IMPROVEMENT OF TRANSMISSION LINES LIGHTNING PERFORMANCE BY MEANS OF EXTRA GROUND WIRE

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Abstract: The work aims to present the use of EGW – Extra Ground Wire as an alternative to improve the performance of transmission lines, comparing it to conventional alternatives. It is developed by simulations in the PSCAD software, where are simulated flashes in a 69kV transmission line, for backflashover simulations. To build the set of data for analysis, the simulations are done for different values of relevant parameters on the overhead transmission lines performance: front time current wave, footing tower resistance value and span length. These same simulations are performed for a transmission line with similar characteristics, however, using EGW positioned at different locations under phase conductors. From these data, a statistical analysis is applied to determine the comparative performance between the EGW transmission line and the conventional transmission line. Further studies are performed simulating changes in footing resistance and insulation level of the transmission line, in order to reach the same performance improvement achieved with EGW providing an overall comparison of three alternatives of three alternatives.

1 INTRODUCTION

Overvoltages in transmission lines originating from lightning are objects of great concern in companies and utilities involved in transmission and distribution of electric energy [1].

As well as power companies, some large industries with large areas installed as the steel sector, are subject to interference in its processes due to this phenomenon.

In most cases, failures in the transmission and distribution of industrial plants generate major disruptions in the production process, equipment breakdowns, and loss of supplies and pre-finished products, characterizing large financial losses.

These and other factors, such as the cost of electricity in the final product, make this a strategic input in the management of industrial processes, making it also strategically throughout the installation of generation and transmission of electric power in large industrial parks.

Thus, managing the operational risk of an electrical industrial large, with respect to transmission and distribution of electricity, involves studies and investments for improving the performance of transmission lines.

In this context, this paper aims to present the use of extra grounding wire, as an alternative to improve the performance of transmission lines.

The work uses as its object of study, a 69kV transmission line, part of electrical system from a large industrial plant.

2 CASE

The formulation of the results from this work involves two main steps, simulations and statistical analysis. The first one, the step of simulations, is developed based on two objectives, benchmarking the performance of the transmission line against back flashover, considering the use of extra grounding wire and explicit calculation of the stresses imposed on the insulators during the phenomenon.

To this end, the following items have worked out the parameters for modeling the line under study and the conditions set for the simulations. It also presents the parameters that represent the inclusion of extra grounding wire in this transmission line circuit.

2.1 Ligthning

The waveform and parameters of the discharge current can vary quite significantly, however, when constituting the appropriate references to compare the records, notes that the composition of the main body of the wave and changes in the parameters follows certain behaviours allowing us to create representations with satisfactory results.

In order to provide simulations involving the injection of current from a lightning in an electrical circuit, different analytical functions are proposed in the literature, some more complex, sometimes with simple mathematical functions.

The choice of the function that best represents the atmospheric discharge current depends on the object of study. Are three commonly used representations of double exponential, the curve Heidler and Triangular.

The triangular curve is the simplest mathematical expression presented within this topic. However, it is widely used and has excellent results in certain applications.

These results are comparative in nature, therefore, a more complex representation of the current wave, is not necessary. Thus, we used the Curve for Triangular representation achieved through the function of Surge Generator PSCAD. The function was parameterized so as to generate three different types of waveform, according to Table 1.

TABLE 1
LIGHTNING CURRENT REPRESENTATION CURVES

Parameter	Time (μs)		
Front wave start	0	0	0
Front wave end	1	2	5
Decay start	1,1	2,1	5,1
Decay end	100	100	100

The Figure 1 shows the three different representations of the lightning currents used in the study.

Fig. 1 – Wave shape of Lightning Current at PSCAD sw

2.2 Towers

The towers of a transmission line can be represented by different ways. Simple inductances, three-dimensional models and parameters of vertical transmission lines are some options.

The representation by means of a short vertical transmission line with constant surge impedance and grounded at one end by the foot tower impedance is usually adopted because it enables seamless integration with other models of electric equipment and has excellent results.

This representation considers the length of the tower, surge impedance and propagation velocity.

This study uses the representation by a transmission line with Bergeron model. The input data in the model are the surge impedance and propagation time.

Typical values of surge impedance range between 100Ω and 300Ω and also geometry classes approximations, according to Figure 2, are techniques with results very close to those using measurements and simulations with reduced scale models.

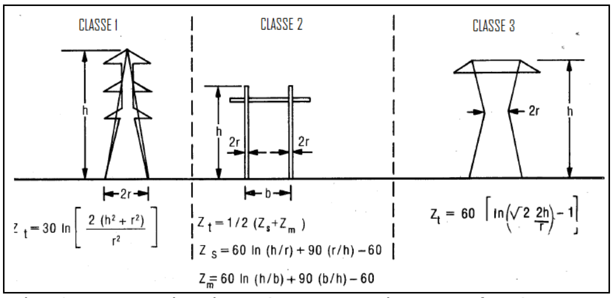

Fig. 2 – Approximations Surge Impedance Zt for Geometry Classes [6]

The tower geometry used in this study is similar to the towers of Class 1 and therefore to calculate the impedance of an outbreak, we used the following expression:

$$Z_t = 30\ln\left(2\frac{h^2 + r^2}{r^2}\right) \qquad (1)$$

Where:

- tower height (h) = 20.30 meters
- base radius (r) = 4 meters

The transit time (τ) is given by the total length of the tower divided by the speed of wave propagation through the body of the tower, given the speed of light, 300 m/ms.

2.3 Grounding

To model the grounding system of the transmission line under study, data regarding the characteristics of the soil and of the type of grounding used were considered.

The geographic region where the facility is located has a singular soil characteristics, with significant variations when compared to the characteristics of the region. So, was performed the measure of soil resistivity along the transmission line.

To this end, we used the method of Frank Werner, with probes spiked 0.30 meters depth. The standard used as a reference is the NBR 7117/1981.

The Figure 3 and Figure 4 shows a graph of the soil stratification and its diagram illustrating the values found in measurements.

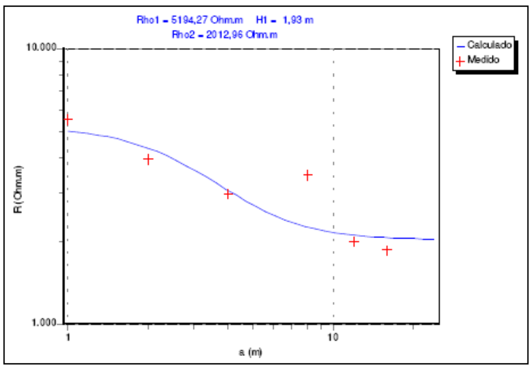

Figure. 2 – Soil Stratification Chart

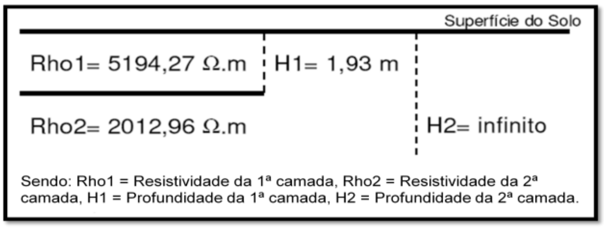

Figure 3 - Diagram of Soil Stratification in Two Layers

The grounding system used in the transmission line under study consists of four counter-weight cables formed by 5 mm galvanized wire.

The determination of the equivalent resistance of this configuration for modeling in PSCAD software, although simple, was not necessary, since there is the recent measurement of the impedance grounding of all the towers of the line under study.

The method used for measuring the grounding impedance was the DDP Method, with the current probe length of 100 meters. Standard 5410/1997.

The Figure 5 shows the values found and Figure 6 illustrates the measurements taken at the Tower 4.

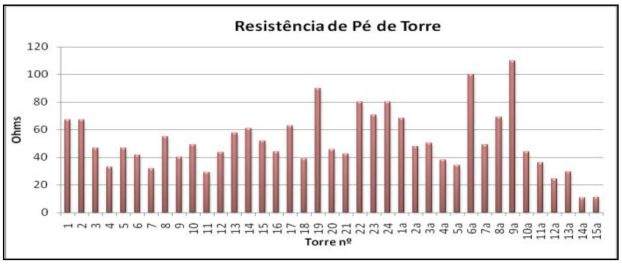

Fig. 4 – Ground Resistance Measurement

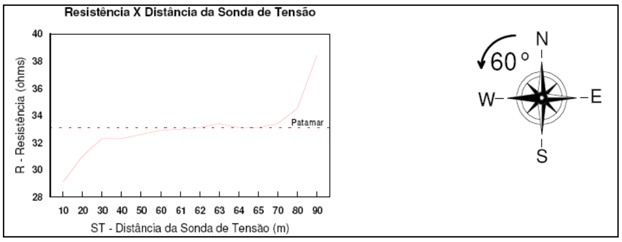

Fig. 5 – Result of Ground Impedance Measurement - Tower 4

2.4 Mechanical General Data

The designed minimum distance of the conductor to ground at 50 °C is 7 meters, the bays average is 250 meters and the maximum is 735 meters.

The power cables are the "Penguin", with following characteristics:

- Section: 107.2 mm^2;
- Training: 6/1 yarn;
- Breaking load: 3820 kgf;
- Weight: 0.4325 kg/m;

The grounding cable is made by galvanized steel, with the following characteristics:

- Section: 38.30 mm^2;
- Training: 7-wire;
- Breaking load: 3630 kgf;
- Weight: 0.305 Kg/m

The modeling was performed in PSCAD software from the block called "Universal Tower Line" that allows the manual entry of parameters of the line.

Thus, by the geometric tower distances, the mechanical properties reported in this item and data cables and grounding conductors, was created the model to the transmission line under study.

The Figure 7 shows the input data mask for transmission line in the PSCAD software.

Tower: S13 Tower Centre 0 [m]
Conductors: PENGUIM --> Ground_Wires: 5/16" Aço Galv. HS 7 fios

Cond. #	Connection Phasing #	X (from tower centre)	Y (at tower)	GW. #	Connection Phasing #	X (from tower centre)	Y (at tower)
1	2	-2 [m]	18 [m]	1	1	0 [m]	20.3 [m]
2	3	2 [m]	16.5 [m]				
3	4	-2 [m]	15 [m]				

Figure 6 – Input Data Mask for LT - SW PSCAD

The model used for the transmission line was "Frequency Dependent (Phase) Model." This model was chosen for providing with good accuracy, extensive simulations on a range of frequencies, thus meeting the requirements of results in simulations involving lightning strikes frequencies.

2.5 Circuit Simulations

The Figure 8 illustrates the circuit used in the simulations in the PSCAD software. Some considerations should be made to better understand the circuit and the simulation results.

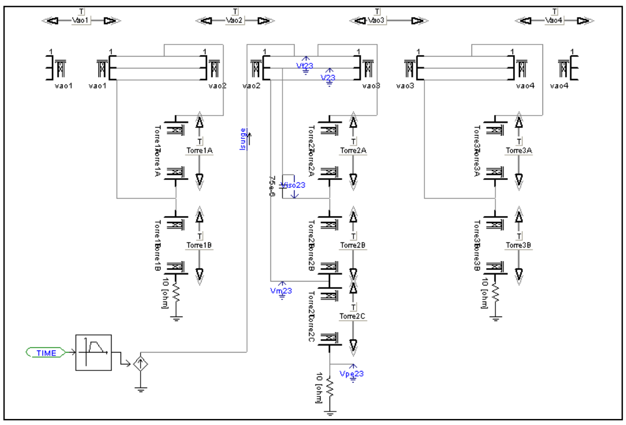

Figure 7 – Simulations Circuit

- The bays 1 and 4 were parameterized as of infinite length. Thus, the reflections in the towers after the surrounding towers of the discharge point, are not considered in the simulations;
- The towers will located between bays 1 and 2 and between bays 3 and 4 arel represented by two segments of transmission line. As the lengths of transmission line are input data manually, this feature allows the introduction of a second cable in the desired position along the length of the tower;
- The tower between bays 2 and 3 is represented by three segments of transmission lines. This is the point considered for injection of the lightning current and measurements os overvoltages at insulators. Therefore, this tower requires three connections.
- The resistance found in the last line segment of vertical transmission line of each tower represents the resistance of foot tower, remembering that the soil resistivity data are provided in the software by the transmission line input block.
- The resulting tension in the insulators is measured in the circuit, at the element V_{iso23}.

3 DESENVOLVIMENTO DEVELOPMENT

This chapter will show every step of the development work and their results. It is important to reinforce this point that this study, as in its purpose, aims to provide affordable engineering solutions to improve the performance of transmission lines.

Therefore, this chapter will begin by an investigative step, where some models have been tested until founding the best representation of the transmission line under study. Having defined the model line, the second stage is characterized by the insertion of the second grounding cable at the transmission line under study.

In this new configuration, some tests were carried out aiming the best position to fix the extra grounding wire.

Subsequently, comparative simulations from surges resulting in transmission lines insulators were initiated using extra grounding wire and using the traditional configuration, for different values of three parameters of great importance in studies of performance of transmission lines: ground resistance, bay between towers and the front time wave shape of discharge current. From various simulations with different parameter and considering the probabilistic nature of the discharge current, were calculated the odds of disruption of the insulation and then compared their results. The reduction achieved with the use of extra grounding wire has been crafted to be presented as a function of the grounding resistance.

The handling of this comparison led to an analytical expression that applied to the actual values of earth resistance, resulted in the actual reduction achieved with the use of extra grounding wire.

To better understand and visualize the sequence of work, Table 2 consolidates and titrate each stage of development.

TABLE 2
DEVELOPMENT STEPS

Etapa 1	-	*Models Tests*
Etapa 2	-	*Extra Grounding Wire Tests*
Etapa 3	-	*Comparative Simulations*
Etapa 4	-	*Disruption Probability*

3.1 Models Tests

In order to simplify the models managing in the PSCAD software, aiming to several changes in positioning of the extra grounding cables, phases cables and conventional grounding cables, it was decided to adopt a single-phase model to represent the transmission line, but which contained however, all data necessary for analysis proposals. The insulation of the phase located in the lower position of the tower is, between the three phases of the system, the insulation most required in a surge event. Thus, it is understood that a model where only the phase C of the transmission line under study was considered, was enough.

To ensure the decision to adopt the representation of a single phase, three-phase model was created with only one cable arrester, which was applied a current amplitude equal to 1kA with a 5μs front time wave. Its important to mention that the choice of this time value of wave front was only for better graphical display, since the same behavior can be found with the other time values used in front time wave simulations.

The Figure 9 and Figure 10 illustrate the behavior of the surge in the three phases and their insulations, respectively.

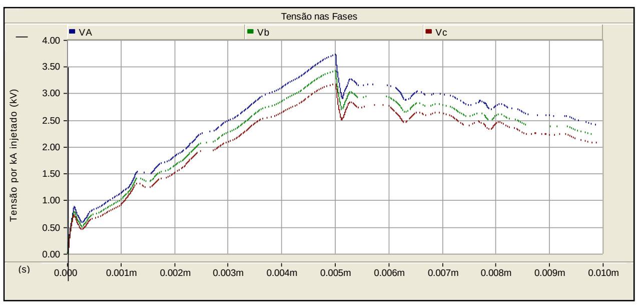

Figure 9 - Overvoltages phases for Injection 1kA with 5μs front time wave

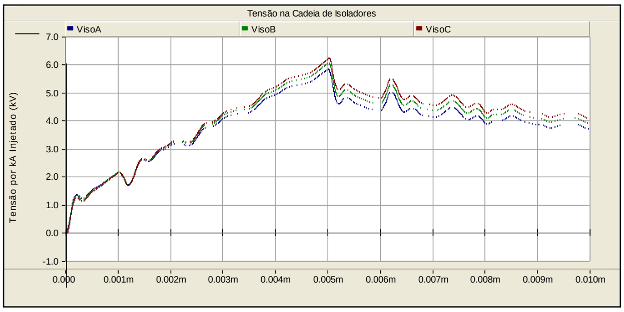

Figure 10 - Surge in insulation for Injection 1kA with 5μs front time wave

These curves confirm the request of insulation of phase C, positioned at the bottom of the tower, and thus validate the decision by the simplified model.

3.2 Extra Grounding Wire Tests

Defined as a basic model, it was possible to move to step considered crucial in the work development. The first results of these simulations led to the important decisions about the study development.

This step inserts the extra grounding wire in circuit simulation. Several models were tested, where basically, the difference was the point placement of extra grounding wire. To better understand and visualize the results will be presented three alternative positioning of the cable arrester extra.

1 - Above the phase C - 15.75 meters from the ground;
2 - Aligned with the phase C - 15.00 meters from the ground;
3 - Below the phase C - 12.70 meters from the ground.

This grouping of several alternatives simulated in just three, is sufficiently representative, as the results found within each of the three groups showed little variation. It is important to note that some positions were simulated for a investigative purposes only, where their practical applicability have obvious impediments.

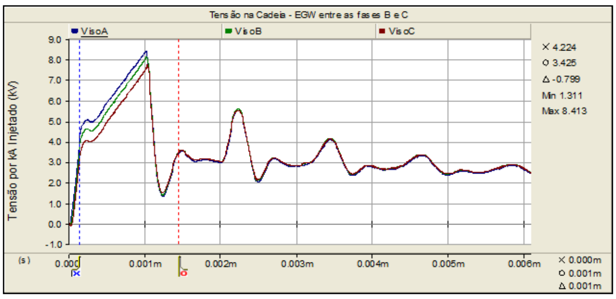

Figure 11 - Circuit-phase arrester cable with extra soil to 15.75 meters

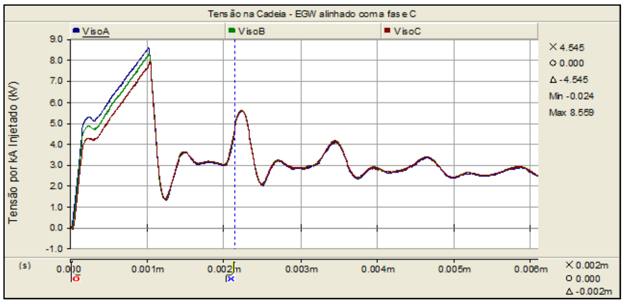

Figure 12 - Circuit-phase arrester cable with extra soil to 15.00 meters

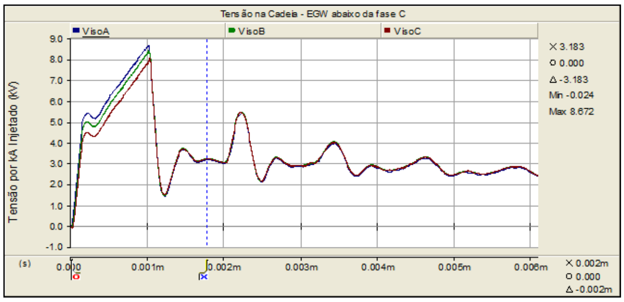

Figure 13 - Circuit-phase arrester cable with extra soil to 12.70 meters

The alternative adopted to continue the study was the first alternative. Importantly to relate that the difference found between the adopted alternative and the alternative with lower value of overvoltage is relatively small, 8.413 kV at alternative 1 and 8.671 kV at alternative 3, which reinforces the decision for an alternative 1 to continuing the work.

3.3 Comparative Simulations

Once defined the configuration to be adopted during the study, the simulations initiated could provide a comparison of results obtained using the extra grounding wire and performance results of a traditional configuration transmission line.

Two assumptions need to be mentioned, were considered only anchor chains to determine the connection point of extra grounding wire. The distance between the grounding cable and phase A, located at the top of the tower has also been applied to the distance between the phase C, located at the bottom and the extra grounding wire.

In this step, start to be simulated changes in the parameters of transmission lines. Simulations were conducted for three different values of foot tower resistance, three different values of bay length and three different front wave time values. The Table 3 summarizes these alternatives and their combinations that are presented in the graphs below.

TABLE 3
VARIATIONS IN LINE PARAMETERS FOR SIMULATION

R (Ω)	*t_f (μs)*	*L (m)*
10	1	150
50	2	250
100	5	350

Seen in Figure 14, there is no linear relationship between reductions in stress values with the variation of some parameters. As might be expected, the resistance variation of foot tower is more relevant impact on the results of voltage variation when compared to the bay length or the front wave time.

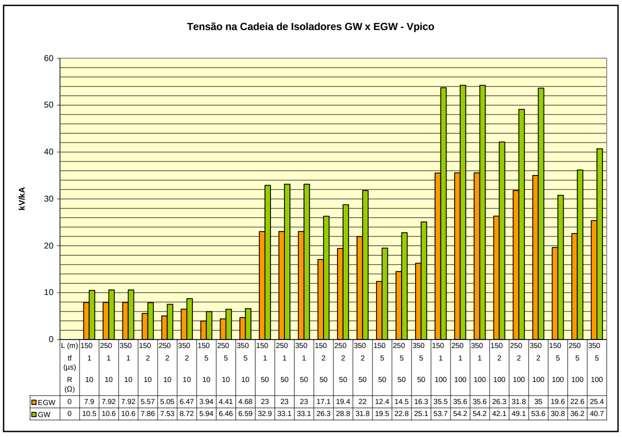

Figure 14 - Voltage Peak Values

The Figure 15 considers the fixed time of the front wave in 5μs, and varies the other two parameters. Note that the influence of the bay length is almost the same, where the effective reduction of overvoltage is maintained close to 36% for foot tower resistance values above 50Ω.

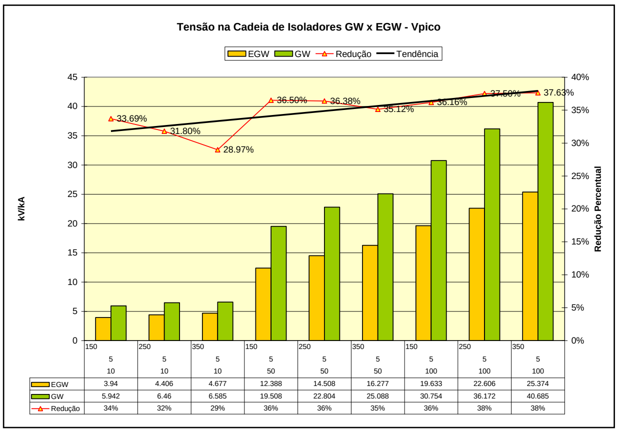

Figure 15 - Comparative Results - Time Front Wave Fixed in 5μs

In Figure 16 the bay length is fixed in 250 meters. Note the clearly influence of front wave time on the peak voltage results.

It is interesting to note that for all variable parameters the influence the foot tower resistance is predominant. The relationship between the three peak voltage values obtained for the three front wave times the when the foot tower resistance is low is different than this same ratio when the foot tower resistance is high. The mean relative reduction between the two settings for 10Ω, 50Ω, 100Ω foot tower resistance varying the others parameters are 29%, 33% and 36% respectively.

The relative overvoltage reduction in insulators is higher for higher values of foot of the tower resistance.

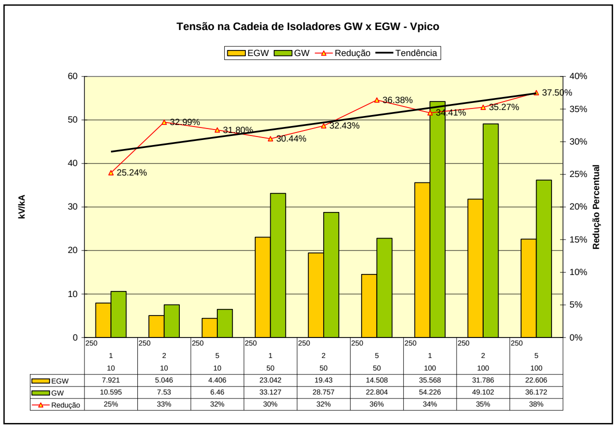

Figure 16 - Comparative Results - Fixed Bay Length Values

3.4 Probability of Disruption

In this step of work, were chosen to apply a statistical analysis of the results obtained previously. It is intended with this alternative, to convert the voltage values resulting at insulators found in the simulations at values related to performance of the transmission line face lightning currents.

Based on measurements, Anderson and Ericksson [21] formulated the expression (2) to determine the probability of a peak current at any atmospheric discharge exceeds the critical current discharge. It's important to report that this equation is an approximation, but has reasonable accuracy for discharge currents between 5 and 200kA.

$$P_1 = \frac{1}{1+\left(\frac{I}{31}\right)^{2,6}} \qquad (2)$$

Thus, the probabilities were calculated for all simulated cases. The results are shown in Figure 17, which compares the odds of failure by backflashover, with and without extra grounding wire.

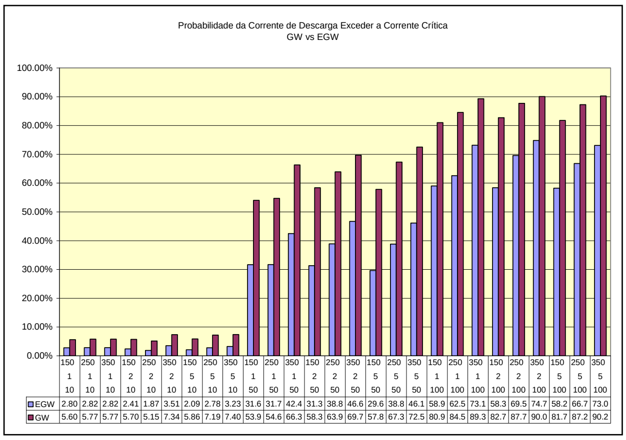

Figure 17 – Probability of Discharge Current Exceed the Critical Current

These values give us a more quantitative overview about benefits achieved with the implementation of this alternative.

The Figure 18 shows the relative reduction between EGW and GW, of the probability of failure by back flashover. Note that this decrease reach approximately 65%, ranging to about 15%, depending on the combination of simulated parameters.

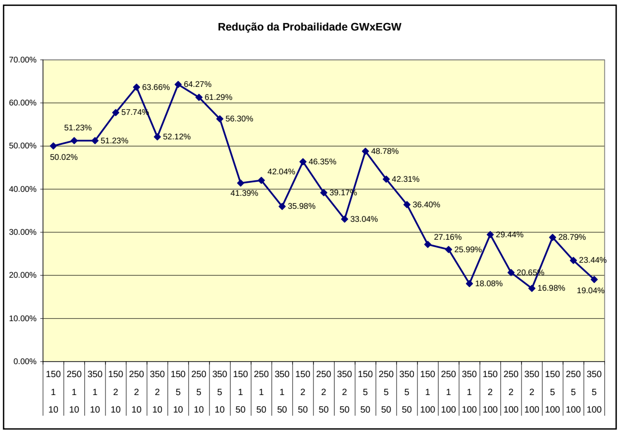

Figure 18 - Reduction of Failure Probability with the Application of EGW

The Figure 18 reinforces a clear influence and with significant impact about the foot tower resistance. This relationship has brought an interesting perspective to the work. The determination of an expression that relates the performance improvement of the transmission line under study with the application of the EGW, depending on foot tower resistance values, brings a more tangible measurement of work results.

This quantification is possible, once in possession of this expression, applying the real values of the foot tower resistance of transmission line under study, it will generate a value that represents the reduction in back flashover failure probability with the insertion of extra grounding wire for each tower of the transmission line under study.

Thus it was necessary then, work on this relationship shown in Figure 19, so that, from this curve was created the expression (3), discussed above and presented below.

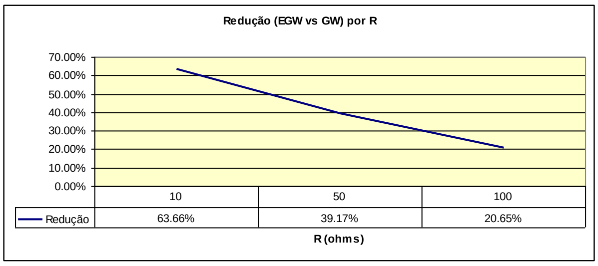

Figure 19 - Reduction EGW vs GW as a Function of Foot Tower Resistance

$$f(R) = 0{,}027 \cdot R^2 - 0{,}77 \cdot R + 71 \qquad (3)$$

At this point of the work, is showed the expression that relates the performance of the transmission line with foot tower resistance.

Using the foot tower resistance measurement of transmission line under study, one can find a profile of improvement in the performance of this transmission line, applying the solution advocated in this work.

In possession of the measured values of grounding resistance of all the towers of the transmission line under study, presented in Figure 5, is then, designed the graph shown in Figure 20.

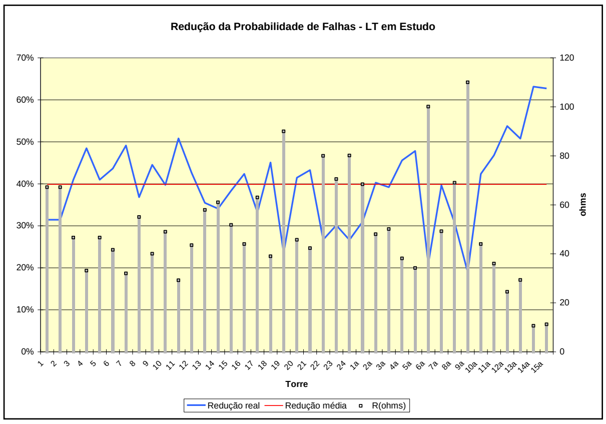

Figure 20 - Reducing the Probability of Failure as a Function of R (ohms) - LT Study

As expected, the reduction achieved with the use of EGW, has close links with the foot tower resistance. Note that for low values of the foot tower resistance, as the 14th and 15th towers, the reduction reaches values of 63%, while for high values of foot tower resistance, we have reductions of about 20% shown in the 10th tower.

4 CONCLUSION

This study proposed an alternative for improving performance in transmission lines, face to lightning events, obtaining satisfactory results both as regards the effectiveness of the proposed technique for their viability against other techniques for the same purpose.

The use of a extra grounding cable under the phase cables of a transmission line was highly effective in reducing the overvoltage values in the insulators, caused by back flashover. In the transmission line under study were achieved reduction values up to 63%, which is hardly achieved with conventional techniques of performance improvement as grounding or isolation level improvement techniques. It is also an excellent result in terms of return of investment, since the implementation of this solution is relatively simple, does not require large investments and can be performed without major disruptions in energy supply.

Another important point is the presentation of the relationship between the reduction in BFO failure probability as a function of foot tower resistance. As mentioned in the preceding paragraph, were found reductions on failure probability ranging from 20% to 63%, indicating that depending on the value of the foot tower resistance, the effectiveness of the solution can pass through a combination of techniques. Soil treatment, improved grounding connection, use of grading rings, or even the installation of lightning arresters on specific towers are some of them that associated to EGW technique could even achieve better results.

Besides this information, the paper presents interesting relationships to reduce the probability of failure by BFO according to other parameters, namely, the bay length and front wave time. In both cases, there is a lower probability of failure.

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