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EXPERT SYSTEM FOR INDUCED OVERVOLTAGE ANALYSIS IN DISTRIBUTION LINES TO EQUIPMENT PROTECTION PURPOSES

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ABSTRACT

The objective of this paper consists of presenting a design of expert system that assists the procedures involved with the protection specification of transformers and equipments against atmospheric discharges, llowing also to analyze in a detailed and systematic way the behavior of the respective voltage transients that are generated at the supplying área belong to Bandeirante Energia S/A. For such purpose, the expert system developed in this research makes the 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.

KEYWORDS

Lightning, expert systems, distribution lines, power system protection, transformers.

1.0 INTRODUCTION

In this paper, the main studies achieved in the research project developed by Bandeirante Energia S/A in association with USP and UNESP are presented, which have as goals the development of expert systems dedicated to estimate induced voltages in distribution lines, as well as providing the correct specification of the most appropriate arrester for equipments and distribution transformers protection against incidence of atmospheric discharges. 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 to 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 specially developed to simulate the voltage transients caused by atmospheric discharges in distribution lines, and the objective of the same is the computation of several parameters related with 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 of Bandeirante Energia S/A. The use of the developed tool has allowed the correct specification of equipments and transformers protection devices belonging to distribution system, enabling that differentiated protection strategies can be specified according to the particularities of each region, contributing then for value aggregation to services provided by the distribution company, since the available tools proportionate a more optimized efficiency of procedures involved with the protection specification. Therefore, in this paper, 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 distribution system of Bandeirante Energia S/A, are taken into account by the expert system.

2.0 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. The developed methodology in [1] is widely used 2 for induced voltage estimation in overhead distribution and transmission lines generated from indirect atmospheric discharges occurred near to the line. The induced voltage estimation methodology presented in [1] 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 [2] is mathematically demonstrated that the studies presented in [1] for resultant electric field computation of return current is correct. This fact hás contributed to increase the reliability in relation to method developed by Rusck. 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 [3, 4], 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[5]. 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 equation (1). 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).

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

where:

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

$$\beta = \frac{v}{c} \approx \sqrt{\frac{1}{1 + \frac{5.10^5}{I}}} \qquad (3)$$

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:

$$V_{max} \approx \frac{30 \cdot I \cdot h}{y} \qquad (4)$$

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 Figure 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.

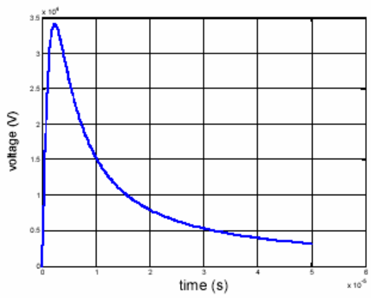

Fig. 1. Induced voltage in relation to the maximum voltage point in infinite line with 10m of height and atmospheric discharge of 10kA in perpendicular distance of 100m from the line.

I 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 Figure 2. It is observed from Figure 2 that the induced voltage waveform modifies in relation to the distance between the maximum voltage point and the measurement point.

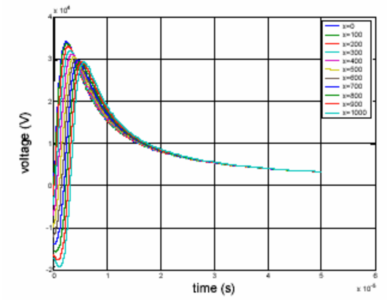

Fig. 2. Induced voltages in infinite distribution line with 10m fheight and atmospheric discharge of 10kA in perpendicular distance of 100m from the line in relation to several points along the line.

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, Figures 3 and 4 present how these parameters are altered in relation to the distance between the maximum voltage point and a point along this conductor. From Figure 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 na attenuation generated from high frequencies involved with the propagation process as well as from energy dissipation in relation to the metallic conductors. Figure 4 illustrates how rising time alters along the distribution line. We can certify that this parameter tends 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

From simulations accomplished and presented in this section and taking also into account the formulation proposed in [1], it is verified that the obtained results by Rusck's method are coherent with those obtained through field experiments [5] or even with those results produced using reduced model techniques [3, 4]. However, some modifications in this method are necessary in order to transpose this methodology to practical situations involved with the distribution system of Bandeirante Energia S/A.

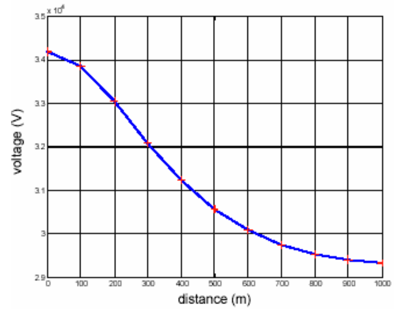

Fig. 3. Maximum induced voltage variation along the line.

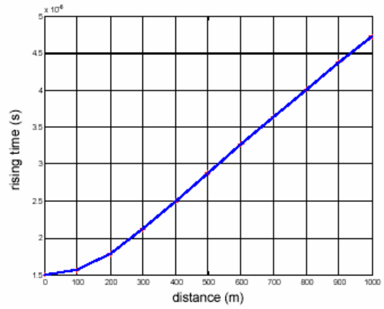

Fig. 4. Rising time variation along the distribution line.

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 [1] are conducted in order to complement the existent theory, becoming it appropriate for practical applications.

3.0 MODIFICATION OF THE CONVENTIONAL THEORY FOR INDUCED VOLTAGE ESTIMATION IN PRACTICAL APPLICATIONS

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:

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

where:

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

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

and:

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

Equation (6) is an example of Heidler's functions. An alternative frequently employed in atmospheric discharge odeling is double exponential. Nevertheless, the modeling through two Heidler's function, as presented in (5), ovides 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 Figure 5 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 $0{,}81\text{x}10^{-6}$ s.
Supposing that the system to be linear, it is possible the use of Duhamel's integral [6] 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 Figure 5, can be provided as shown in Figure 6.
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 Figure 5, occurring in a distance of 100m from infinite distribution line with 10m of height, the voltage waveform at the point x=0m (point of maximum voltage value) can be represented as in Figure 7.
Rusck's expression for induced voltage calculation in distribution lines is composed of two parcels, which can be observed through the following equation (9).

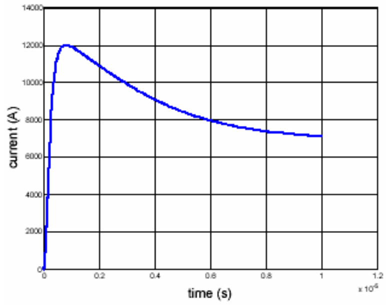

Fig. 5. Current waveform for atmospheric discharge modeling.

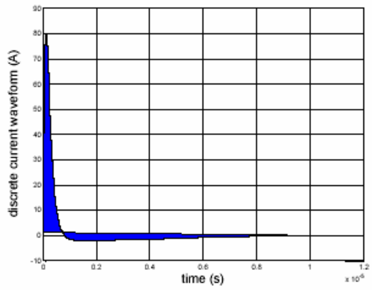

Fig. 6. Discrete current waveform composed by steps.

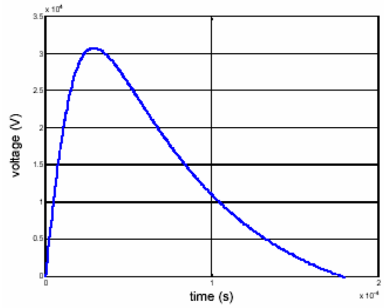

Fig. 7. Induced voltage at the point of maximum voltage value for a current waveform expressed in terms of Heidler's function.

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

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 Figure 8 is presented the interpretation of induced voltage proposed in the formulation suggested by Rusck.

Fig. 8. Induced voltage composition at the point x0 of the line.

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 $x1$ with impedance of termination Rf as indicated in Figure 9.

If the line were infinite, the voltage at the point $x1$ would be given by:

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

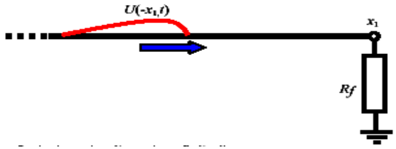

Fig. 9. Induced voltage in a finite line.

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 $x1$ 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 alter 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:

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

The function $u(t - tf)$ is a unit step function and tf is the travel time between the point x and $x1$.

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

where v_0 is the propagation velocity, which for the simulations in question will be assumed as being equal to the velocity of light [7].

The same procedure can be achieved supposing a discontinuity at the left of x. Then, assuming a finiteline, 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:

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

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 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 Energia S/A, 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

Figure 10, the transformer registration window adequately filled for a distribution transformer of 75kVA. After registration of each component of the electric system, inclusively of the arresters, the protection design can be registered. Figure 11 illustrates the project registration window, as well as it emphasizes the preliminary results of simulations. Besides providing which arresters are suitable to the transformer protection, the expert system presents how such arresters should be also installed to protect the distribution network against electrical flashovers. Figure 12 presents the window where indicates how each selected arrester for transformer protection can be also employed for protection of distribution network nearby the transformer.
Therefore, we have a unique computational platform that incorporates all registration functionalities referent to the distribution system elements, correlating them with the levels and topologies of the atmospheric discharges observed in each concession region, which become possible to define differenced protection strategies against atmospheric discharges in order to optimize the protection involved with the distribution system of Bandeirante Energia S/A.

5. CONCLUSION

In this paper, it has been briefly 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 subsidies 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.
Preliminaries evaluations of performance 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. Complementary implementations of the expert system have also allowed specifying the protection parameters against over voltage from atmospheric origin for voltage regulators and automatic reclosers.

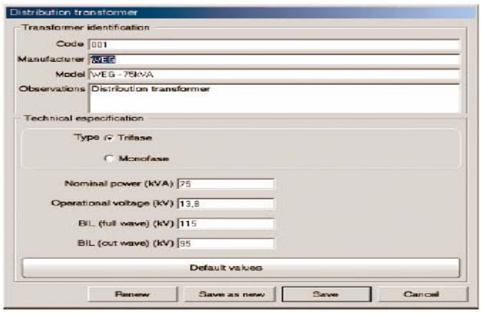

Fig. 10. Transformer registration window.

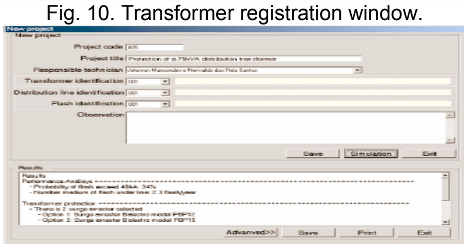
Fig. 11. Project registration window presenting preliminary results.

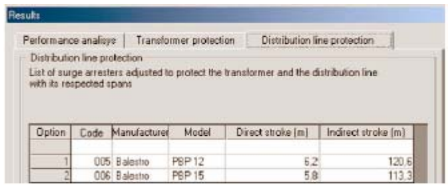

Fig. 12. Window indicating installation distance between arresters aiming the distribution line protection against atmospheric discharges.

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