm and 150 kV insulators in all phases.

Fig. 5. Three-phase structure with metallic crossarm and 150 kV CFO insulator. (Courtesy of Vilson Coelho).

The replacement of wooden crossarm as insulation and structural part in rural distribution networks structures, maintaining the high CFO, has been tackled by several power utilities around the world. UFMG has conducted a research work, supported by CEMIG-D [12]-[13], on this issue evaluating alternatives to the present standard which is based on wooden crossarms. Several alternatives were considered and tested in laboratory. Those adequate to rural distribution networks, according to CEMIG-D needs, were installed and monitored in a test network. Fig. 6 and Fig. 7 show examples of structures tested in laboratory and tested in field. These field trials are under way and the results will be reported in future.

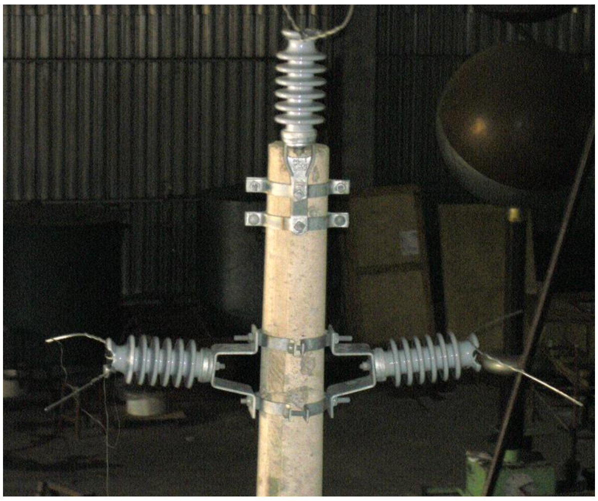

Figure 6 – Vertical/horizontal post insulators (150 kV CFO) installed directly on the concrete pole.

Figure 7 – Structure using a combination of fiberglass crossarm, post insulators and polymer insulators.

III. Lightning Performance Assessment

A land-mark in the assessment of the lightning performance of distribution lines is the work carried out by Borguetti *et al.* [14], which was lately incorporated in the IEEE Guide [11]. The referred methodology uses a probabilistic model, based on the Monte Carlo method, which considers the random nature of the lightning flashes. Moreover, the methodology takes into account several relevant parameters that were disregarded in the previous models, such as the effect of the finite ground resistivity on the LIVs.

However, the full computation of the LIV waveforms requires a significant computer effort and the Monte Carlo method needs many thousands of simulations to provide stable results. Different approaches have been developed to mitigate this problem, which includes the use of parallel processing [15] and modified sampling techniques [16].

Another possibility to overcome this problem is to assess the indirect flashover rate based on the peak-value of the LIVs. This approach is facilitated by the availability of relatively accurate peak-value formulas [17]-[18]. Moreover, the response of the line insulation to the LIV waveshape could be represented by applying an adequate correction factor to the line CFO [19]. The use of peak-value formulas with the Monte Carlo method has been used by the authors to assess the flashover rate of distribution lines and the results agree with those obtained with the rigorous methodology [20]-[21].

A. *The effects of multi-grounded neutral*

The presence of multi-grounded neutral has two distinct effects on the indirect flashover rate. The first one is the shielding provided to the phase conductors, which leads to a reduction on the phase-to-ground LIVs. Another effect is due to the transference of the neutral potential to the conductive pole. As the insulation between the neutral conductor and the conductive pole is low, the LIV is likely to produce a flashover from the neutral to the pole (see Fig. 2). As a result, the voltage applied to the line insulation is the line-to-neutral voltage, instead of the line-to-ground voltage.

Fig. 8 shows a high-CFO structure without neutral conductor. In this case, the line insulation is stressed by the line-to-pole LIV which, in this case, is equal to the line-to-ground LIV. As shown in Fig. 9, the situation is quite different in the case of a line with multi-grounded neutral. In this case, the neutral-to-ground LIV is very likely to produce a flashover across the neutral insulation, which means that the line insulation will be stressed by the phase-to-neutral LIV.

The assessment of the phase-to-neutral (U_{PN}) voltage can be obtained from the phase-to-ground (U_{PG}) and the neutral-to-ground (U_{NG}) LIVs. From observing Fig. 7 one can conclude that:

$$U_{PN} = U_{PG} - U_{NG} \ , \qquad (1)$$

where it is implicit that the neutral is connected to the pole. This connection may be intentional (when there is a neutral grounding at the pole) or incidental (when there is a flashover across the neutral insulator.

B. *Indirect Flashover Rate Assessment*

This section presents some simulations performed with a probabilistic approach similar to the one used by Borghetti *et al.* [14]. The LIV were calculated using the TIDA code described in [22], which computes the full LIV waveform. The annual indirect lightning-induced voltage flashover rate is calculated for an overhead line 12 km long, with phase conductor at 10 m high (h_P), neutral conductor at 8.9 m high (h_N), and in a region with ground flash density $N_g = 1$ flash / km / year. The ground resistivity value used in the simulation is ρ = 1700 Ω·m, the return stroke current velocity is v = 120 m/µs, and the neutral is grounded at each 90 m by 500 Ω grounding resistance, as shown in Fig. 10.

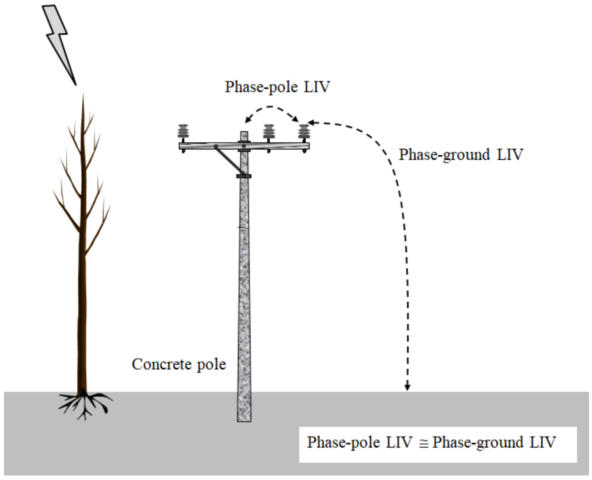

Fig. 8. LIVs in a line without neutral conductor (the pole is conductive).

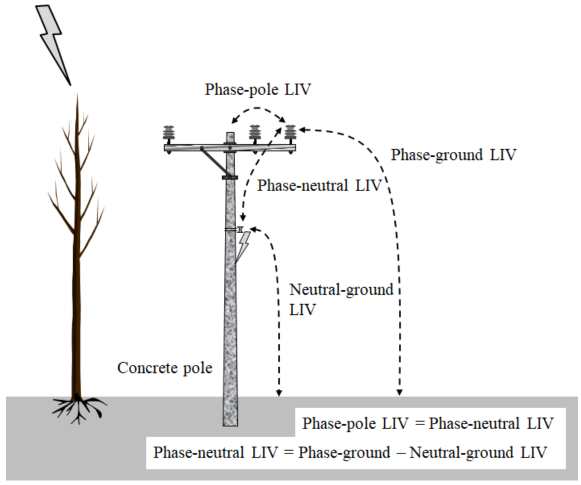

Fig. 9. LIVs in a line with multi-grounded neutral conductor (the pole is conductive).

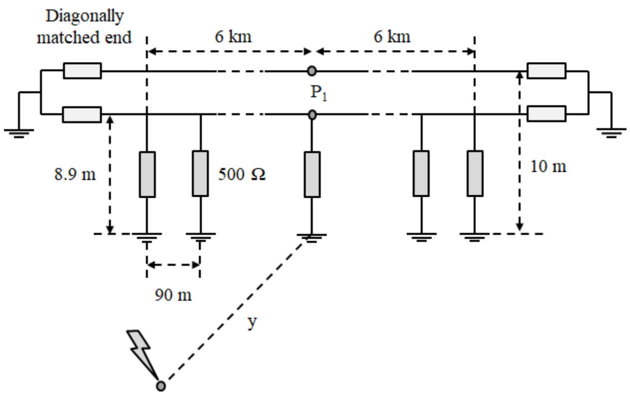

Fig.10. Diagram for the calculation of LIVs in a two-wire line, with one of them multi-grounded.

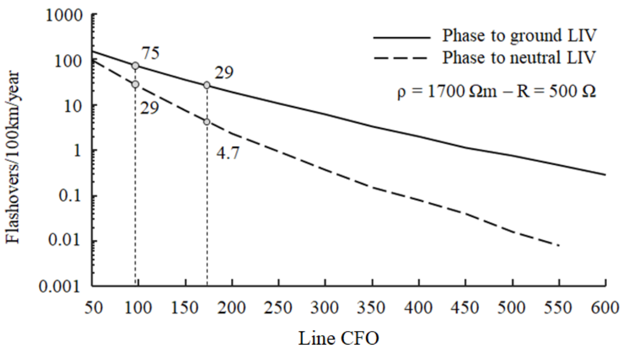

Fig. 11. Annual indirect flashover rate considering phase-to-ground and phase-to-neutral LIVs. N_g = 1 flash/km^2/year, h_P = 10 m, h_N = 8.9 m, ρ = 1700 Ωm, and v = 120 m/µs. The neutral is grounded at each 90 m by 500 Ω grounding resistance.

Fig. 11 shows the annual indirect flashover rate considering the phase-to-ground and the phase-to-neutral LIVs. The results were obtained using a regular personal computer and 30.000 cases were simulated. The results shown in Fig. 11 are based on the LIV at the middle of the line (point P1 in Fig. 10), for both phase-to-ground and phase-to-neutral LIVs. A flashover is computed whenever the LIV is higher than the line CFO.

It is clear in Fig. 11 that the flashover rate is much lower for the phase-to-neutral than for the phase-to-ground LIVs, which means that the multi-grounded neutral has an important contribution to improve the indirect lightning performance of the line, in case of conductive poles.

It is worth to highlight that the LIVs in a three-phase line are very similar to those in a single-phase line [14], so that the results obtained for the single-phase line shown in Fig. 10 are also applied to three-phase lines.

IV. Lightning Performance of Typical CEMIG's Lines

A. Theoretical Assessment

CEMIG distribution lines in rural areas use steel-reinforced concrete structures with an average distance between consecutive poles equal to 100 m (average). Both single-phase and three-phase lines have neutral conductors, which are grounded approximately at each 5 spans using a 2.4 m long vertical rod, which provides 700 Ω grounding resistance for the 1700 Ω·m median ground resistivity value (see Fig. 1). The pole base is buried about 1.8 m in the ground, which makes an incidental grounding system with 500 Ω resistance [23]. Due to the higher number of poles than grounding rods, the effect of the latter is disregarded and the neutral is assumed in this paper as grounded at each 90 m with 500 Ω grounding resistance.

The line shielding against direct strikes by nearby objects was neglected, as the flashes that are diverted from the line are very likely to produce line flashovers due to the LIVs [11]. Moreover, it is assumed that every direct flash produces a line flashover, as the lines are not equipped with overhead ground wire.

The indirect lightning flashover rate is shown in Fig. 11 for the conditions considered. The relevant values for the CFO equal to 95 kV and 170 kV are taken from Fig. 11 and inserted in Table I, which also shows the flashover rates due to indirect and direct flashes. The data in Table I shows a significant reduction in the flashover rate due to the increase in the line CFO. As discussed before, the relevant voltages for the structure considered are the phase-to-neutral LIVs. Therefore, increasing the line CFO produced a reduction from 29 to 4.7 flashovers / 100km / year (4.7 / 29 = 0.16) if only the indirect flashes are considered, and from 41 to 17 flashovers / 100km / year (17 / 41 = 0.41) if indirect and direct flashes are considered.

TABLE I. Calculated Flashover rates for the Typical CEMIG's Rural Distribution Line (per 100 km per year)

Source of Flashover (N_g = 1 flash/km^2/year)		**Line CFO 95 kV**	**Line CFO 170 kV**
Phase-to-ground LIV	Indirect flashes	75	29
Phase-to-ground LIV	Direct and indirect flashes	87	41
Phase-to-neutral LIV	Indirect flashes	29	4.7
Phase-to-neutral LIV	Direct and indirect flashes	41	16

B. Sustained Power Outages based on Field Data

Ávila [3] produced a comprehensive evaluation of the lightning performance of CEMIG's distribution lines. The data considered covered the period from 2001 to 2004 (four years). Lightning flashes were identified as responsible for 42% of the sustained power outages in the distribution system. Moreover, 12% of the sustained power outages were registered as due to "unsuccessful automatic reclosure", which are likely associated with lightning. Therefore, Ávila quantified the power outage rates with two limits: a lower limit considering only the power outages classified as due to "lightning flashes" and an upper limit considering the power outages classified as "lightning flashes" or as "unsuccessful automatic reclosure". It is assumed that the actual flashover rate is located somewhere between these two limits.

In his work, Ávila evaluated the effect of increasing the line CFO on the flashover rate. To this aim, he focused on two feeders installed in the same region (Serra da Mantiqueira, Minas Gerais State), so that the same median ground resistivity value and the same ground flash density could be assumed. Let us identify these feeders as Feeder A and Feeder B.

The Mantiqueira CEMIG Regional System is composed by 35 substations with 150 feeders distributed among those substations. This system is located in the area with the highest ground flash density of Minas Gerais State.

Feeder A has 95 kV CFO and 440 km total length, with 10 km in the trunk circuit and 430 km in the branch circuits. The feeder length is also composed of 96 km of three-phase circuits and 344 km of single-phase circuits. During the period considered, 1237 sustained power outages due to "lightning flashes" were recorded in this feeder, while 850 sustained power outages were recorded as "unsuccessful automatic reclosure".

Feeder B has 170 kV CFO and 642 km total length, with 9 km in the trunk circuit and 633 km in the branch circuits. The feeder length is also composed of 187 km of three-phase circuits and 455 km of single-phase circuits. During the period considered, 977 sustained power outages due to "lightning flashes" were recorded in this feeder, while 736 sustained power outages were recorded as "unsuccessful automatic reclosure".

The average ground flash density for the region in the period considered is 6.22 flashes / km^2 / year and the median ground resistivity is assumed as 1700 Ω·m [6]. Surge arresters are sparsely installed in these feeders, with an average distance between arresters of about 600 m. Table II shows the sustained outage rates for these feeders considering those due to "lightning flashes" and those due to "lightning flashes" or "unsuccessful automatic reclosure". The values in this table are based on those presented by Ávila [3] but were normalized to $N_g = 1$ flash / km^2 / year, 100 km of line extension, and one-year period. It is worth to highlight that these data refer only to sustained power outages, i.e., they do not include the transient power outages (i.e., those that are eliminated by a successful automatic reclosure).

If the average value between the two boundaries presented in Table II is assumed as representative for the feeder performance, then Feeder A and Feeder B experienced 15.2 and 8.4 normalized sustained power outages, respectively. These numbers show a reduction factor of 0.55 in the outage rate for Feeder B, which may be attributed to its higher CFO value. It is interesting to note that this reduction factor is not far from the theoretical ones obtained from Table I. However, when comparing the data of Tables I and II, it is important to have in mind that the former consider the total number of line flashovers, while the latter consider only those that led to sustained faults. This issue is investigated in the following.

TABLE II. NUMBER OF SUSTAINED POWER OUTAGES FOR TO 1 FLASH / KM^2 / YEAR AND 100 KM (ADAPTED FROM [3])

Feeder	Line CFO (kV)	Cause of Power Outage	
		Lightning flashes	Lightning flashes + unsuccessful automatic reclosure
A	95	11.3	19.1
B	170	6.1	10.7

C. *Assessment of the Total Power Outages from Field Data*

The field data presented and analyzed by Ávila [3] focus on the sustained power failures, as these are critical to the reliability of the power delivery and affects significantly the power quality indexes. On the other hand, the theoretical assessment of the line outage rates cannot distinguish between sustained and transient power outages, as the success of a line reclosure cannot be predicted by the simulation code. Therefore, it is desired to assess the number of total power outages from the number of sustained ones, so that the data of the theoretical assessment (Table I) could be compared with the field data (Table II).

Hidayat *et al.* [24] presented an interesting set of data on the lightning performance of rural distribution lines. The structures of the lines considered in [24] are similar to those used by CEMIG, which includes steel reinforced poles, 125 kV CFO structures, and sparsely installed surges arresters. Moreover, the ground flash density of the region is also similar to the one of Minas Gerais state. The field data presented by Hidayat *et al.* show that the number of sustained power outages due to lightning is close to the number of transient power outages. Given the similarities between the distribution lines, this proportion between sustained and transient power outages will be applied in this paper to CEMIG's field data. In other words, it will be assumed that the number of sustained power outages due to lightning is 50% of the total number of power outages due to lightning. It is worth to mention that this proportion may vary significantly from one type of network to the other. For instance, Chisholm *et al.* [25] analyzed two feeders and found 53% and 27% for the ratio between sustained and total power outages due to lightning.

Applying the 50% factor to the data of Table II leads to the data of Table III, where the power outage sources referred as "Lightning flashes" and "Lightning flashes + Unsuccessful automatic reclosure" where renamed as "Lower limit" and "Upper limit", respectively. In this table are also shown the data from Table I (Theoretical assessment) corresponding to the last line, i.e., flashover rates due to phase-to-neutral LIVs and considering both indirect and direct flashes.

It can be seen in Table III that the value for Feeder B (16 flashovers / 100 km / year) fits very well in the range of field data values (12.2 to 21.4). Indeed, the middle value of this range (16.8) is very close to the theoretical value. However, the flashover rate for Feeder A lays somewhat outside the range of field data values.

One possible explanation for this behavior is the presence of surges arresters along the feeders. The IEEE Guide [11] states that the presence of surges arresters, even if sparsely installed, may reduce significantly the flashover rate. According to the guide, the use of arresters spaced about 600 m provides a reduction of at least 25% in the flashover rate due to indirect flashes but has negligible effect on the flashover rate due to direct flashes. Applying this factor to the theoretical values leads to the last line of Table III. The flashover rate for Feeder B changed very little, due to the minor contribution of the indirect flashes in this case. On the other hand, the flashover rate for Feeder A was reduced to 33 and now lays comfortably inside the range of field data values.

TABLE III. NUMBER OF TOTAL POWER OUTAGES FOR TO 1 FLASH / KM^2 / YEAR AND 100 KM (ADAPTED FROM [3] AND [22])

Source		Feeder A	Feeder B
Field data	Lower limit	22.6	12.2
	Upper limit	38.2	21.4
Theoretical assessment	Without surge arresters	41	16
	With surge arresters	33	15

Considering the middle value of the field data range as reference, the theoretical values considering surge arresters differ from the reference values by 9% and -11% for Feeders A and B, respectively. These differences can be considered as small, given the uncertainties involved both in the input data for the simulations and the field data classification. On the other hand, if the phase-to-ground LIVs are considered (see Table I), these differences raise to 123% and 98% for Feeders A and B, respectively. Therefore, one may conclude that the lightning performance of these feeders is determined by the direct flashes and the phase-to-neutral LIVs, as previously assumed.

V. Discussion

As described in Section II, the original research project that resulted in raising the CFO of the structures used by CEMIG in rural areas was largely based on the work carried out by Eriksson *et al*. [9], which was based on the models developed by Rusck [10] considering a single wire above perfect ground. Fig. 10, adapted from [9], shows the flashover rate for an aerial wire above perfect ground, considering N_g = 7.5 flashes / km^2 / year, 100 km of line length and one year. The values corresponding to 95 kV CFO and 170 kV CFO are highlighted in the figure, and they ratio shows that increasing the CFO of the line would reduce its lightning flashover rate to about half value.

Table IV is similar to Table III, but the data corresponding to the theoretical assessment were taken from Fig. 12 and normalized to N_g = 1 flash / km^2 / year. The effect of surge arresters is the same described in Section IV.C.

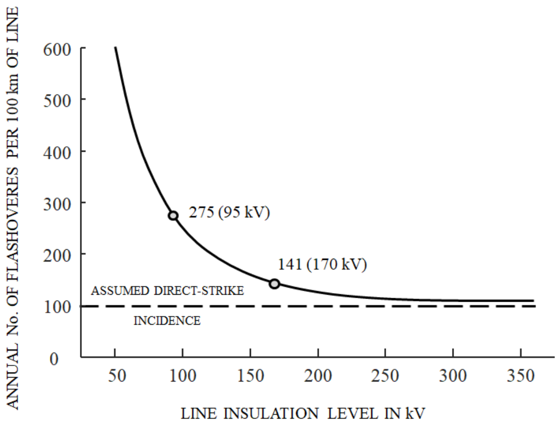

Fig. 12. Theoretical annual flashover rate as a function of insulation level (CFO) for N_g = 7.5 / km^2 / year and considering a single wire above perfect ground. Adapted from [9].

TABLE IV. Number of Power Outages with the Theoretical Assessment based on a Single Wire above Perfect Ground

Source		Feeder A	Feeder B
Field data	Lower limit	22.6	12.2
	Upper limit	38.2	21.4
Theoretical assessment	Without surge arresters	37	19
	With surge arresters	31	17

Interestingly, the theoretical assessment based on a single wire above perfect ground provided results that fitted well in the range of values obtained from field data. Indeed, these results are close to those obtained from a more realistic model (see Table III). This unexpected result could be explained as follows.

The single-wire assumption implies that the flashover rate assessment is based on the phase-to-ground LIVs. As seen in Section III, this situation increases significantly the flashover rate, when compared with the situation where the flashover rate is based on the phase-to-neutral LIVs. On the other hand, the perfect-ground assumption reduces significantly the flashover rate, when compared with the flashover rate calculated for lossy ground. This is particularly true for the high ground resistivity values of Minas Gerais state.

Therefore, the two simplifying assumptions (single wire and perfect ground) affect the flashover rate in opposite directions. For the specific conditions of CEMIG's distribution lines, these opposite effects largely compensate each other, so that the resulting flashover rate assessment stood within the range provided by the field data. However, it is important to highlight that this is a mere coincidence for this specific case, and it certainly does not mean that such simplifications could be used. For instance, if CEMIG lines had no neutral conductor, the flashover rate predicted by these simplifying assumptions would be much lower than the one provided by field data. Therefore, it is important to highlight that the more complete is the model, the more accurate is the flashover rate assessment.

VI. Conclusions

The results presented in this paper show that the validation of a model for flashover rate assessment shall not be based on a single set of field data, as simplifying assumptions may provide compensating effects and lead to misleading conclusions. The results also show that considering the characteristics of the distribution line structure and of the local environment provides results that agree fairly well with field data.

During the preparation of this paper, the authors searched for field data on the lightning performance of distribution line feeders, but the literature on this subject is scarce. Moreover, the available data often are not complete, with important information missing. As the lightning performance assessment would be significantly improved if more field data are available, power utilities are encouraged to publish data on this subject.

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