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Intelligent Expert System for Protection Optimization Purposes in Electric Power Distribution Systems

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1. Introduction

The objective of this chapter consists of presenting an expert system that assists the procedures involved with the protection specification of transformers and equipments against atmospheric discharges, allowing also to analyze in a detailed and systematic way the behavior of the respective voltage transients that are generated at the supplying area.

For such purpose, the expert system developed makes efficient integration of approaches and techniques that take into account the characteristic aspects of the atmospheric discharges, the experimental analyses that represent the phenomenon and the mathematical models that allow to map the process involved with the formation of the lightning.

The results obtained from the experimental application of the expert system have contributed in a substantial way to optimize the processes involved with the efficient specification of protection devices associated with the transformers and equipments of the distribution system.

The decision process taken into account by the expert system is based on information provided by the software "SimSurto", which was especially developed to simulate the voltage transients caused by atmospheric discharges in distribution lines, and its objective is the computation of several parameters related to the respective transients, considering the equipments already installed, the geographical location of the distribution line and the respective incidence of atmospheric discharges in the distribution system.

The use of the developed tool has allowed the optimized specification for protection devices of equipments and transformers belonging to distribution system, enabling that differentiated protection strategies can be applied according to the particularities of each

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region, contributing then for value aggregation to services provided by the distribution company, since the available tools proportionate more optimized analyses in relation to the procedures involved with the protection specification.

Therefore, in this chapter, the particularities for estimation of induced voltages in real distribution networks, such as the network discontinuity, the phase conductor arrangement, the intrinsic characteristics of the incident atmospheric discharges in each region of the considered distribution system, are taken into account by the expert system. Performance evaluations indicate that the expert system provides coherent results and its practical application contributes to optimize the processes involved with parameters specification related to the protection of equipments and transformers.

For such purpose, this paper is organized as follows. In Section 2, a brief summary about induced voltage estimation techniques are presented. In Section 3, the achieved modifications in relation to the conventional techniques are introduced in order to produce a greater accuracy when compared to the results obtained from real situations. The expert system for protection specification against atmospheric discharges, named by Protection Plus, is briefly described in Section 4. The expert system for optimized design of grounding systems is presented in Section 5. Finally, in Section 6, the key issues raised in the paper are summarized and conclusions are drawn.

2. Rusck's conventional model for induced voltage estimation in overhead distribution lines

In this section the main aspects concerning to Rusck's methodology for induced voltage estimation in distribution lines caused by atmospheric discharges are presented.

Therefore, it is achieved a general study regarding induced voltage estimation in distribution lines through use of conventional methods discussed in the technical literature.

Although the methodology originally developed in Rusck (1957) has some limitations to areas with soil resistivity less than $100 \Omega\text{m}$, it is still widely used for induced voltage estimation in overhead distribution and transmission lines generated from indirect atmospheric discharges occurred near to the respective line.

The induced voltage estimation methodology presented in Rusck (1957) has as start point the modeling of the return current imposed by the atmospheric discharge in the distribution line. Rusck's method calculates the electric field generated by this return current in the ground surface and, from this electric field and from the line multi-wire arrangement, the theory provides the resultant values of induced voltages along the distribution line.

In Rubinstein & Uman (1989) is mathematically demonstrated that the studies presented in Rusck (1957) for resultant electric field computation of return current is correct. This fact has contributed to increase the reliability in relation to method developed by Rusck. Other additional procedures involved with models for induced voltage are also found in Cooray (2003).

An existent question related to this theory is that it estimates induced voltage values for conductors of a multi-wire line taking just into account the conductor geometric

localization in relation to incidence point of the atmospheric discharge, that is, the induced voltage values produced in a line composed by several conductors of same height and with a small horizontal spacing, such as in distribution lines, would be equal in each conductor.

Measurements achieved with the reduced model technique (Paula et al., 2001; Salari & Portela, 2007), as well as measurements in fields made in South Africa, demonstrate that the results provided by Rusck's theory is coherent with those obtained by experimental results (Eriksson et al., 1982). Originally, Rusck proposed a current wave to the atmospheric discharge represented by a step function with amplitude I . The induced voltage produced by this discharge in relation to an infinite line can be computed by:

$$V(x,t) = U(x,t) + U(-x,t) \quad (1)$$

where:

$$U(x,t) = 30 \cdot I \cdot h \cdot \beta \cdot \frac{(c \cdot t - x)}{[y^2 + \beta^2 (c \cdot t - x)^2]} \cdot \left(1 + \frac{x + \beta^2 (c \cdot t - x)}{\sqrt{(\beta \cdot c \cdot t)^2 + (1 - \beta^2)(x^2 + y^2)}}\right) \quad (2)$$

$$\beta = \frac{v}{c} \approx \sqrt{\frac{1}{1 + \frac{5 \cdot 10^5}{I}}} \quad (3)$$

In this case, $V(x,t)$ is the induced voltage (V) at a point x of the line; t is the time in seconds; c is the velocity of light in free space (m/s); I is the return-peak current value (A); h is the average height of the distribution line; y is the closest distance between the discharge incidence point and the distribution line (m) and x is a point along the line (m).

Equations (1), (2) and (3) express Rusck's theory basis. In (4) the expression for the maximum induced voltage at the point $x=0m$ is given by:

$$V_{\max} \approx \frac{38.8 \cdot I \cdot h}{y} \quad (4)$$

From the previous expressions is possible to identify that they provide an analytic form for the computation of induced voltage in a distribution line, whereas other existent theories provide just iterative expressions that have high computational effort to perform the same estimation.

In Fig. 1 is presented the induced voltage at the point $x=0m$ for an atmospheric discharge represented by a step function with amplitude $I=10$ kA in relation to an infinite line with 10 meters of height, where the distance between the atmospheric discharge from the distribution line is 100 meters.

In order to illustrate how the proposed formulation in this section is efficient for induced voltage estimation in overhead distribution lines, the induced voltage profile for different positions along the distribution line is presented in Fig. 2.

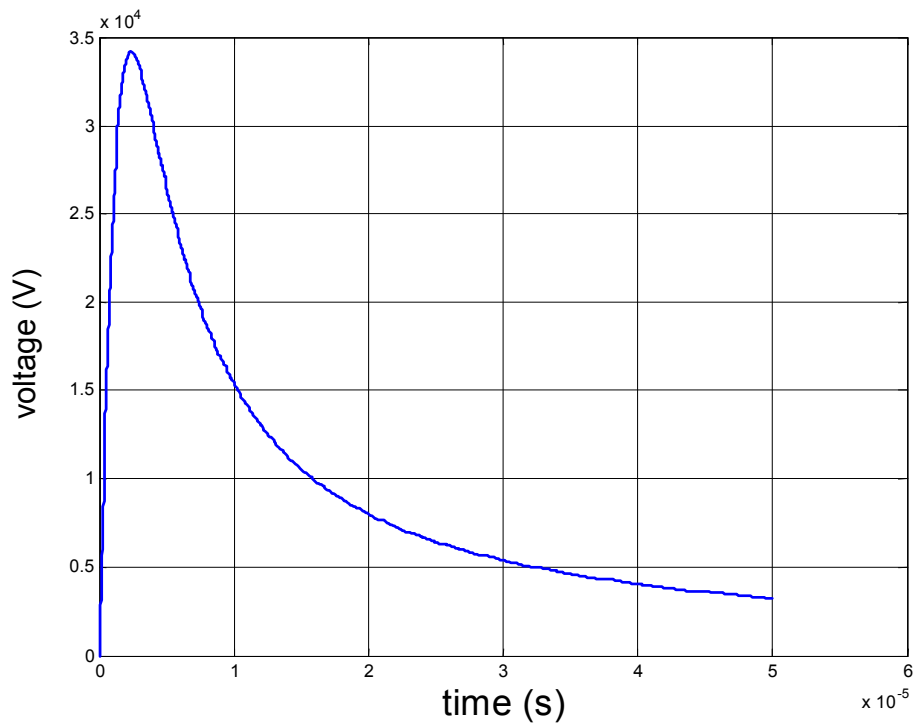


Fig. 1. Induced voltage in relation to the maximum voltage point in infinite line with 10m of height and atmospheric discharge of 10kA in perpendicular distance of 100m from the line.

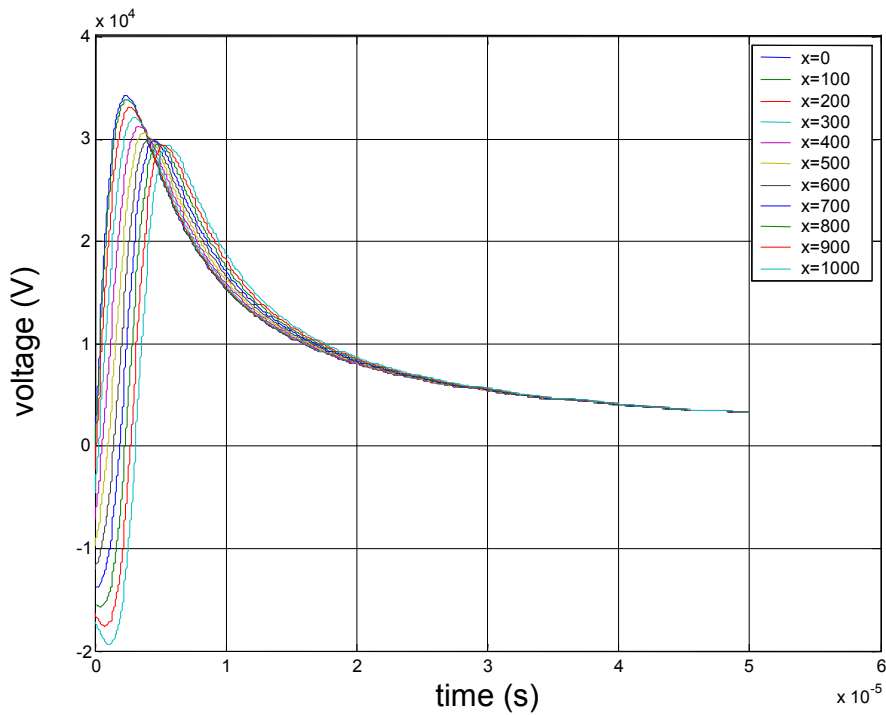


Fig. 2. Induced voltages in infinite distribution line with 10m of height and atmospheric discharge of 10kA in perpendicular distance of 100m from the line in relation to several points along the line.

It is observed from Fig. 2 that the induced voltage waveform modifies in relation to the distance between the maximum voltage point and the measurement point. The alterations in the induced voltage waveforms along the distribution line can be better verified through their parameters, such as maximum induced voltage, rising time, peak time and half-wave time.

For comparative effects, it is assumed as rising time that necessary time for the voltage wavefront to reach 90% of its maximum value, considering half-wave time as that necessary time for the voltage wavefront to reach 50% of peak value after the occurrence of its maximum value. Therefore, Fig. 3 to 6 presents how these parameters are altered in relation to the distance between the maximum voltage point and a point along this conductor.

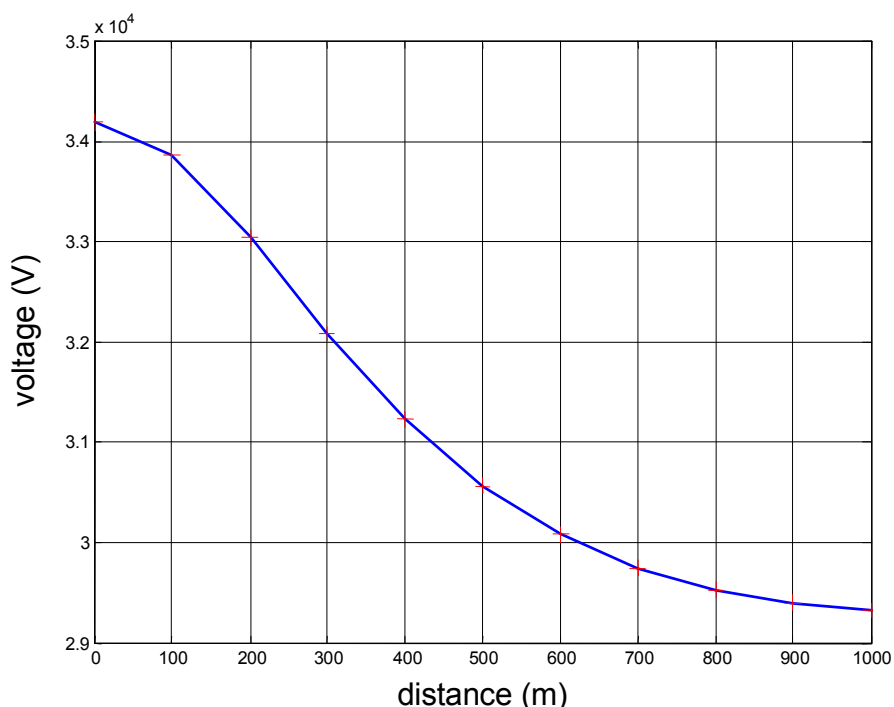


Fig. 3. Maximum induced voltage variation along the line.

From Fig. 3, it is observed that the voltage along the line length reduces at a rate practically linear in relation to the distance from the atmospheric discharge occurrence point. This observation indicates that the voltage wave along the distribution line suffers an attenuation generated from high frequencies involved with the propagation process as well as from energy dissipation in relation to the metallic conductors.

Figs. 4 to 6 illustrate how rising time, peak time and half-wave time alter along the distribution line. We can certify that these three parameters tend to increase at a rate practically constant along the distribution line.

This fact indicates that the voltage waveform loses energy in relation to the distance along the line since that rising time, peak time and half-wave time higher cause voltage gradients more smooth along the line.

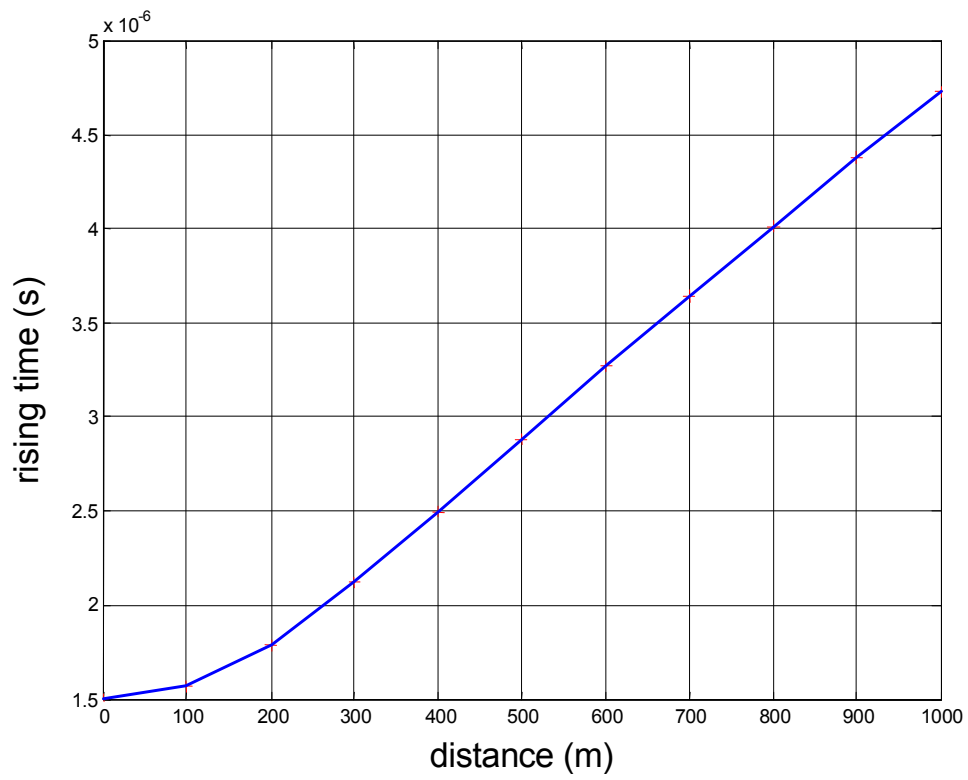


Fig. 4. Rising time variation along the distribution line.

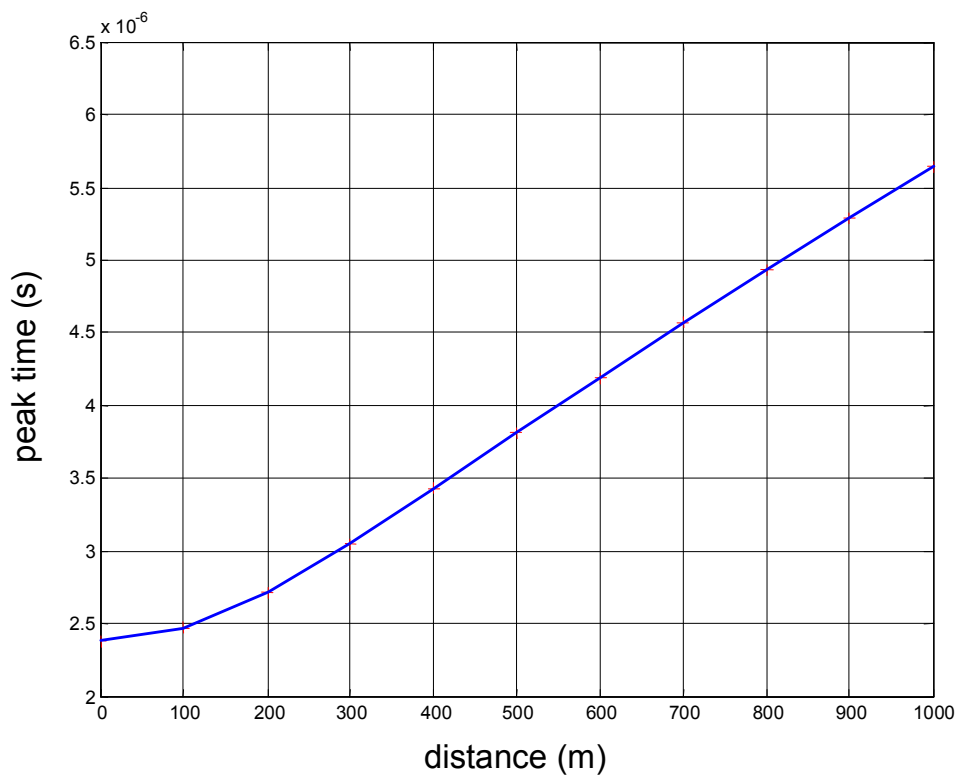


Fig. 5. Peak time variation along the distribution line.

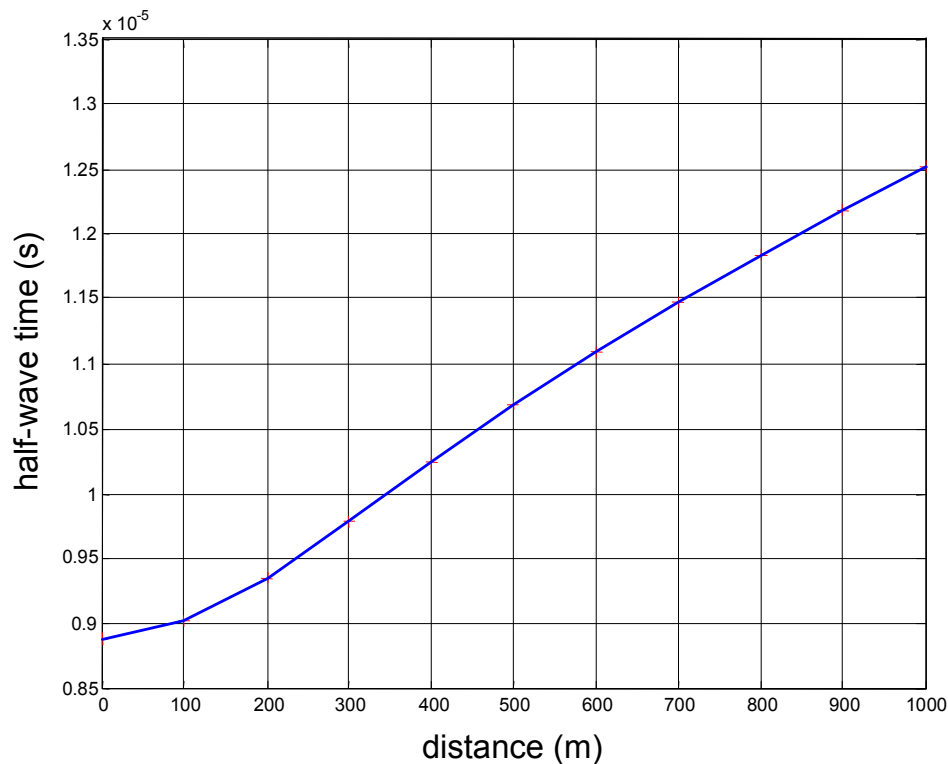


Fig. 6. Half-wave time variation along the distribution line.

From simulations accomplished and presented in this section and taking also into account the formulation proposed in Rusck (1957), it is verified that the obtained results by Rusck's method are coherent with those obtained through field experiments (Eriksson et al., 1982) or even with those results produced using reduced model techniques (Paula et al., 2001; Salari & Portela, 2007).

However, some modifications in this method are necessary in order to transpose this methodology to practical situations involved with real distribution systems. Basically, it is necessary the consideration of current waveforms for the atmospheric discharge similar to those found in the nature. It is needed due to the atmospheric discharge characteristics considered in Rusck's method.

As presented at the beginning of this section, the waveform for the atmospheric discharge current used in Rusck's methodology has been a step function. In the next section, the necessary modifications in the approach proposed in Rusck (1957) are conducted in order to complement the existent theory, becoming it appropriate for practical applications.

Other works involving practical extension of Rusck's formula for maximum lightning-induced voltages that accounts for ground resistivity and improved procedures for the assessment of overhead line indirect lightning performance can also be found in Darveniza (2007) and Borghetti et al. (2007).

3. Modification of the conventional theory for induced voltage estimation in practical applications

3.1 Generalization of rusck's methodology for generic discharge current waveform

Rusck's formulation presupposes that the atmospheric discharge can be represented by a waveform represented by a step function. However, measurements achieved in field have evidenced that the current waveform characteristics influence in the induced voltage in distribution lines located nearby the discharge occurrence point.

More specifically, parameters such as rising time and current waveform peak time have high correlation with the voltage induction process in distribution lines. Therefore, it is suggested that the induced voltage estimation in distribution lines to be achieved considering a waveform for discharge current near to that found in nature.

An approach often adopted for the atmospheric discharge current modeling can be provided as in (5), that is:

$$i(t) = i_{h1}(t) + i_{h2}(t) + i_{de}(t) \quad (5)$$

where:

$$i_{hm}(t) = \frac{I_{0m}}{\eta_m} \frac{\left(\frac{t}{\tau_{m1}}\right)^{nm}}{1 + \left(\frac{t}{\tau_{m1}}\right)^{nm}} \exp\left(-\frac{t}{\tau_{m2}}\right) \quad (6)$$

$$i_{de}(t) = [(1 - \exp(\alpha)) - (1 - \exp(\beta))] \quad (7)$$

and:

$$\eta_m = \exp\left[-\left(\frac{\tau_{m1}}{\tau_{m2}}\right) \cdot \left(nm \frac{\tau_{m2}}{\tau_{m1}}\right)^{\frac{1}{nm}}\right] \quad (8)$$

Equation (6) is an example of Heidler's functions. An alternative frequently employed in atmospheric discharge modeling is double exponential.

Nevertheless, the modeling through two Heidler's function, as presented in (5), provides a more appropriate approximation for representation of the real phenomenon since the derivative of current at the instant $t=0s$ is null. This fact is proved by innumerous practical cases.

In Fig. 7 is illustrated the current waveform results from modeling presented in this section, where the current has a peak value near to 12kA with a time of $0,81 \times 10^{-6}$ s.

Supposing that the system to be linear, it is possible the use of Duhamel's integral (Greenwood, 1992) in order to represent the current waveform through a successive series of

steps. Thus, the value of each one of them, which represent the current waveform presented in Fig. 7, can be provided as shown in Fig. 8.

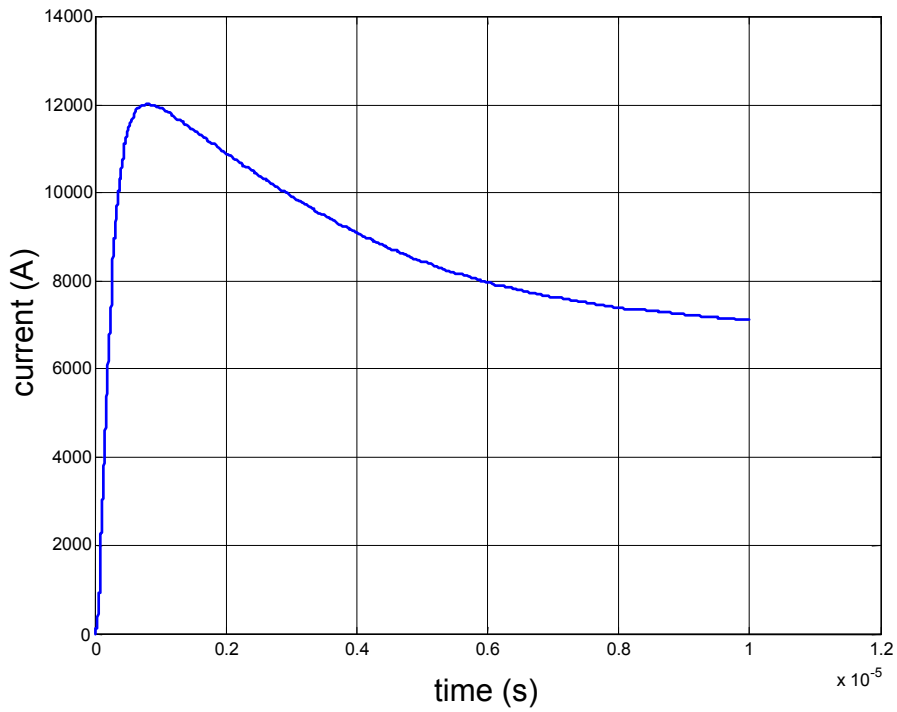


Fig. 7. Current waveform for atmospheric discharge modeling.

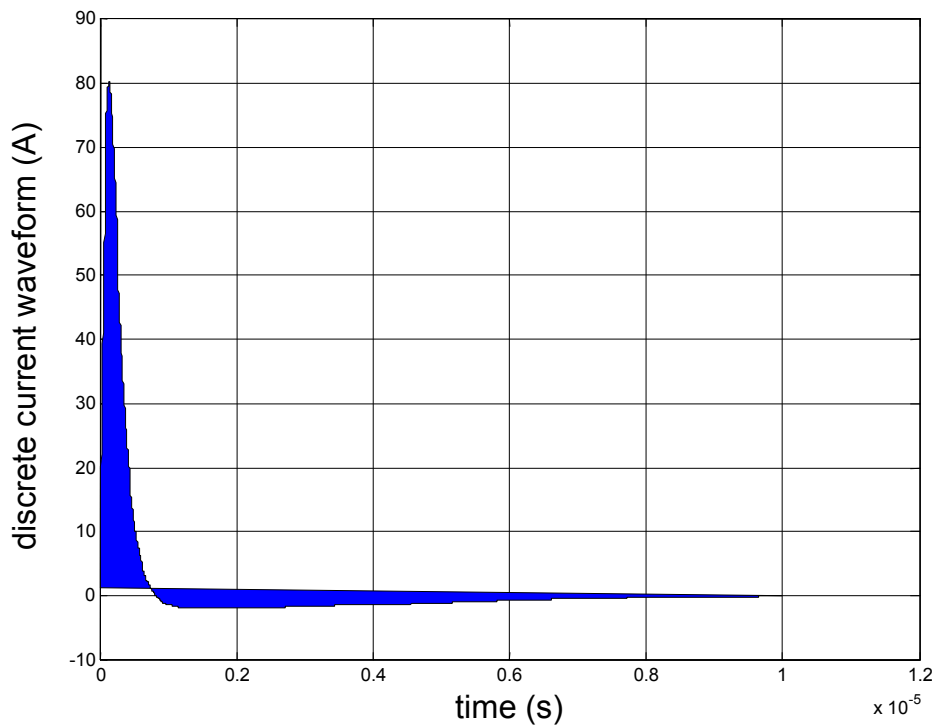


Fig. 8. Discrete current waveform composed by steps.

From this modification, the induced voltage at any point x in the distribution line can be given by the sum of individual contribution in relation to each discrete current component.

Supposing an atmospheric discharge characterized as in Fig. 7, occurring in a distance of 100m from infinite distribution line with 10m of height, the voltage waveform at the point $x=0$ m (point of maximum voltage value) can be represented as in Fig. 9.

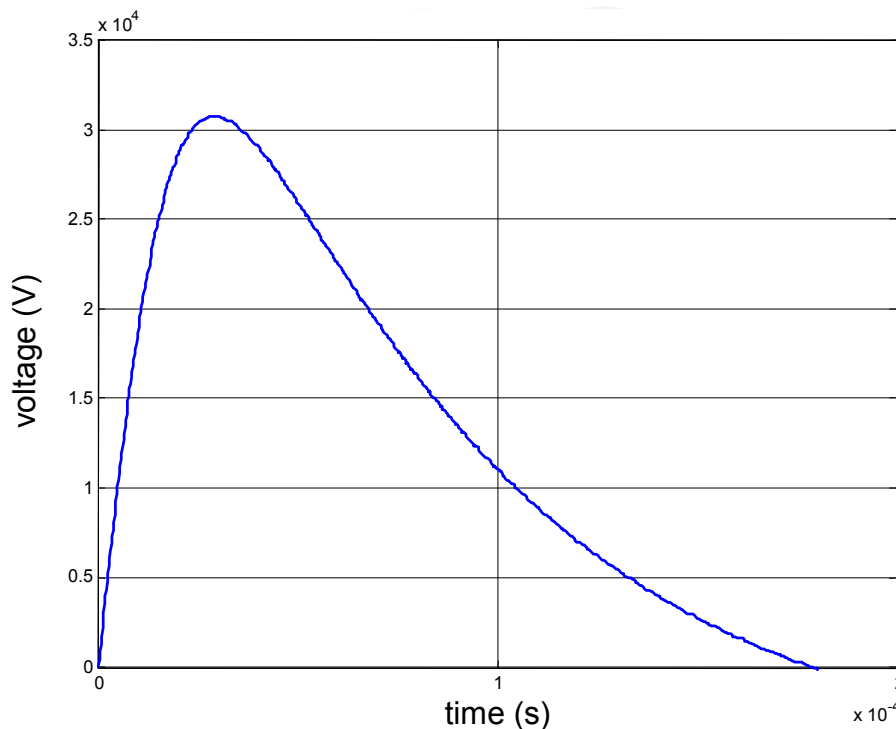


Fig. 9. Induced voltage at the point of maximum voltage value for a current waveform expressed in terms of Heidler's function.

3.2 Considerations for induced voltage estimation in finite lines

Rusck's expression for induced voltage calculation in distribution lines is composed of two parcels, which can be observed through the following equation:

$$V(x_0, t) = U(x_0, t) + U(-x_0, t) \quad (9)$$

where $V(x_0, t)$ is the induced voltage at the point x of the line; $U(x_0, t)$ is the induced voltage component due to the load contribution located at the right part of this point and $U(-x_0, t)$ is the induced voltage component due to the load contribution located at the left part of x_0 .

In Fig. 10 is presented the interpretation of induced voltage proposed in the formulation suggested by Rusck.

In case of a finite line, some modifications in Rusck's theory must be incorporated in order to enable that the induced voltage estimation in any point of the distribution line to be modeled adequately according to real situations.

Hence, we assume a line with termination in x_1 with impedance of termination R_f as indicated in Fig. 11.

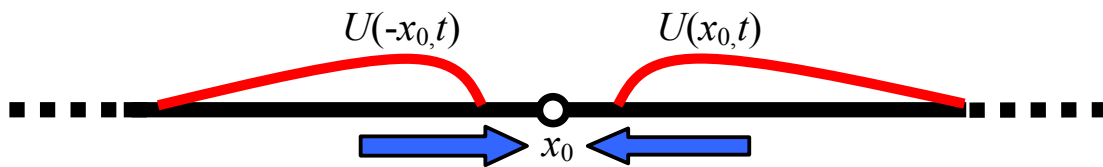


Fig. 10. Induced voltage composition at the point x_0 of the line.

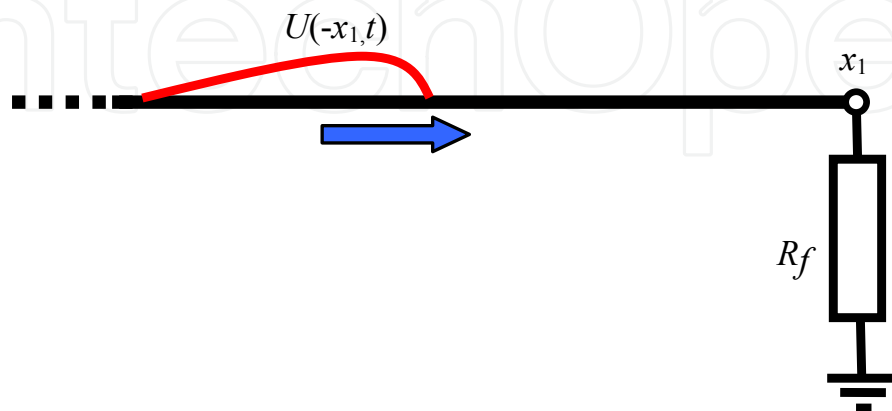


Fig. 11. Induced voltage in a finite line.

If the line was infinite, the voltage at the point x_1 would be given by:

$$V(x_1, t) = U(x_1, t) + U(-x_1, t) \quad (10)$$

As there is no line located at the right part of the point x_1 , there is no contribution of loads coming from the right of x_1 , that is, the voltage contribution $U(x_1, t)$ is null. As the line has termination impedance, the voltage at the point x_1 can be computed as follows:

$$V(x_1, t) = U(-x_1, t) + \Gamma U(-x_1, t) \quad (11)$$

where Γ is the reflection coefficient. The expression to obtain Γ is given by:

$$\Gamma = \frac{R_f - |Z_L|}{R_f + |Z_L|} \quad (12)$$

where Z_L is the characteristic impedance of the distribution line. The numeric value for Z_L is provided by:

$$Z_L = 138 \cdot \log\left(2 \frac{h}{r}\right) \quad (13)$$

where h is the height of the distribution line and r is the conductor diameter.

Supposing that the discontinuity at the point x_1 to be substituted by a compensation source, the value of this source can be computed according to the following development:

$$V(x_1, t) + \Delta V = U(-x_1, t) + \Gamma U(-x_1, t) \quad (14)$$

$$U(x_1, t) + U(-x_1, t) + \Delta V = U(-x_1, t) + \Gamma U(-x_1, t) \quad (15)$$

$$\Delta V = \Gamma U(-x_1, t) - U(x_1, t) \quad (16)$$

The compensation source of value ΔV is applied in the point x_1 , but its effect must be propagated throughout the line, since the non existence of line in the right of x_1 alters the induced voltage values along whole line.

In order to compute the voltage at any point x , we can sum the induced voltage computed for the point x , assuming an infinite line, to the value of the compensation source applied in x_1 .

However, the compensation source located at x_1 suffers a time delay during the trajectory between x and x_1 , that is:

$$V(x, t) = U(x, t) + U(-x, t) + [\Gamma U(-x_1, t) - U(x_1, t)]u(t - t_f) \quad (17)$$

The function $u(t - t_f)$ is a unit step function and t_f is the travel time between the point x and x_1 , i.e.:

$$t_f = \frac{|x - x_1|}{v_0} \quad (18)$$

where v_0 is the propagation velocity, which for the simulations in question will be assumed as being equal to the velocity of light.

The same procedure can be achieved supposing a discontinuity at the left of x . Then, assuming a finite line, with the origin at the point x_0 and termination in x_f , the induced voltage at a point x along the distribution line can be estimated according to the following expression:

$$V(x, t) = U(x, t) + U(-x, t) + [\Gamma_f U(-x_f, t) - U(x_f, t)] \cdot u(t - t_f) + \dots \\ \dots + [\Gamma_0 U(x_0, t) - U(-x_0, t)] \cdot u(t - t_0) \quad (19)$$

The replacement of the line discontinuity effect by a voltage compensation source is an effective procedure, mainly when is desired to produce computational algorithms.

4. Expert system for specification of transformers and equipments protection against atmospheric discharges

The expert system proposed in this work, which was developed in order to help in the arresters specification for equipments and distribution transformer protection, has its implementation aspects based on the studies about induced voltages presented in previous sections. Besides using those suggested modifications, the expert system incorporates in a integrated way the databases referent to equipments installed on the distribution lines of Bandeirante Energy, as well as the databases involved with arresters and atmospheric discharge characteristics incident in its concession region.

Therefore, the transformers and equipments protection designs, through this expert system, consider the induced voltage in distribution line where the transformer is installed, the distribution network topology, as well as the atmospheric discharge characteristics of the region.

As the system operates through these databases, before the specification of a determined design, it is necessary that each one of the system elements to be adequately registered. Then, it is presented in Fig. 12, the transformer registration window adequately filled for a distribution transformer of 75kVA.

Distribution transformer

Transformer identification

Code 001

Manufacturer WEG

Model WEG - 75kVA

Observations Distribution transformer

Technical specification

Type Trifase
 Monofase

Nominal power (kVA) 75

Operational voltage (kV) 13,8

BIL (full wave) (kV) 115

BIL (cut wave) (kV) 95

Default values

Renew Save as new Save Cancel

Fig. 12. Transformer registration window.

After registration of each component of the electric system, inclusively of the arresters, the protection design can be registered. Fig. 13 illustrates the project registration window, as well as it emphasizes the preliminary results of simulations.

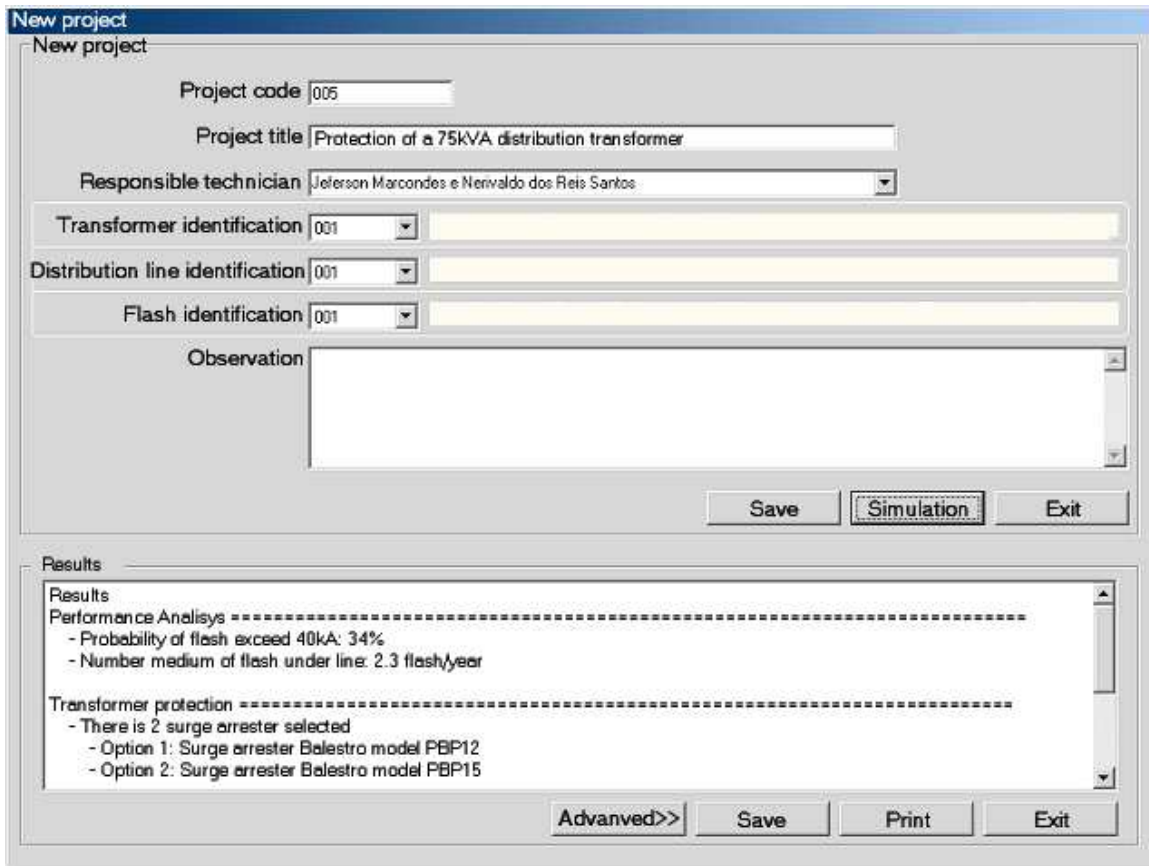


Fig. 13. Project registration window presenting preliminary results.

Fig. 14 presents the window where indicates how each selected arrester can be also employed for protection of distribution network nearby the transformer.

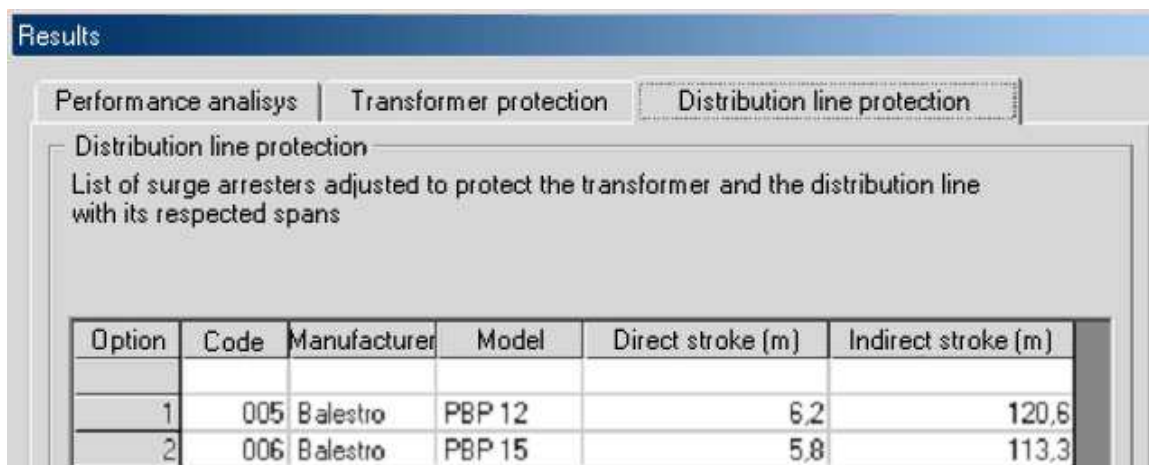


Fig. 14. Window indicating installation distance between arresters aiming the distribution line protection against atmospheric discharges.

5. Expert system for optimized design of grounding systems

Other expert system treated in this chapter involves the creation of a computational platform that helps in the specification and decision making regarding the optimized design of grounding systems, which must take into account the particularities of the distribution system under consideration, such as extension of the network, installed equipment and even the performance requirements expected for such system.

However, the effects of lightning should still be considered, since the voltages induced on the line are higher than those where the surge arresters operate, which imply in current flowing to ground.

Thus, analyzing in terms of optimizing the grounding system, the best arrangement must be defined according to the desired type of grounding, which is characterized as a problem of structural optimization. Furthermore, it is of fundamental importance to determine the parameters of the chosen arrangement, such as distance, depth, number of stems etc. The search of these variables characterizes a parametric adjustment problem, whose objective is to determine a grounding system where impedance, and not resistance, is minimal.

A representation of the operation of the expert system for optimization of grounding design can be seen in Fig. 15.

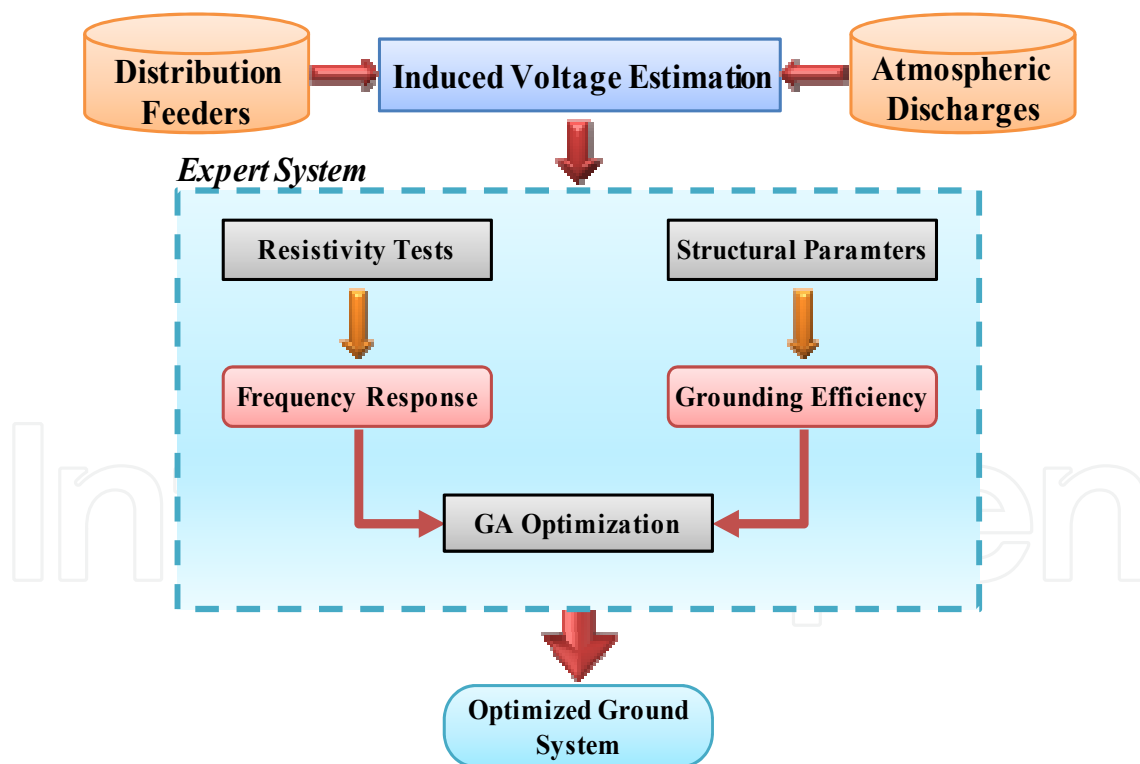


Fig. 15. Diagram representing the expert system for optimized design of grounding systems.

The efficiency of the grounding system must be checked every iteration of the optimization process with the purpose of verifying how the parametric and structural adjustments are improving it.

Thus, at the end of the process, the result should be an optimized grounding system. To evaluate this, the electrical parameters of the grounding system will be initially estimated, taking into account its own structural parameters, such as number of stems, distance between them and their depths.

Once the electrical parameters of the grounding system are known, the characteristic impedance of the grounding can then be calculated. This characteristic impedance is a value that allows relating the propagation of voltage induced by the distribution system to the propagation by the grounding system. To relate both modes of propagation, it is necessary to consider the electrical data of the feeder.

Once the parameters to model the distribution system at high frequencies are known, as well as the characteristic impedance of the grounding system, it is then possible to conduct simulations to verify impulsive voltage in the system.

To illustrate this evaluation procedure, a feeder in which the grounding system is not optimally implemented will be considered. This feeder belongs to the substation BIR of EDP Bandeirante. The induced voltage in the distribution system was calculated by assuming standard data for the lightning. The temporal behavior of the induced voltages is presented in Figure 16.

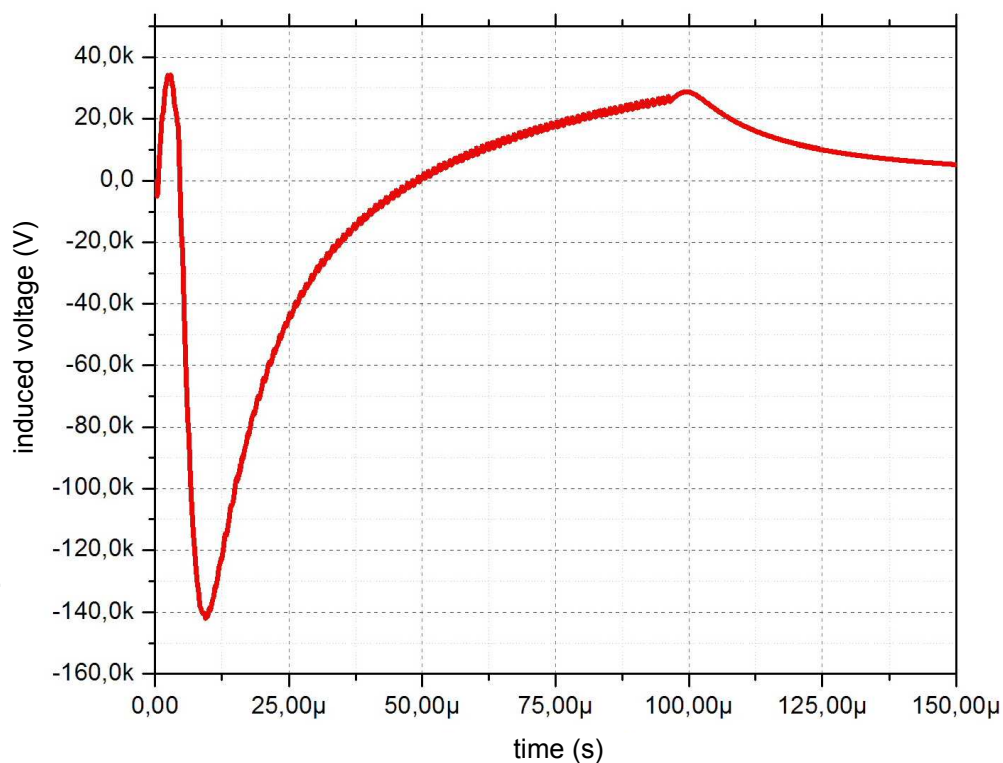


Fig. 16. Behavior of induced voltages for a non-optimized grounding system.

Fig. 16 shows that the peak value of induced voltage to a non-optimized grounding system was above 140 kV (in module). These magnitudes can be compared with those obtained when considering an optimized grounding system.

The graph, in Fig. 17, highlights the behavior of the induced voltage in a distribution system, considering an optimized grounding system and using those same lightning data used for obtaining the results illustrated in Fig. 16. Depending on the optimization of the grounding system, there is a reduction of the peak value of induced voltage, which is now approximately 35 kV.

Besides reduction of four times to the peak value, it is possible to verify that the duration of this electromagnetic event was less than that situation characterized by non-optimized grounding system.

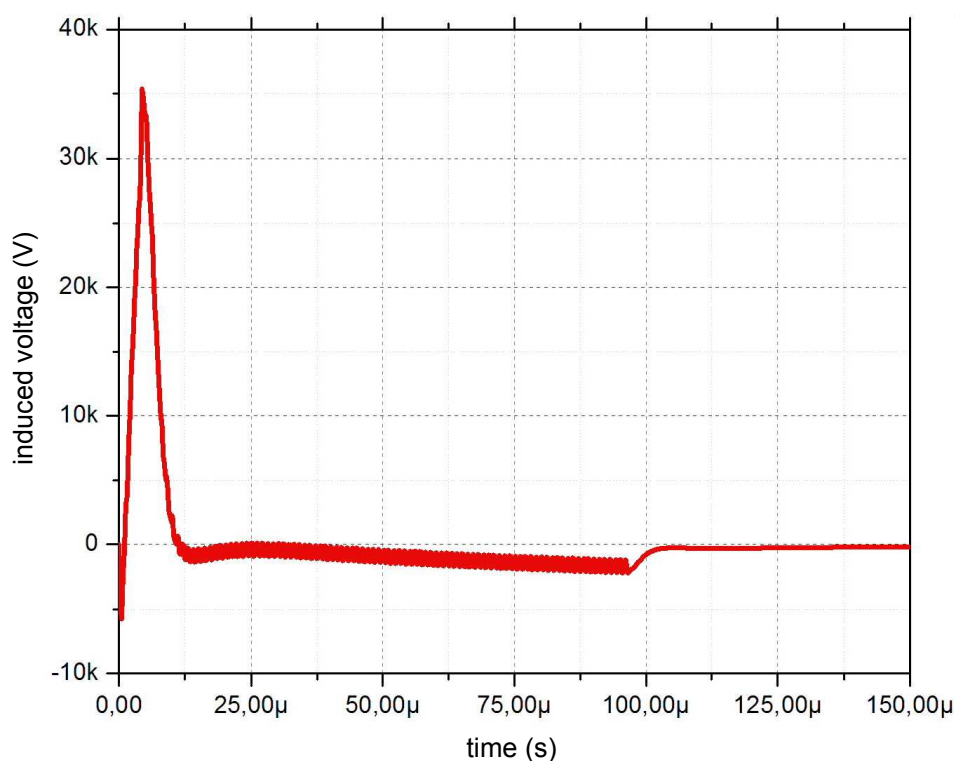


Fig. 17. Behavior of induced voltages for an optimized grounding system.

The expert system for optimizing new designs of grounding systems, called B-TERRA, uses, to start its calculations, the feeders database, which contains structural information, as well as information on lightning that occurred in the analyzed region.

While the database, with information about the feeders, are loaded, the operator can contemplate the evolution of the analysis of lightning, as illustrated in Fig. 18.

The procedures performed by the B-TERRA software allow the identification of the area of influence of lightning on the devices registered in the database of EDP Bandeirante circuits, as indicated by a rectangle highlighted in Fig. 19.

In this figure, it is possible to see an example where the device 2047568 is selected and, consequently, the area of influence of lightning has been highlighted on the screen at the right side of the B-TERRA software.

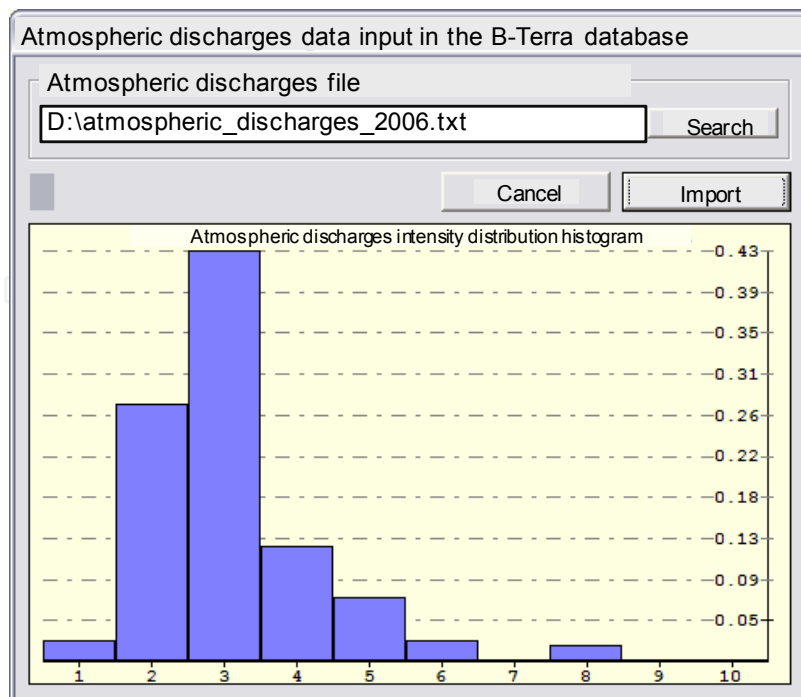


Fig. 18. Results of evolution analysis of lightning intensity.

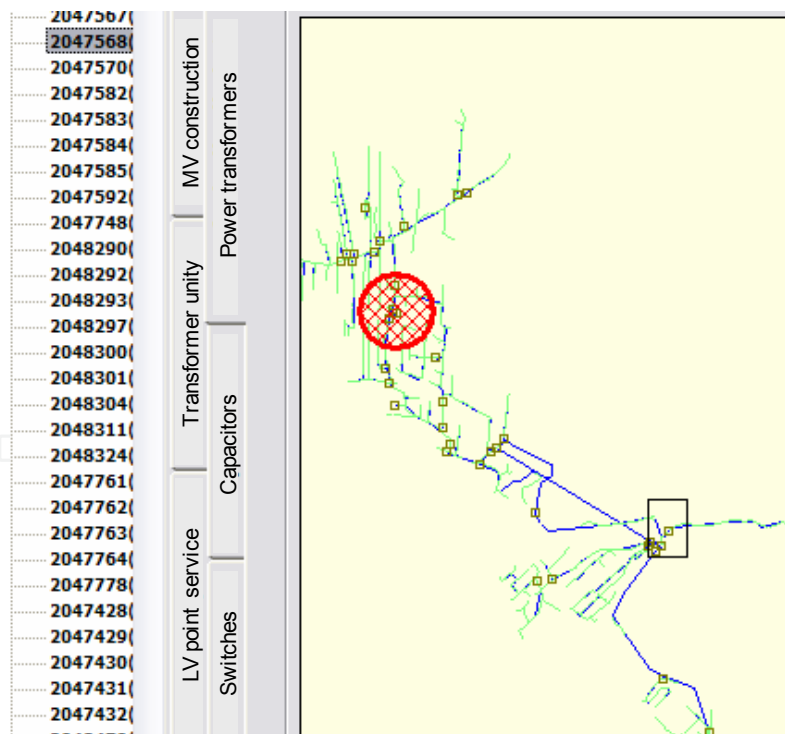


Fig. 19. Area identification where the devices are influenced by the lightning.

After accomplishment of all optimization procedures, through genetic algorithms, B-TERRA software provides as one of its answers the configuration of the best grounding design for the selected device, as shown in Figure 20.

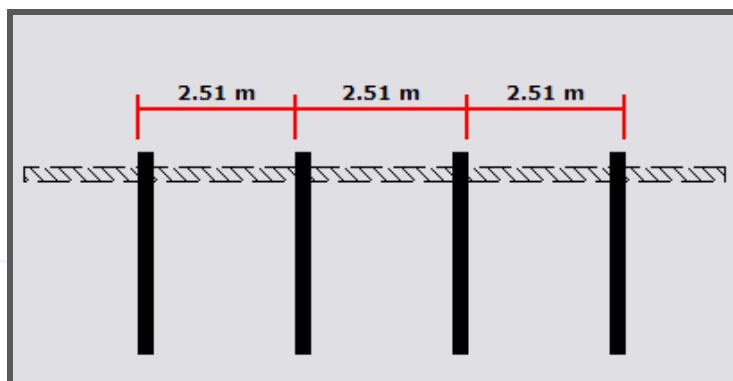


Fig. 20. Output of the B-TERRA software related to the best grounding design for the selected device.

6. Conclusion

In this chapter, it has been presented the theoretical development employed to estimate induced voltages in overhead distribution lines supposing a generic discharge current waveform, as well as assuming a finite distribution line.

Taking into account the results provided by the developed technique, an expert system to help in the equipments and distribution transformers protection specification was implemented in order to provide indicatives about the best protection to be adopted to transformers, as well as the best installation distance between arresters, aiming the full protection of the distribution line where these equipments are inserted.

Performance evaluations indicate that the expert system provides coherent results and its practical application contributes to optimize the processes involved with parameters specification related to the equipments and transformers protection.

Additionally, an expert system to assist in the specification of parameters for grounding designs was also implemented. Regarding the grounding system optimized with this tool, we can state that energy to be dissipated on the distribution system is lower than that observed in a non-optimized system, as shown in the charts in Section 5.

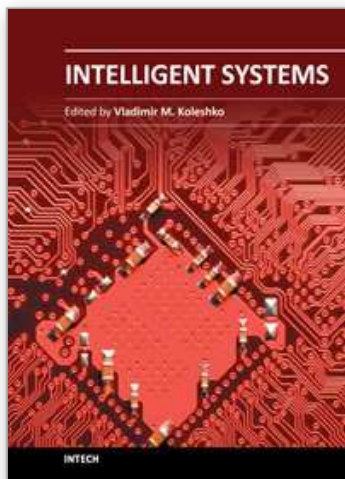
The difference in energy between the two cases implies in the energy that flows through the grounding system, i.e., for being better designed the optimized grounding system allows more energy to flow by itself compared to that case of non-optimized system. Experimental evaluations indicate that they provide very consistent results and their practical applications help for optimizing the processes involved with the protection of distribution systems.

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This book is dedicated to intelligent systems of broad-spectrum application, such as personal and social biosafety or use of intelligent sensory micro-nanosystems such as "e-nose", "e-tongue" and "e-eye". In addition to that, effective acquiring information, knowledge management and improved knowledge transfer in any media, as well as modeling its information content using meta-and hyper heuristics and semantic reasoning all benefit from the systems covered in this book. Intelligent systems can also be applied in education and generating the intelligent distributed eLearning architecture, as well as in a large number of technical fields, such as industrial design, manufacturing and utilization, e.g., in precision agriculture, cartography, electric power distribution systems, intelligent building management systems, drilling operations etc. Furthermore, decision making using fuzzy logic models, computational recognition of comprehension uncertainty and the joint synthesis of goals and means of intelligent behavior biosystems, as well as diagnostic and human support in the healthcare environment have also been made easier.

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