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COMPARATIVE PERFORMANCE OF PROJECTS OF MEDIUM VOLTAGE OVERHEAD DISTRIBUTION LINES UNDER INDUCED VOLTAGES

Marco A. M. Saran Manuel L. B. Martinez Rafael R. Bonon
High Voltage Laboratory, Federal University of Itajubá, Brazil

Hermes R. P. M. de Oliveira
AES Sul Utility Company, Brazil

Carlo A. Nucci Mario Paolone
University of Bologna, Italy

Abstract – The aim of this research is to present the results collected from the partnership among AES Sul Utility Company, Federal University of Itajubá and University of Bologna. The data are analyzed concerning the performance of possible projects of medium voltage overhead distribution networks, furthermore detailing the procedures used for the simulations. 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 are presented.

1 - INTRODUCTION

The insulation coordination of medium voltage overhead lines performed by means of statistical methods is based on the calculation of the flashover risk. This last can be estimated when both overvoltage statistical distribution and insulation strength are known.

A method developed at the University of Bologna for the calculation of the statistical distribution of indirect-lightning induced voltages on overhead distribution lines is first described, and then applied to the AES Sul 25 kV class standard medium voltage distribution line.

The assessment of indirect-lightning performance of distribution lines involves the accurate modeling of the overvoltages induction mechanism. Additionally, for achieving proper insulation coordination, it is necessary to take into account the presence of protection devices, basically constituted by surge arresters and/or grounded shielding wire.

The consequent complexity of the involved phenomena, and the high number of non-linearities, result in a difficult estimation of induced voltages. For such reasons, in the last years, more accurate models, compared with those proposed in the literature of the first part of the last century, have been presented by Nucci and Rachidi [2-5].

In what follows the statistical procedure, to evaluate the overhead line lightning performance, presented by Nucci and Borghetti [6] are extended by Borghetti, Nucci and Paolone [7-10]. Such a procedure is based on more accurate models, thus allowing more accurate description of the overvoltage induction mechanism of indirect lightning, and on the Monte Carlo statistical method.

2 - THE STATISTICAL PROCEDURE

The statistical procedure to infer the indirect lightning performance of an overhead distribution line developed at the University of Bologna, is based on the calculation of lightning induced voltages by means of the models implemented in the LIOV code [2-4] and on the Monte Carlo method.

It is worth reminding that the calculation of the lightning induced voltages with the LIOV code is performed in two subsequent phases.

In the first phase, the lightning return-stroke electromagnetic field change is calculated at a number of points along the line, employing a lightning return-stroke current model, namely a model that describes the form of the return stroke current as a function of height and time along the vertical channel. To this purpose, the return stroke channel is generally considered as a straight vertical antenna.

Secondly, the electromagnetic field (LEMP – Lightning Electro Magnetic Pulse) is then evaluated and used to calculate the induced overvoltages making use of a coupling model, which describes the interaction between the field and the line conductors.

The LIOV code is based on the field-to-transmission line coupling formulation of Agrawal et al. [11], 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. More recently, a 2nd order FDTD integration scheme has been applied [12,13] in order to improve the numerical stability of the code.

A specific routine is implemented to calculate the electromagnetic field originated by indirect lightning [14], by adopting the MTLE return-stroke engineering model [15,16] and by using the Cooray-Rubinstein formula [17-19], improved according to the remarks by Wait [20], 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 [21] is used.

Indeed, as all the above-mentioned models are implemented in the time domain, the ground transient resistance formula derived by Timotin [22], which corresponds to the Carson formula, is used. Recently, the expression proposed by Rachidi, Loyka, Nucci e Ianoz [23] has been introduced in the LIOV code, which corresponds to the general Sunde's expression for the ground impedance [24].

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.

The statistical procedure, described in details by Borghetti and Nucci [6-10], 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 Ip, its front time tf (whose statistical distribution is assumed correlated with that of Ip) 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 [25], 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 [26], with a correlation coefficient equal to 0.47 as proposed in the literature by Chowdhuri [27]. 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 [28], 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, in this study it was considered as 50 kV.

3 – GEOMETRY OF SIMULATIONS

The V-I characteristic of the surge arresters used in this study is adopted as the standard used in medium voltage overhead distribution networks as shown in Fig. 2. The adopted ground conductivities are 0.01 S/m and 0.0033 S/m; the relevant grounding resistances are: 10Ω and 40Ω, respectively the usual value and the maximum acceptable.

All the simulations described in this report 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 is the same as the neutral conductor, that is, the top conductor of the low voltage, as shown in Fig. 1.

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 km^2 and the considered annual number of flashes per squared km per year is N_g=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.

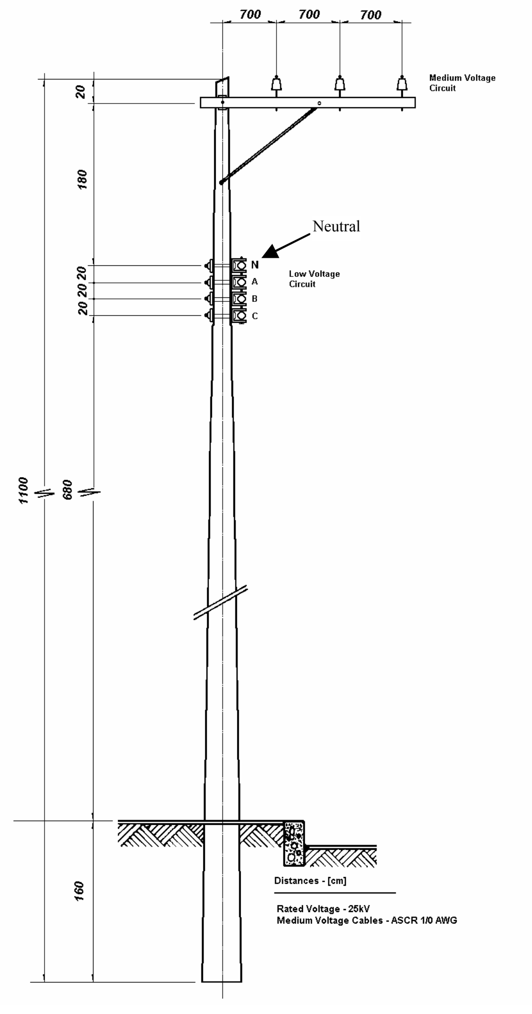

Figure 1 - Conductors geometry of the overhead line

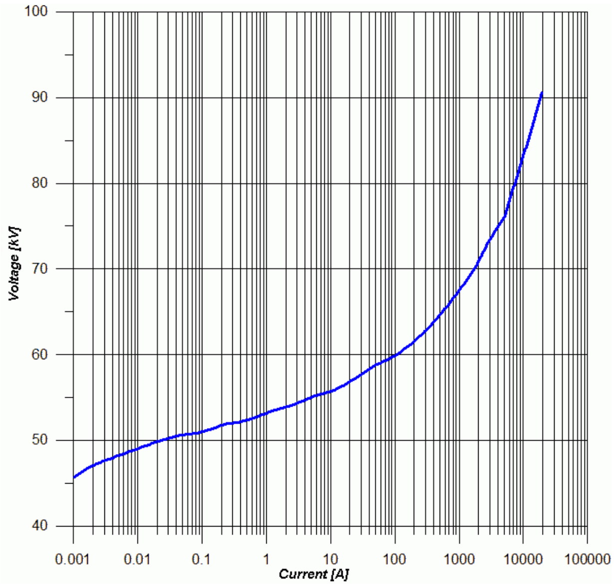

Figure 2 - V-I characteristic of the adopted standard medium voltage arrester

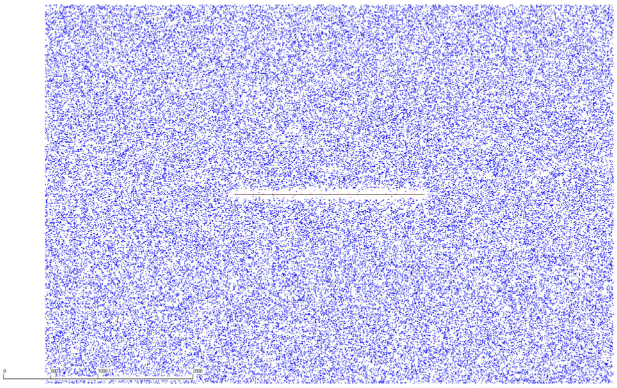
Figure 1 - Indirect stroke area to overhead line (top view)

4 – SIMULATIONS RESULTS

Eight different line constructions were simulated for analysis, all of those based in the same standard structure, which considers a three-phase system and a matched line in one or both terminations. Cases particularities consist of the presence of surge arresters and its location, presence of grounded cable, grounding resistance and soil conductivity.

The four first cases consider a matched line in both terminations, which implies in an infinite line, where the lightning discharge occurs in random positions among the area, without the influence of terminal reflections.

The Table 1 shows a typical calculation result of induced overvoltage for the studied medium voltage lines. It is possible to observe that the number of lightning discharges, for a specified BIL, between the phases is practically the same. Being thus the amplitude of the three-phase induced voltages can be considered equal. This reflects the common way effect of the induction phenomena associated to the proximity between the conductors. As a result, all the calculations of insulation coordination can be carried through for only one phase, and extended for the number of phases of the circuit under analysis. Therefore, for one determined BIL, a three-phase line presents a failure risk of 3 times the risk calculated for one single phase.

Table 1 – Discharges above BIL (Basic Insulation Level) for GDF = 1 discharges to ground by km² by year

Discharges Above BIL			
BIL [kV]	**Phase 1 - A**	**Phase 2 – B**	**Phase 3 – C**
50	49,62	48,84	49,62
75	24,72	24,48	24,72
100	15,00	14,64	15,00
125	9,12	9,00	9,12
150	5,58	5,52	5,58
175	2,88	2,88	2,88
200	1,74	1,56	1,74
225	0,78	0,72	0,78
250	0,48	0,48	0,48
275	0,18	0,18	0,18

Laboratory tests have demonstrated that there is no effective dielectric improvement with the utilization of wood cross arms. Consequently, Figure 4 presents the relation between failure risks, calculated as being the integral of the withstanding curve, in function of the set of insulators BIL. For the condition where neither have surge arresters nor grounded cable, and for a soil conductivity of 0.0033 S/m.

The Figure 4 shows that the failure risk of a distribution line considering an influence distance of 10 or 20 poles is virtually the same. Furthermore, it is also visible that the insulation is most requested on the right pole next to the discharge point. As a result, the existence of tall structures next to the line implies the necessity of installation of surge arresters on the pole next to the download conductors of the lightning protection system.

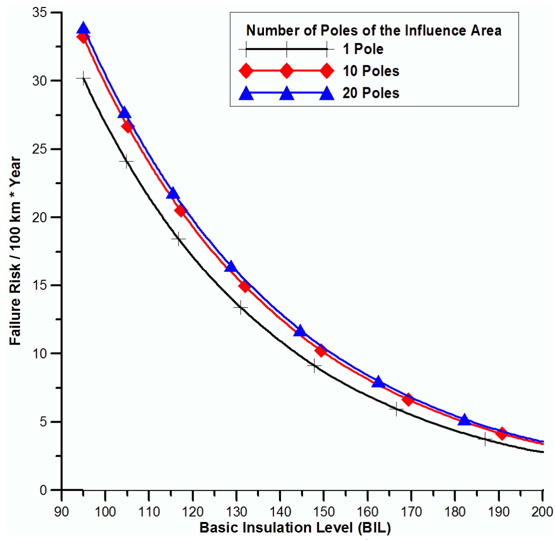

Figure 2 - Failure Risk by Phase x BIL for a Distribution Line without Grounded Cable or Surge Arrester and Ground Conductivity of 0.0033 S/m, for GDF= 1 per km^2 per Year

The Figure 5 presents the failure risk calculations for all the simulated cases, for the condition of an infinite line, 20 poles of influence distance and ground conductivity of 0.01 S/m, condition that imposes the lesser request.

As Figure 5 shows, the constructed lines, for example, with 3 conductors and surge arresters installed at each 400 m has, front the induced surge, a behavior very close to the lines constructed with 4 conductors, neutral grounded to each 100 m and without surge arresters, mainly when the system insulators have a BIL of the order of 100 kV.

The same can be observed to lines constructed, for example, with 4 conductors and surge arresters at each 400 m, and lines constructed with 3 conductors and surge arresters at each 200 m, this tendency is more visible for systems where the insulators have BIL above 175 kV. Above 200 kV all the studied solutions presents similar behavior front induced surge.

In a complementary way, Figure 5 also allows to choose insulators configuration (BIL) from an adopted value of failure risk. Therefore, for a risk of 4 failures per 100 km per year, it is possible to work with the following configurations:

I- 3 Conductors System, Insulators with BIL = 113 kV and Surge Arresters at each 200 m;
II- 4 Conductors System, Insulators with BIL = 118 kV and Surge Arresters at each 400 m;
III- 3 Conductors System, Insulators with BIL = 131 kV and Surge Arresters at each 400 m;
IV- 4 Conductors System, Insulators with BIL = 140 kV and neutral grounded to each 100 m;
V- 4 Conductors System, Insulators with BIL = 154 kV and neutral grounded to each 1000 m;
VI- 3 Conductors System, Insulators with BIL = 168 kV.

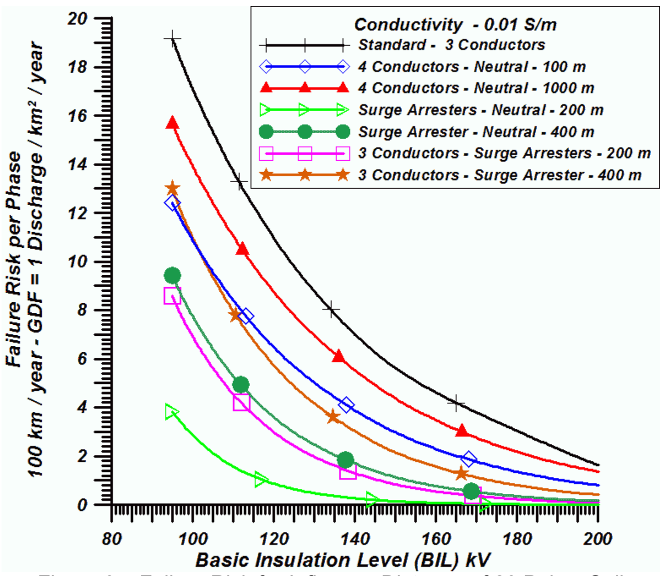

Figure 3 – Failure Risk for Influence Distance of 20 Poles, Soil Conductivity = 0.01 S/m and GDF = 1 Discharge to Ground per km^2 per Year

As shown, the rise of the system insulator's BIL implies in the possibility of reduction of the complexity of the net, when the failure risk is the same. The cost difference between insulators of BIL 107 kV and 157 kV should be compared with the cost of acquisition and installation of surge arresters, for example, to each 200 meters. In this case, the decision is, basically, economical.

The Figure 6 presents the calculation results of failure risk for all the simulated cases in the condition of a infinite line, 20 poles of influence distance and 0.0033 S/m of soil conductivity, condition this that imposes the biggest system request.

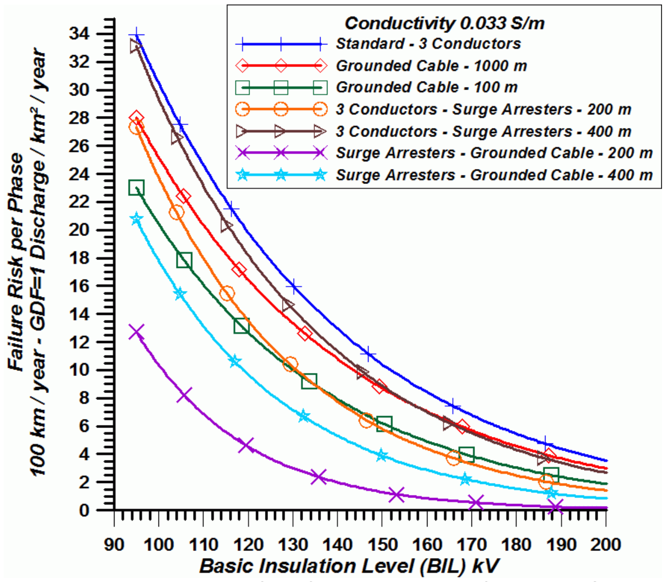

Figure 4 - Failure Risk for Influence Distance of 20 Poles, Soil Conductivity = 0.003 S/m and GDF = 1 Discharge to Ground per km^2 per Year

The Figure 6 analysis shows that the solutions involving the use of insulators with BIL superior to 200kV presents, as expected, reduction of failure risks induced by surges. In these cases, even the most complex constructions, as the one that involves the use of surge arresters to each 200 meters and grounded cable, do not present significant differences in relation to the standard case, without surge arresters nor grounded cable.

It is also possible to observe that the use of surge arresters to each 400 meters and the construction with neutral grounded at each 1 km, posses similar failure risk, mainly when using 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 neutral grounded only in equipments poles, is equivalent to 3 conductors system with surge arresters to each 400 meters, including equipment surge arresters.

As it could be seen in the Figure 6, in the 3 conductors systems with insulators BIL under 200 kV, the efficiency increase is only possible with the installation of surge arresters to each 200 meters. The same could be done between the constructions with 3 conductors and surge arresters to each 200 meters and the constructions with 4 conductors and neutral grounded at each 100 m.

For insulators with BIL greater or equal to 200 kV, the inclusion of surge arresters to each 200 or 400 meters presents, in a practical way, the same effect of the maintenance of the standard construction with 3 conductors.

5 – CONCLUSIONS

The presented simulation allows determining the relation between expected failure risk of distribution systems and structures basic insulation level, the insulators BIL in this case. As verified in laboratory, the dielectric properties of the wood cannot be considered for the type of construction and rain conditions.

When an acceptable failure risk, front induced surge, is established, it is possible with the aid of simplified graphs to choose which alternatives can be considered, and to associate them with the installation and maintenance costs. This 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 superior to 170kV. In this way, systems where the insulators BIL are inferior to 125kV and it is protected by surge arresters to each 400 meters, presents failure risk higher than the systems constructed without surge arresters and with insulators BIL above 170kV.

It is always possible to criticize that the surge arresters installed in distribution networks act in the direction of reducing the number of failures by direct lightning discharges. However, this only has meant for the first component of the discharge that presents rise time relatively reduced, average front time about 5.5 μs.

Although, the same is not valid for the subsequent components, which presents average front time about 1.1 μs. Thus implies that for the subsequent discharges the surge arresters reflection phenomena do not have sufficient time to make present.

In this way, as first result of this study, it is possible to conclude that the solution for the 3 conductors construction lines, without surge arresters nor grounded cable and basic insulation level greater than 200kV, is a valid alternative and should be studied.

This alternative presents economic potential, as much for equipments as for hardware, however with a bigger cost with regard to the standard insulators. Finally, as it does not use grounded cable nor earth groundings that can be stolen, as well as surge arresters that can fail, the 3 conductors solution should also presents low operation costs.

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Main author
Name: Marco Aurélio Moreira Saran
Address: Rua Coronel Rennó, 7, Centro
Itajubá, MG, Brazil 37500-050
Phone/FAX: +55 35 3622-3546
E-mail: marco@msaran.com