Performance of Medium Voltage Urban and Rural Distribution Lines Front Lightning Discharges and Induced Surges

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Abstract: This paper has as objective to present preliminary results of a study of lightning performance for medium voltage distribution networks, submitted to direct and induced lightning overvoltages. In order to define actions to reduce the network rate of failure the main parameters responsible for the increase of the network failure rate are investigate.
In this stage of the study, some simplifications had been considered. However, the result show that is possible to direct the actions for an economic solution of a series of problems, which represents the great majority of the occurrences involving lightning discharges.

1 INTRODUCTION

Nowadays many actions for the protection of overhead distribution lines are not well defined and normally without any transient performance study. As a result, many of them besides of presenting high costs are not effective. This study has the purpose of leading to an efficient method for the reduction and mitigation of the effects of the lightning discharges in medium voltage overhead distribution lines.
The lightning discharges are one the main causes of interruptions of medium voltage overhead distribution lines, being the reason of great concern for the utility companies. Its destructive effects frequently extends to equipments and connected installations, with the possibility to cause personal injuries and material damages, beyond economic losses, due to out of income and the possibility of indemnities, penalties and fines applied by ANEEL (National Agency of Electric Energy).
With the beginning of the deregulation of the electric energy supply, some actions were been taken by the utilities for the prevention and minimization of the damages associated to the lightning discharges. However, as the lightning discharges are random events, consequently, difficult to predict, the majority of these actions does not follow a study or a detailed analysis of the problem.
By this way, in most of the cases the actions were taken based on the knowledge of the engineer in charge, or based in rules defined without any effective evidence, by means of studies or even by laboratory tests. Therefore, the results are not the most satisfactory and do not achieve a suitable rate of cost by benefit.
Among others, the distribution network reliability depends directly on its exposition to the lightning discharges. To determine the exposition level of the line, the designer should know the number of discharges to the ground per unit of area per unit of time.
Once that the atmospheric discharges phenomena are random, this paper considers that the parameter generation of the discharges follows the statistical data proposed by Anderson and Eriksson [3]. The Monte Carlo Method is used to generate the incidence distribution of the discharges and the Electro Geometrical Model for determining the interception point of the discharge.

2 MEDIUM VOLTAGE DISTRIBUTION NETWORK

The standard medium voltage distribution networks are subjected to the incidence of direct lightning discharges and of induced overvoltages. The majority of damages to the distribution network are caused by direct discharges. However, they can be deviated by tall structures, such as towers, buildings, high constructions, and trees.
When the lightning strikes the network directly, they commonly cause permanent damages, because they present high intensity discharges with high rate of rise. For this kind of damage, the network remains disconnected until repair. Even when the lightning does not intercept the network, they induce surges that travel throughout the lines. These surges are also able to cause some damages to the distribution network. In order to get one short view on which of these phenomena is the most probably source of network damages this paper deals basically with the ratio between direct discharges and induced overvoltages.
As can be observed, the topology of the distribution network is the major factor of influence in these analyses. Because its density and distribution in the geographic area make possible a higher or lower probability of incidence of direct lightning discharges.

3 LIGHTNING DISCHARGES

To verify the performance of a specific distribution network the present study consider an annual analysis of the lightning activity. The Monte Carlo Method and the

average density of lightning discharges to ground per square kilometre per year are the defining factors for the modelled discharge to ground starting point.
The discharges intensities are also randomly generated, according to the current method of calculation proposed by Anderson's Model, which introduces a convenient approach to the lognormal distribution of peak currents given by Anderson and Eriksson. An average current of 31kA results in a probability value of P=0.5, the probabilities becomes more reduced with the increase of the current intensities I [kA].
The equation is easily inverted to correspond to a desired level of probability P, as follow:

$$P = \frac{1}{1 + \left(\frac{I}{31}\right)^{2,6}} \quad (1)$$

$$I = 31\left(\frac{1-P}{P}\right)^{1/2,6} \quad (2)$$

Once defined the starting point of the discharge and its intensity, it is necessary to verify its incidence point, observing if it intercepts directly the network or if it generates an induced overvoltage. Many methods are possible for this; however, the most common is the Electro-Geometrical Model.
The Electro-Geometrical model was developed from the Wagner's Model, of the lightning return speed, being updated by Armstrong, Whitehead and Love. It is characterized by a rolling sphere concept, with a radius given by the current intensity of the discharge, according to the IEEE – Std. 1410 [6] formula:

$$SD = 10.I^{0,65} \quad (3)$$

Calculated the dimensions and attraction limits, it is verified if the discharge intercepts the conductors of the network. In this way, for a pre-defined time range, it is obtained the number of times that the network was intercepted per year as well as the corresponding number of times that the network was submitted to induced overvoltages and all the parameters associated with lightning discharges to the ground.

4 SIMPLIFICATIONS AND APPROXIMATIONS

This study considers some simplifications, as the adoption of a plain surface, by the difficulty to obtain digital information of topography levels. As well as a perfectly conductive soil for the calculation of the induced overvoltages amplitude, and a manual inclusion of tall structures, like towers, buildings, and trees. These approximations leads to a critical condition, being thus all the results are overestimated.
The manually inclusion of tall structures is possible; however these tall points are considered in a higher layer in the system topology. Therefore, these points intercept the discharges, playing the role of the tall structures. This reduces the number of direct discharges for a value probably close to that obtained from the occurrence data reports, issued by maintenance teams of the utilities.

5 ANALYSIS PROCESS

The analysis process is annual, that is, all the lightning discharges are generated for a year based on the flash density to ground per year per square kilometre, which can also be assumed as random in the analysis period. The discharges are randomly distributed along the area, the intensities and rate of rise of the discharge current are obtained randomly according to the statistical data of the IEEE – Std 1410.

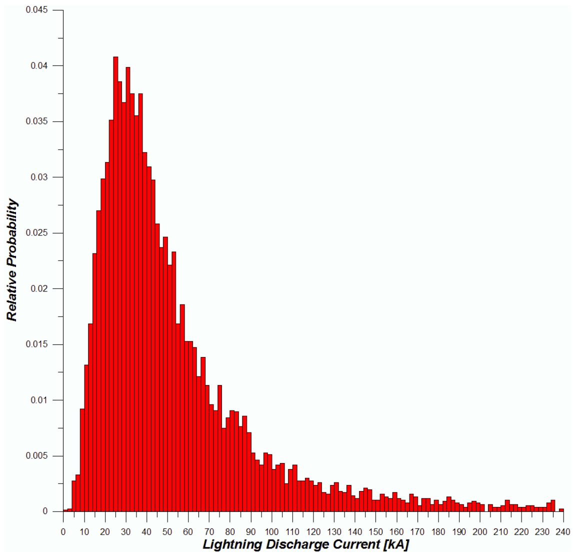

Fig. 1 – Probability Distribution of Lightning Currents

Fig. 1 shows the probability distribution of direct discharges currents in a medium voltage rural distribution network.
When the position and the intensity of the lightning discharge are generated, the Electro-Geometrical Model is applied to verify if it intercept the network. In this way, it is calculated the number and percentage of direct discharges to the network, its average current, and standard deviation associated. This process can be repeated automatically for a maximum period of 100 years, generating data for the average and standard deviation, percentage of direct discharges and corresponding current intensity.

6 RESULTS

Three results of analysis of lightning discharges in medium voltage distribution network will be presented, respectively a rural system, an urban without considering tall structures and an urban simulating tall structure.

All the analyses are based on real distribution networks of the AES Sul Utility.

6.1. Rural Distribution Network

The great majority of the rural networks have a reduced length by area relation. In this way, they possess less probability of being intercepted by direct lightning discharges.

The Fig. 2 presents a permanence curve for the discharges current that directly intercepted the distribution network. The values of current with 50% of probability (Median), 100kA discharge current probability and the smaller current intensity, that have 100% of probability of being exceeded, are shown.

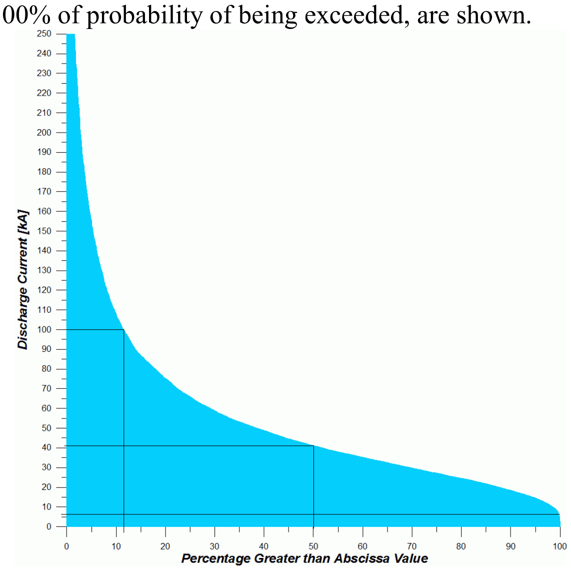

Fig. 2 – Discharge Current Permanence Curve for Rural Network

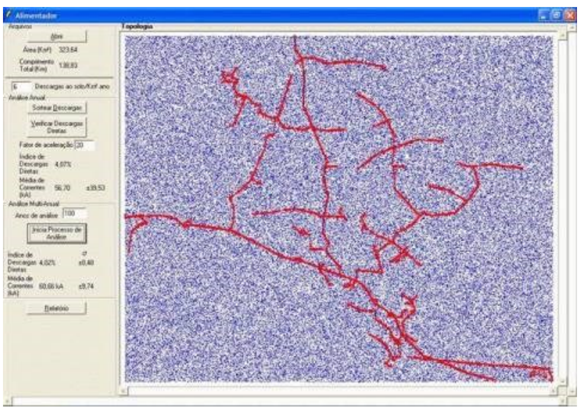

Fig. 3 – Simulation Program Image with a Rural Distribution Network and 100 Years of Simulation

The network under analysis has an area of 323.64 km² and a total length of 138.83 km. In the simulations, it was obtained a level of direct lightning discharges interception by the network of 4.02% with a standard deviation of 0.48. In this case, the average value of direct discharges current intensity is about 41kA, from the median value, according to the Fig. 2.

The Fig. 3 shows a screen image of the simulation program, with the topology and results of analysis.

This data had been obtained with a flash density of 6 discharges to the ground per square kilometre per year. In this way, for a density of 1 discharge to the ground per square kilometre per year, the network responds with a density of 9.28 discharges per 100 km per year.

As a result, in accordance with Fig. 2, for 6 discharges to ground per km² per year to each 100 km of network, 27.84 discharges presents current intensity higher than 41kA, as well as 6.68 discharges exceeds 100kA of current intensity.

Although the developed method has the capacity to indicate which percentage of the surge arresters had been exposed to discharge current with intensities higher than the rated value, this is not object of the present discussion.

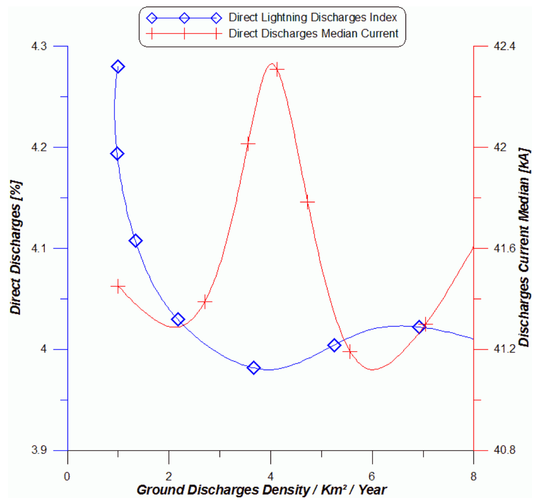

Fig. 4 – Direct Discharges, Median Current by Number of Discharges to the Ground per km² per Year for a Rural Network

Fig. 4 presents the results of this circuit for different conditions of density of lightning discharges to the ground for the rural distribution network.

6.2. Urban Distribution Network – Without Considering Tall Structures

The large majority of the urban distribution networks presents a high relation between the total length and area and, therefore, a higher probability of been intercepted by direct lightning discharges. However, in urban areas the presence of tall structures, such as towers, high buildings and trees, deviate many of the

discharges that would have intercepted the distribution network.
The data acquisition regarding tall structures is complex and laborious, as a result the analysis program do not consider them automatically. Therefore, as a first approach for the study, the urban network was analyzed without taking the presence of tall structures in consideration.
In a similar way to the previous method applied to the rural network, Fig. 5 presents the permanence curve for the discharges current that intercepted directly the urban network under analysis. The values of current with 50% of probability (Median), 100kA discharge current probability and the smaller current intensity, that have 100% of probability of being exceeded, are shown.
This network has an area of 22.28 km² and 100.62 km of total length. In the simulations, it was obtained a rate of lightning direct discharges to the network of about 30.87% with a standard deviation of 4.14, in relation to the total discharges to the ground during the period of 100 years.

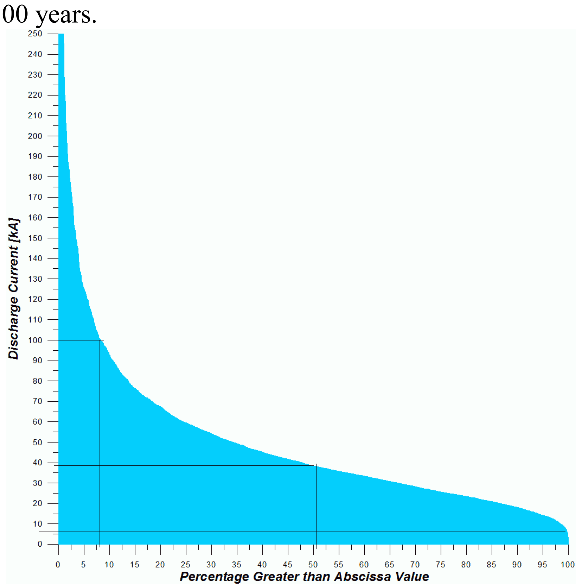

Fig. 5 - Discharge Current Permanence Curve for Urban Network

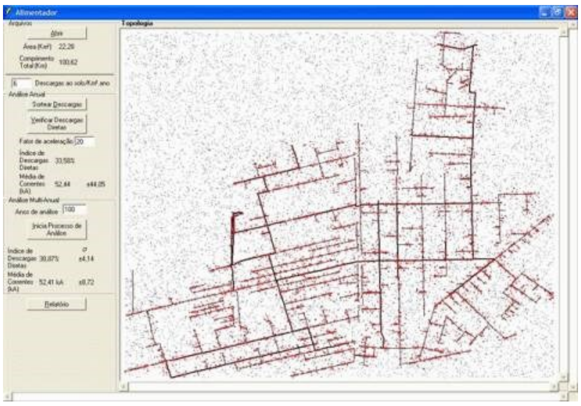

Fig. 6 - Simulation Program Image with an Urban Distribution Network and 100 Years of Simulation

Fig. 6 shows a screen image of the simulation program, with the topology and results of analysis.
In this case, the median current intensity for the direct discharges, as shown in Fig. 5, was about 39kA. These data had been obtained with a flash density of 6 discharges to ground per km² per year. As a result, for a density of 1 discharge to the ground per km² per year, the system presents a density of 6.82 discharges per 100km per year.
In accordance to Fig. 5, for 6 discharges to ground per km² per year to each 100 km of network, 20.44 discharges presents current intensity greater than 39kA, as well as 3.27 discharges exceeds 100kA of current intensity.

6.3. Urban Distribution Network – Simulating Tall Structures

The tall structures simulation considers the manual inclusion of diverse points along the network. With this artifice, the obtained results are more close to the real urban cases. This has as objective to incorporate the natural shielding supplied by trees, towers, high buildings, among others.
In the case shown in Fig. 7, the tall structures had been inserted with average spacing of 10m for the lines, 40m between two consecutive structures, and with height little superior to the network, around 15m. Fig. 7 presents the topology of the urban network detaching the points of tall structures.

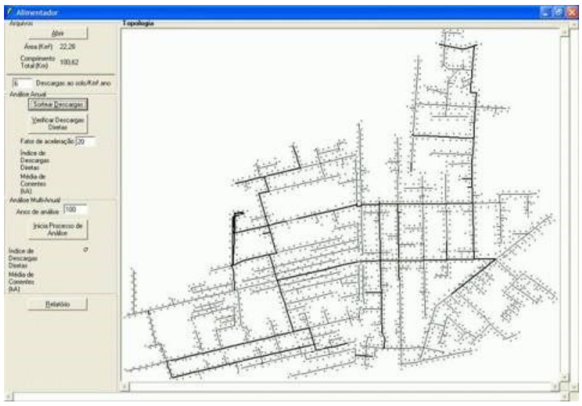

Fig. 7 – Urban Distribution Network with the Presence of Simulated Tall Structures

This network possess the same area and length of the urban network simulated previously, however, it considers the presence of tall structures. In this way, in the obtained simulations the average rate of direct discharges to the conductors, trough 100 years, is about 2.24% with a standard deviation of 1.17. This case presents the median value of direct discharge current of 12kA.
These data had been obtained with a flash density of 6 discharges to ground per km² per year. As a result, for a density of 1 discharge to the ground per km² per year,

the system presents a density of 0.24 discharges per 100km per year.
As observed, for 6 discharges to ground per km² per year and to each 100 km of network, 0.73 discharges present current intensity greater than 12kA. As well as discharges with current above 100kA of current magnitude were not found, what proves the effectiveness of the shield effect, provided by tall structures, in the system performance against lightning discharges.

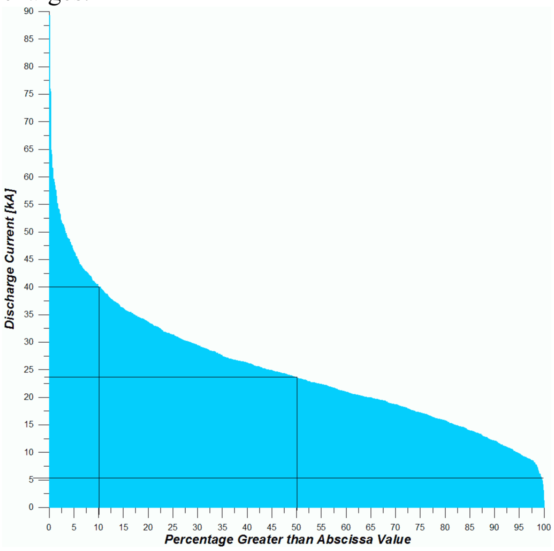

Fig. 8 - Discharge Current Permanence Curve for Urban Network with Simulated Tall Structures

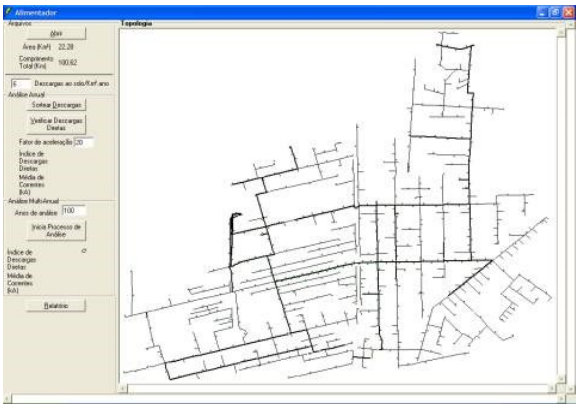

Fig. 9 – Urban Distribution Network with the Presence of Simulated and Less Concentrated Tall Structures

In the case shown in Fig. 7, the amount and localization of the tall structures causes a relatively high shielding effect on the network, where only low intensity discharges can reach the network. Another case with the tall structures nearest to the network, however more spaced between it, about 80 to 200 meters, are also simulated. This new case corresponds to an urban area with a lower density of constructions or structures. Fig. 9 shows the topology of this case.
The Fig. 8 presents the permanence curve for the discharge currents that have intercepted the network for the case of the Fig. 9. The values of current with 50% of probability (Median), 100kA discharge current probability and the smaller current intensity, that have 100% of probability of being exceeded, are shown.

Fig. 10 - I_{LD}=20 kA

Fig. 11 – I_{LD}=7,5 kA

Fig. 12 – I_{LD}=2,14 kA

In this case, in the obtained simulations the average rate of direct discharges to the conductors, trough 100 years, is about 15.43% with a standard deviation of 3.36. This case presents the median value of direct discharge current of 23kA.
These data had been obtained with a flash density of 6 discharges to ground per km² per year. As a result, for a density of 1 discharge to the ground per km² per year, the system presents a density of 2.22 discharges per 100km per year.
In accordance with Fig. 8, for 6 discharges to ground per km² per year and to each 100 km of network, 6.68 discharges present current intensity greater than 23kA. As well as discharges with current above 100kA of

current magnitude were not found, what proves the effectiveness of the shield effect provided by tall structures.
These current intensities could be, indirectly confirmed by Figs. 10-12, where lightning discharges in the electrodes of conventional surge arresters are shown. The damaged area, etchings, reflects the discharged current intensity. The number of surge arresters with area compatible with lightning current bellow 20 kA is high reaching, in preliminary results, the order of 66.4% of 372 analysed surge arresters removed from the field.

7 CONCLUSIONS

The carried studies demonstrate that a low number of direct lightning discharges intercept the urban distribution network, mainly when the circuits are naturally shielded by tall structures. In the cases analyzed, between 2% to 16% of the lightning reaches directly the urban distribution network. For a density of 1 discharge to the ground per square kilometre per year, between 0.24 and 2.22 discharges intercept the network per 100 kilometres per year.
In a complementary way, the amplitude of the average discharge currents that intercept the network is between 12 and 23 kA. As a result, the main factor of study for the improvement of the lightning performance of urban distribution systems is associated to induced overvoltages.
In these cases, the presence of surge arresters and transformers should be carefully investigated before taking any standard protection practices, mainly when it is in mind that the protection of “better quality” is individual by equipment.
In this study, with the adopted simplifications, the urban distribution networks without shielding had suffered with a larger amount of discharges, as direct as induced. This can be addressed to the fact that they have a higher density compared with rural ones. However, as tall structures had not been considered, it is necessary to observe that the number of direct discharges in these cases is overestimated.
Based in the median current intensities obtained, it is possible to affirm that direct discharges intercepting the network results in dielectric failure of the system, and in the failure of transformers, when considering the transformers insulation quality.
Observing the reduction in the discharges current intensity provided by tall structures, it is considered inadequate the application of indiscriminate indemnity polices without the presence of strong evidence, through correlated events in the network.
The studies demonstrated that the majority of direct discharge currents is below 40 kA at urban systems, with 10% of probability of being surpassed. According to Fig. 8, the average discharge current is of the order of 25 kA. This means in the possibility of use of surge arresters tuned for these magnitude, as a result, with lower cost.
Otherwise, for rural networks and urban networks with low natural shielding or tall structures, 10% of the discharge currents have magnitude higher than 100 kA. However, this does not imply that the surge arresters for those networks must have the capacity of withstanding 100 kA or more, once, for a density of 1 discharge per square kilometre per year, around 1.1 discharges per 100 km intercept the network with intensity larger than 100 kA.
This high current is equally divided in both directions of the intercepted network, and the process of travelling waves thus established is responsible for a series of insulation failures, until a set of surge arresters is reached.
On the other hand, the average discharge current is about 40 kA, according to Figs. 2 and 5, what partialy confirms the values of discharge current used in the type, routine, and reception tests of medium voltage surge arresters.

8 REFERENCES

[1] Nucci, Carlo Alberto; Paolone, Mario; Borghetti, Alberto. “Effect of tall-instrumented towers on the statistical distributions of lightning current parameters and its influence on the power system lightning performance assessment.”, VII SIPDA, Curitiba, November, 2003.

[2] IEEE Guide for Improving the lightning performance of electric power overhead distribution lines, IEEE Standard 1410-1997, June 1997.

[3] Anderson R.B., Eriksson A.J., “Lightning parameters for engineering application”, Electra, No. 69, 1980.

[4] Martinez, Manuel L. B.; Mendonça dos Santos, Pedro H. “Induced Voltages in Distribution Networks Study, Guide for Improvement of the Performance of Overhead Distribution Networks Against Lightning Discharges.” High Voltage Laboratory of the Federal University of Itajubá, MG, Brazil, March 2004.

[5] Metwally, I. A.; Heidler, F. H.; Nickel, R. “Computation of collection area and probability of lightning strikes to structures using the Electro geometric model.”, VIII SIPDA, São Paulo, November 2005.

[6] Grzybowski, S.; Rodriguez-Medina, B. “Striking distance dependence on rod height and impulse polarity: A system identification approach.” VIII SIPDA, São Paulo, November 2005.

[7] Torres, Horacio. “Statistical evaluation of lightning induced overvoltages in distribution lines in the presence of transformers and surge arresters.” VII SIPDA, Curitiba, November 2003.