Comparative Performance of Projects of Medium Voltage Overhead Distribution Lines Under Induced Voltages

Marco Saran, Manuel Martinez, Rafael Bonon, Hermes Oliveira, Carlo Nucci, Mario Paolone

Abstract — **The aim of this paper is to present the results of the performance study of medium voltage overhead distribution lines against lightning discharges, in the way to define methodologies to reduce the system failures. The results are obtained within the partnership among the High Voltage Laboratory of the Federal University of Itajubá, AES Sul Utility Company and the University of Bologna. The resultant performance is presented in terms of expected faults for 100 km of line for a density of discharges to the ground (GDF) of 1 discharge/km²/year. Commentaries on the relative performance and comparisons of different construction configurations of overhead lines are presented.**

Index Terms — **distribution, induced, lightning, performance**

I. INTRODUCTION

The standard medium voltage distribution network are subjected to incidence of direct lightning discharges and induced surges, that are one of the main causes of interruptions and failures of the lines.

The majority of the damages to the distribution network are caused by direct discharges, 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.

When the lightning strikes the network directly, they commonly cause permanent damages, because they are high intensity discharges with high growth rate. For this kind of damage, the network remains off until its repair.

However, they can be deviated by tall structures, such as towers, buildings, high constructions, and trees. Even when the lightning does not intercept the network, they induce surges that travel throughout the lines. These surges are able to cause many damages and interruptions to the distribution network. For that reason, this work presents the relations between induced surges and direct discharges.

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 the majority 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 by laboratory tests. As a result, many of them besides of presenting high cost are not effective. Among others, the distribution network reliability depends directly on its exposition to the lightning discharges. The topology of the distribution network is the major factor of influence for analysis [1], and its density and distribution results in a greater or minor probability of incidence of direct lightning discharges.

Once that the atmospheric discharges phenomena are random, this work considers that the parameter generation of the discharges follows the statistical data proposed by Anderson and Eriksson.

The Monte Carlo Method is used for the incidence distribution of the discharges and the Electro Geometrical Model for the interception point of the discharge.

II. DIRECT DISCHARGE AND INDUCED LIGHTNING SURGE

When 100 years of lightning discharges are simulated into a real urban distribution network, a low number of direct discharges intercept the network [1], mainly when the circuits are naturally shielded by tall structures, like buildings, towers, and trees. Between 2% to 16% of the lightning reaches directly the urban distribution network.

In complementary way, the amplitude of the average discharge currents that intercept the network stays between 12 and 23 kA.

The majority of direct discharge currents stay below 40 kA at urban systems, with 10% of probability of being surpassed.

Based on the median current intensities, it is possible to affirm that direct discharges intercepting the network results in dielectric failure of the system, and in the failure of not properly protected transformers.

As a result, the main factor of study for the performance improvement of urban distribution systems, front lightning, is induced surges. For this reason, this paper is focused on the assessment of the indirect-lightning performance of an AES 25 kV class standard medium voltage distribution line (see Fig. 1).

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III. CALCULATION OF THE INDIRECT-LIGHTNING PERFORMANCE OF DISTRIBUTION LINES

The statistical procedure used to infer the indirect lightning performance of the AES 25 kV class overhead distribution line is based on the calculation of lightning induced voltages by means of the models implemented in the LIOV code [5-8] and on the Monte Carlo method.

The LIOV code allows for the calculation of lightning-induced voltages along a multiconductor overhead line as a function of lightning current waveshape (amplitude, front steepness, and duration), return stroke velocity, line geometry (height, length, number and position of conductors), values of termination impedance, ground resistivity and relative permittivity.

In particular, the LIOV code is based on the field-to-transmission line coupling formulation of Agrawal et al. [5], suitably adapted for the case of an overhead line above a lossy ground. The equations are numerically solved by a finite difference time domain (FTDT) approach [5, 9]. The LIOV Code calculates the electromagnetic field originated by indirect lightning [16] by adopting the MTLE return-stroke engineering model [17, 18] and by using the Cooray-Rubinstein formula [19-21], improved according to the remarks by Wait [22], to take into account, in the field calculation, the finite value of the ground resistivity.

Concerning the effect of the ground resistivity in the calculation of the line parameters, with particular reference to the ground impedance, the Carson expression [23] is used. Indeed, as all the above-mentioned models are implemented in the time domain, the ground transient resistance formula derived by Timotin [24], which corresponds to the Carson formula, is used. Recently, the expression proposed Rachidi et al. in [25] has been introduced in the LIOV code, which corresponds to the general Sunde's expression for the ground impedance [26].

Concerning the statistical procedure, described in details in [12-14], it is based on the combined use of the Monte Carlo method and the LIOV code. The Monte Carlo method is applied to generate a significant number of events (al least 10^4). Each event is characterized by four random variables: the peak amplitude of the lightning current I_p, its front time t_f (whose statistical distribution is assumed correlated with that of I_p) and the two co-ordinates of the stroke location uniformly distributed within the surface around the line.

The lateral attractive distance expression adopted by the IEEE Working Group on Lightning performance of transmission lines is used to distinguish direct from indirect lightning events [3], only the latter being considered in this study.

The adopted parameters of the current peak and its front time lognormal statistical distributions are those proposed by Anderson and Eriksson [10], with a correlation coefficient equal to 0.47 [11]. These statistical distributions have been obtained by using experimental records collected by elevated structures.

Although the presence of the elevated structure has an influence on the parameters of the statistical distributions [27], such an influence is here disregarded and the statistical distributions of Anderson and Eriksson are considered to be those of the lightning events hitting the ground. This allows, further, for a more straightforward comparison of our results with those already presented in the literature on the subject.

The stroke locations are supposed uniformly distributed within a 'striking area' around the line wide enough to include all the lightning events causing induced voltages with amplitude larger than the considered minimum insulation level of the line, which was here considered to be equal to 50 kV.

IV. GEOMETRY OF SIMULATIONS

All the simulations described in this paper refer to a 2 km line length with a distance between two subsequent poles equal to 100 m. The line conductor's geometry is one of the patterns adopted by AES Sul, where the grounded conductor corresponds to the neutral conductor shown in Fig. 1.

According to the indications reported in [4], the surge arresters are modelled using a V-I non-linear characteristics, which has been obtained by the standard 1.2/50 μs (see Fig. 2).

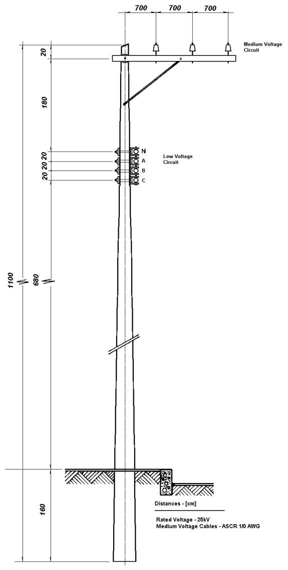

Fig. 1. Conductors geometry of the overhead line

Two values of ground conductivities are considered, namely: 0.01 S/m and 0.0033 S/m. For each value of ground conductivity the following grounding resistances are assumed: 10Ω and 40Ω.

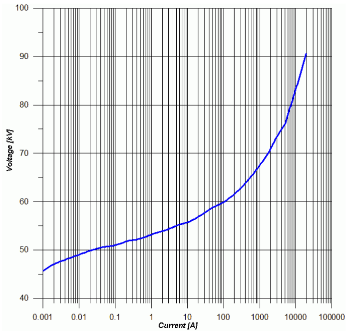

Fig. 2. V-I characteristic of the adopted standard medium voltage arrester

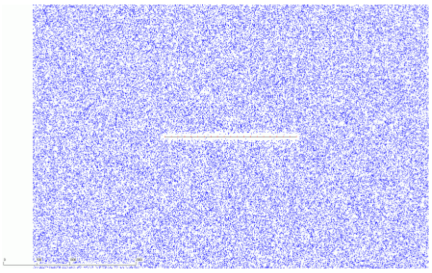

Fig. 3. Indirect stroke area to overhead line (top view).

The randomly generated stroke locations in the area around the line ($80 \cdot 10^3$ events) are reported in Fig. 3. Such area is of 24 km² and the considered annual number of flashes per squared km per year is Ng=1. In the statistical procedure, the return stroke speed can be considered as a random variable, dependent to the return stroke current [5] or assumed with a fixed value. In these simulations, such a value is assumed constant and equal to $1.5 \cdot 10^8$ m/s.

V. SIMULATIONS RESULTS

Different line configurations, based on the same standard 2km line structure, are considered. The cases differ for the soil conductivity, grounding resistance, number, position of surge arresters and grounding points and, finally, line boundary conditions.

As usually reported in the literature on the argument [3], the reported results refer to 100 km of line length and are specified for each conductor of the line.

Due to the predominant common mode coupling between LEMP and multiconductor lines, and to the identical height of the different line conductors, the number of events exceeding the BIL is practically the same for each phase. As a result, in a first approximation the calculations could be carried out for one phase only.

Fig. 4 shows that the flashover risk for the considered distribution line assuming an influence distance, from the striking point, of 10 or 20 poles, in each direction of the distribution line, is virtually the same.

Laboratory tests have demonstrated that there is no effective dielectric improvement with the utilization of wood cross arms [15]. Accordingly, Fig. 4 presents the relation between flashover risks, calculated as being the integral of the withstanding curve, as function of the set of insulators BIL. For a line with no surge arresters nor grounded wire and for a soil conductivity of 0.0033 S/m.

Fig. 5 presents the flashover risk calculations for all the simulated line configurations, for a line matched at both terminations, 20 poles of influence distance and ground conductivity of 0.01 S/m.

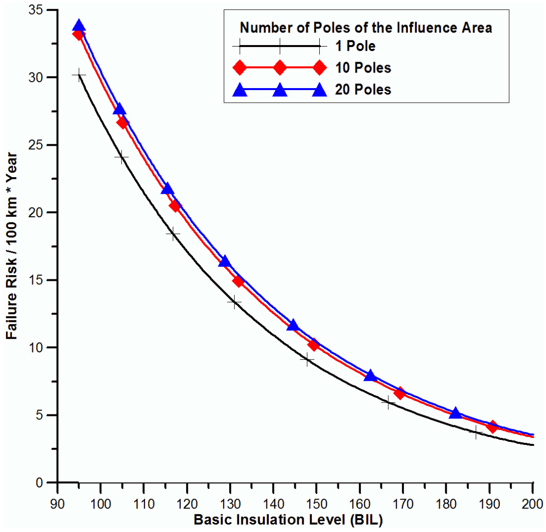

Fig. 4. Failure risk by phase x BIL for a distribution line without the presence of grounded conductors and surge arresters; ground conductivity of 0.0033 S/m, for GDF= 1 fl/km²/Year

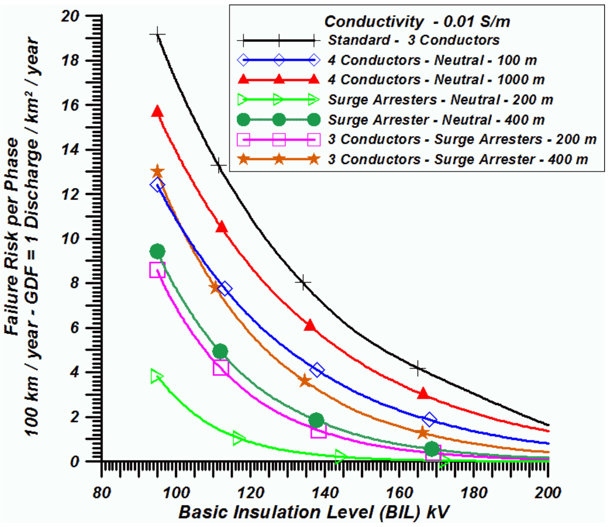

Fig. 5. Failure risk for influence distance of 20 poles, soil conductivity = 0.01 S/m and GDF = 1 fl/km²/Year

The results of Fig. 5 show that equivalent line configurations can be obtained. For instance, for system insulators having a BIL of 100 kV, the line configuration with surge arresters installed each 400 m has a performance close to the line configuration with a grounded conductor each 100 m.

Fig. 5 can be used to support the selection of the appropriate line configuration. In order to provide an example, let assume as an acceptable risk level the value of 4 failures per 100 km per year, from Fig. 5 it is possible to select the equivalent configurations as shown in Fig. 6.

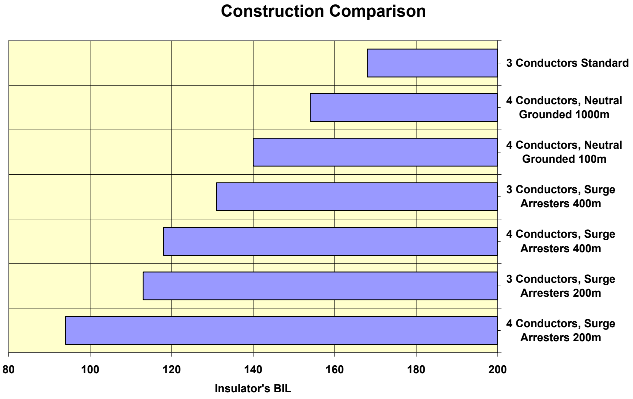

Fig. 6. Construction Comparison by Insulator's BIL

Any selection, which will allow obtaining a specific BIL vs. flashover risk, is basically dependent on the different costs related to the adoption of the different protection measures.

As a consequence of Fig. 5, it can be observed that the increase of the system insulator's BIL implies a simplification of the line configuration with particular reference to the adopted protection systems.

Based in Fig. 6, a construction cost comparison of the different alternatives can be made for the possible solutions, leading to the Table 1.

Table 1 – Construction Cost Comparison

Risk Level of 4 Failures per 100 km per year		
Construction	**Standardised Insulator's BIL**	**Cost US$/km**
4 Conductors, Surge Arresters 200m	95 kV	11,296.30
3 Conductors, Surge Arresters 200m	125 kV	9,975.20
4 Conductors, Surge Arresters 400m	125 kV	10,482.47
3 Conductors, Surge Arresters 400m	150 kV	9,501.65
4 Conductors, Neutral Grounded 100m	150 kV	9,987.56
4 Conductors, Neutral Grounded 1000m	150 kV	9,638.47
3 Conductors Standard	170 kV	9,005.24

Fig. 7 presents the flashover risk calculations for all the simulated line configurations, for a line matched at both terminations, 20 poles of influence distance and ground conductivity of 0.0033 S/m.

Fig. 7 shows that the solutions involving the use of insulators with BIL greater than 200kV presents, as expected, reduction of flashover risks induced by surges. In these cases, even the most complex constructions, as the one that involves the use of surge arresters each 200 meters and grounded cable, do not present significant differences in relation to the standard case, without surge arresters nor grounded wires.

It is also possible to observe that the line configuration with surge arresters placed each 400 meters and the one with grounded wire each 1 km, provide similar flashover risk for insulators with BIL greater than 150 kV. Therefore, it is possible to conclude that, for soils with high resistivity and high grounding resistance, the 4 conductors system, with the grounded wire each 1 km, is equivalent to 3 conductors system with surge arresters to each 400 meters.

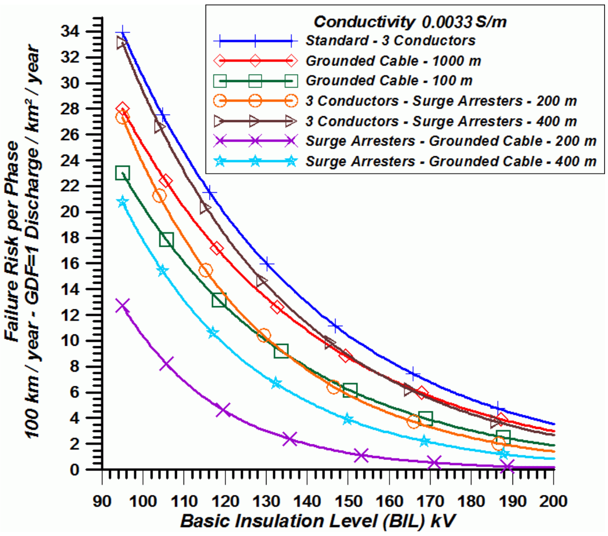

Fig. 7. Flashover risk for Influence Distance of 20 Poles, Soil Conductivity = 0.003 S/m and GDF = 1 fl/km^2/Year

As it could be seen in Fig. 7, in the 3-conductor systems with insulators BIL below 200 kV, the efficiency is increased only with the installation of surge arresters placed each 200 meters. The same result could be obtained with the line constructions with 3 conductors and surge arresters placed each 200 meters and the line constructions with 4 conductors with grounded wire each 100 m.

As stated in the IEEE Std. 1410 [3], the Cigré defines the lightning current parameters as in the Table 2.

Table 2 – CIGRÉ Lightning Current Parameters

CIGRÉ	First-Strike	Subsequent
Front µs	5.63	0.75
Tail µs	77.5	30.2
Current kA	31.1	12.3

However, these parameters are valid only for the direct discharge. For the lightning induced surge these parameters change, in function of the soil conductivity, distance from the striking point and the line conductor's geometry, among others.

The summarized lightning induced surge parameters, when simulating 80.10^3 events for each case of line construction, are shown in the Table 3.

Table 3 – Lightning Induced Surge Parameters

Soil Conductivity	**0.0033 S/m**		**0.01 S/m**	
	Mean	**Median**	**Mean**	**Median**
Time to peak µs	7.29	5.54	5.99	4.53
Time to half peak µs	13.74	13.67	9.61	9.19

From Table 3 is possible to observe that with a high conductivity soil the parameters stay close to those of the direct lightning discharge, as shown in table 2. Furthermore, when the soil conductivity has a low value, the induced surge wave shape is slower.

Concerning the effect of the different line constructions on the lightning induced surge, some patterns were noticed. Firstly, the use of a surge arrester at each 400 metres, or a grounded cable at each kilometre has almost none positive effect, sometimes with negative effect on the induced surge.

Although, for the systems with surge arresters at each 200 metres, or grounded cable at each 100 metres, there was a positive effect on the induced surge for the great majority of the cases.

These results of analysis of induced surges reaffirm the previous results of failure risk analysis.

VI. CONCLUSIONS

The paper has presented a statistical results aimed at comparing the indirect lightning performance of different overhead distribution line configurations.

The analysis has covered the influence of the presence of surge arresters, of their spacing, of grounded wires and of the spacing of the relevant grounding points on the indirect lightning performance of a typical AES 25 kV distribution line.

Surge arresters removed from AES Sul distribution networks, and analyzed in laboratory, shows, in preliminary results, that 66.4% of it have being hit by a lightning current inferior than 20 kA, from 372 surge-arrester's analyzed. Confirming the median value of 23 kA obtained in the simulations.

When an acceptable flashover risk is established, it is possible with the aid of some charts to choose the appropriate line configurations and to associate them with installation and maintenance costs.

This is based on the assumption that the distribution system configuration can be described adequately as a single multiconductor overhead line and allows taking decisions that capture important economic and technical aspects.

As demonstrated, the surge arresters installation to each 400 meters is not an efficient solution, mainly when collated with solutions where the insulators BIL are larger to 170kV.

In this way, systems where the insulators BIL are lower than 125kV and protected by surge arresters each 400 meters, presents flashover risk higher than the systems constructed without surge arresters and with insulators BIL above 170kV.

A first result of this preliminary study is that the solution for 3-conductors construction line without surge arresters nor grounded wire and BIL larger than 200 kV seems a valid alternative worth of additional studies.

This alternative presents economic potential, as much for equipments as for hardware, however with a bigger cost with regard to the standard insulators.

VII. REFERENCES

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