UNIVERSIDAD NACIONAL DE COLOMBIA
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ADVANCES ON MODELING AND EXPERIMENTATION OF LIGHTNING INDUCED VOLTAGES ON DISTRIBUTION LINES

A thesis submitted in partial fulfillment of the requirements for the degree of
PhD in Engineering
by:

ERNESTO PÉREZ GONZÁLEZ

Advisor:

HORACIO TORRES SÁNCHEZ
Profesor Titular - UN

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Abstract

This Phd Thesis was focused on the lightning induced transients modeling on long and complex networks and the induced voltage measurements on energized distribution networks. Here is described and compared two methodologies for the induced transient calculation which are implemented in three different software linked to a transient analysis program (LIOV-EMTP, LIV-ATP and YALUK-ATP). The YALUK-ATP is a software developed in this PhD thesis which improves the link with the transient program; this new proposal allows make link without including an additional delay on the traveling waves. The developed software (YALUK-ATP) and the LIOV-EMTP showed to have the best features calculating lightning-induced voltage on complex networks; these software are used for the analysis of the network topology on lightning-induced voltages calculation for a different stroke location and ground conductivity. Moreover, as an engineering application, it was developed a new software which uses the advantages of YALUK-ATP and the genetic algorithms technique to locate appropriately surge arresters on a complex distribution network.

As a new contribution, it was built a new lightning-induced voltage measurement system on an energized distribution network which uses fiber optics and solar energy technology in order to reduce the electromagnetic interference. This distribution network is located 100m far away from the Colombian direct natural lightning measurement station where the induced voltage signals are gathered and registered. Nowadays, in Colombia, it has been measured more than 200 induced voltages on two measurement systems which were analyzed on this Phd Thesis. Several measurements have been correlated with the Colombian Lightning Location System and compared with calculations made with the induced voltage software.

Keywords: Lightning Induced Voltages, Power Distribution Systems, ATP, FDTD, Yaluk, Genetic Algorithms
Resumen

Esta tesis de doctorado está enfocada en el modelamiento de tensiones inducidas en sistemas de distribución largos y complejos y la medición en redes energizadas. En este documento se describen y comparan dos metodologías para el cálculo de tensiones inducidas, las cuales están implementadas en 3 programas computacionales vinculados con un programa para análisis transitorio (LIOV-EMTP, LIV-ATP, YALUK-ATP). El YALUK-ATP es un programa computacional desarrollado durante esta tesis doctoral, el cual es vinculado con el ATP por medio de una nueva metodología propuesta en esta tesis. Los programas YALUK-ATP y LIOV-EMTP mostraron ser adecuados para el análisis de tensiones inducidas en sistemas complejos. Adicionalmente, fue realizado un programa computacional como aplicación en ingeniería el cual utiliza las ventajas del uso del YALUK-ATP, para el cálculo de tensiones inducidas, y la técnica de algoritmos genéticos, para optimización. Este nuevo programa estima la localización más adecuada de descargadores de sobretensión en sistemas de distribución complejos.

Como aporte adicional a la investigación mundial fue construido un nuevo sistema de medición de tensiones inducidas en una red energizada, usando técnicas como fibra óptica y tecnología de energía solar para disminuir los efectos de interferencia. La red está localizada a 100m de distancia de la estación de medición directa de rayos colombiana y en ella son registradas todas las mediciones. En la actualidad, en Colombia, se han realizado más de 200 mediciones de tensiones inducidas que fueron descritas y analizadas en esta tesis doctoral. Algunas de las mediciones han sido correlacionadas con el Sistema de Localización de Rayos Colombiano obteniendo los datos de localización y amplitud de los rayos generados. En este documento se describió los resultados encontrados al realizar esta comparación.

Palabras Clave: Tensiones Inducidas por Rayo, Sistemas de Distribución, ATP, FDTD, Algoritmos Genéticos, Yaluk.
Chapter 1: Induced Voltages Theory

This chapter describes the Lightning induced theory used for the modeling.
Chapter 2: Methodologies for Lightning-Induced Voltages Calculation

Several studies have been done in order to solve electromagnetic field coupling models and have more accurate data on the lightning induced voltages calculation. One of the first attempts on this matter was done by Rusck [49] who by means of several assumptions and approximations solve analytically the calculation of lightning-induced voltages obtaining a simple expression which calculates the maximum voltage on a single conductor line over a perfect conducting ground. Despite this equation is suitable just for very simply lines, it is the one most used on the standards, such us IEEE 1410 [69].

Jankov in 1997 [70] propose a methodology to obtain an approximate equation by means of statistical analysis using a multivariate regression; this equation is based on TCS model and Agrawal et al. ones for a line on a perfect conducting ground. Other study made by the author of this thesis using the same methodology of Jankov made a new equation which considers the ground conductivity and the incidence angle to the line [5].

Those equations calculate reasonably induced voltages for several cases, with mean errors around 16% compared with the calculations using Agrawal et al. model [5], however, they are not able to be used on complex networks which has multi-conductors and multiple branches.

Nowadays it has been shown that for having reliable lightning induced voltages calculations on distribution networks, it is necessary to use specialized software which allows modeling more realistic systems including data such as multi-conductor lines, transformers, surge arresters, capacitances, etc [54].

Two of the most known codes for this purpose are the LIV-ATP [7;11;12] and the LIOV-EMTP [16;17]. In this chapter is discuss the advantages and disadvantages of these two codes and is presented a new one based on LIOV-EMTP methodology which is linked in a novel way with the ATP avoiding the inclusion of an additional segment of line to the real system. This new software will be called in this thesis as YALUK-ATP1 [4;71;72].

2.1 Calculation Methodology 1

The methodology described here is the basis of two software; the well known LIOV-EMTP code (Lightning Induced Overvoltages), developed by several researches from Italy and Swiss2 [16;17;38] linked to EMTP and MATLAB using TACS and s-function respectively and the YALUK-ATP code developed in this PhD Thesis.

This methodology is based on the field-to-transmission line coupling formulation of Agrawal et al., suitably adapted for the case of a multiconductor overhead line above a lossy ground

1 Software called YALUK in honor to the lightning God on May Culture
2 This code has been developed in the framework of an international collaboration involving the University of Bologna (Department of Electrical Engineering), the Swiss Federal Institute of Technology (Power Systems Laboratory), and the University of Rome "La Sapienza" (Department of Electrical Engineering)
illuminated by an indirect lightning electromagnetic field. This model is solved numerically using a time domain finite difference time domain method (FDTD). The two codes described here use a second order FDTD method based on Lax-Wendroff [74] algorithm and first proposed for induced voltage calculation by Paolone [75]. This implementation allows considering lossy line and non-linearities along it, such as corona effect.

The return stroke electromagnetic field is calculated by assuming any of the available engineering return stroke model [27;28]. The vertical electric field is computed using well-known expressions derived in [16] assuming a perfectly-conducting ground. The horizontal electric field is computed using the Cooray-Rubinstein formula [45;46], therefore taking into account the presence of a lossy ground. In order to solve this formulation, there is used a piecewise linear transformation proposed by Thomson [79] obtaining an analytical expression in the time domain, which is solved and then applied to the desired waveform by means of a convolution.

2.1.1 Link between LIOV and EMTP/MATLAB

In principle, the LIOV code could be suitably modified, case by case, in order to take into account the presence of the specific type of termination, line-discontinuities (e.g. surge arrester across the line insulators along the line) and of complex system topologies. This procedure requires that the boundary conditions for the transmission-line coupling equations be properly re-written case by case, as discussed in [16]. However, it was found more convenient to link the LIOV code with the EMTP. In [16,17,82], the distribution system network is considered as consisting of a number of illuminated lines connected to each other through shunt admittances (see figure 1). This admittance represents the presence of surge arresters, of groundings of shielding wires, of distribution transformers or of other power components. Each section of the distribution system between two consecutive shunt admittances is modeled as a single line called 'LIOV-line'. The LIOV code has the task of calculating the response of the various lines connecting the two-ports while the EMTP has the task of solving the boundary condition and presents the advantage of making available a large library of power components.

The link between each LIOV-line termination and EMTP is realized by means of a short lossless Bergeron line, (see figure), which longitude depends on the time step of simulation.
This short line could be represented as two decoupled equations as shown in (2.1) and (2.2), with an equivalent circuit shown in figure 2: Addition of short lossless line for achieve the link with EMTP, adopted from [16].

\[
v_0'(t) = Z_c \times i_0'(t) + \frac{d}{dt} (t - D_t) - Z_c \times i_0'(t - D_t) \\
v_0(t) = Z_c \times i_0(t) + U_0(t - D_t) \\
v_0(t) = Z_c \times i_0(t) + \frac{d}{dt} (t - D_t) - Z_c \times i_0'(t - D_t) \\
v_0(t) = Z_c \times i_0(t) + U_0(t - D_t)
\]  

(2.1)  

(2.2)

where:

\( Z_c \): Surge Impedance  
\( \Delta t \): is the voltage and current propagation time along the line.

The data exchange between the LIOV code and EMTP is realized in the following way each time step: the induced currents at the terminal nodes, computed by the modified LIOV code are input to the EMTP via voltage controlled generators, and the voltages calculated by the EMTP are input to the modified LIOV code via voltage sources (see figure 3: Equivalent circuit for Bergeron line at the end of the illuminated line, adopted from [17]).
2.1.2 Link between YALUK and ATP (proposed link)

In this Phd thesis is proposed a link with the transient program which diverge slightly with the one described above. Here is used a short illuminated line solved by means of the characteristics method as was proposed initially by Branin [80]. This methodology doesn’t increment the longitude of the line avoiding the errors produced with the time delay on the traveling waves introduced by the additional short line as was described previously.

The solution to the Agrawal et al. transmission line model could be solved using the characteristic method, if it is assumed that the electromagnetic field is propagated homogeneously along the line with constant velocity without losses. This method transforms the hyperbolic differential equations in ordinary equations. The ordinary differential equations carry on the propagation information of the incident and reflected wave. This yields to have two equations which define the characteristic curves (forward and backward, see (2.3)).

\[
\begin{align*}
    v_{p1} &= \frac{dx}{dt} = \frac{1}{\sqrt{L'C'}} \quad \text{Forward Characteristic} \\
    v_{p2} &= \frac{dx}{dt} = -\frac{1}{\sqrt{L'C'}} \quad \text{Backward Characteristic}
\end{align*}
\]

(2.3)

Where,
\( v_{p1} \): is the propagation velocity, the subscript indicates direction
\( L' \): is the inductance per unit length
\( C' \): is the capacitance per unit length

Using this method the transmission line equations could be rewritten in two ordinary equations as shown in (2.4) which describe the forward and backward characteristic.

\[
\begin{align*}
    dv'(x,y) + Z_c di(x,y) &= (v_{p1}E_x(x,y))dt \quad \text{Forward Characteristic} \\
    dv'(x,y) - Z_c di(x,y) &= (v_{p2}E_x(x,y))dt \quad \text{Backward Characteristic}
\end{align*}
\]

(2.4)

Where,
\( Z_c = \sqrt{\frac{L}{C}} \): surge impedance

Using (2.3) it is obtained that \( dx = v_{p1} \times dt = dx/\sqrt{L'C'} \) and (2.4) become (2.5).
Reorganizing the equations and integrating along the characteristics equations from \( x = 0 \) to \( x = L \), where \( L \) is the line longitude, it is obtained (2.6). This equation solves the field transmission line equation on two decoupled equations, where the scattered voltage and the total current on one side of the line is function of the integral of the horizontal electric field component and the scattered voltage and the total current of the other side of the line delayed \( t \).

\[
\begin{align*}
\frac{dv'}{(x,y)} + Z_c \frac{di}{(x,y)} &= E_x \left( t, x, y \right) dx \\
\frac{dv'}{(x,y)} - Z_c \frac{di}{(x,y)} &= - E_x \left( t, x, y \right) dx
\end{align*}
\]

(2.5)

With this method is obtained two equations similarly to those proposed by Dommel [81], but here are introduced two additional terms which represent the inducing sources.

In this PhD thesis is proposed to calculate the induced voltages on the line, combining two methods, the FDTD and the characteristics methods; this procedure is made by the following way: First the line is discretized, where the two endings segments have a longitude\(^3\) of \( D \times 2 \) and the rest of the line is divided in segments with a longitude\(^4\) \( D \times 5 \) (see Error! No hay texto con el estilo especificado en el documento.-5). Second the electromagnetic field interaction is calculated using the characteristic method for the ending segments and for the segments on the middle part using the FDTD method.

---

\(^3\) The value of this segment depends mainly on the velocity propagation and the time step, \( D \times 2 = v_p \times dt \)

\(^4\) This longitude is constraint with the Coorant criteria [73], \( D \times 5 = v_p \times dt \)
This solving scheme could be represented in a better way as it is shown in figure 5: line discretization scheme for the combination of the FDTD method and characteristic method. The inner part of the line is expressed in terms of scattered voltages and the outer part is expressed in terms of total voltages. Thus, the equations for the characteristic method are rewritten for the left hand circuit (equations (2.7) and (2.8)) and for the right hand circuit (equations (2.9) and (2.10)).
\[ v_{r0}^n = Z_i^n + v_{r0}^{n-1} - Z_c x_i^{n-1} - \frac{Dx^2}{Ur_0^n} \dot{E}_x^n dx - \frac{Dx^2}{Ur_0^n} \dot{E}_z^n dz \] (2.7)

\[ v_{1}^n = - Z_i^1 + v_{r0}^{n-1} + Z_c x_i^{n-1} + \frac{L}{Ur_1^n} \dot{E}_x^n dx + \frac{L}{Ur_1^n} \dot{E}_z^n dz \] (2.8)

\[ v_{rkmax}^n = Z_i^{rkmax} + v_{rkmax}^{n-1} + Z_c x_i^{rkmax - 1} - \frac{L}{Ur_{kmax}^n} \dot{E}_x^n dx - \frac{L}{Ur_{kmax}^n} \dot{E}_z^{rkmax} dz \] (2.9)

\[ v_{kmax - 1}^n = Z_i^{kmax - 1} + v_{rkmax}^{n-1} + Z_c x_i^{rkmax - 1} + \frac{L}{Ur_{kmax - 1}^n} \dot{E}_x^n dx + \frac{L}{Ur_{kmax - 1}^n} \dot{E}_z^{rkmax} dz \] (2.10)

where,

- \( k \): indicates position \([1, 2, \ldots, k_{max}]\)
- \( n \): indicates time position \([1, 2, \ldots, n_{max}]\)
- \( v \): is the scattered voltage
- \( v_t \): is the total voltage
- \( i \): total current on the line
- \( Z_c \): is the surge impedance of the line

In this way the outer part of the circuit could be solved by the ATP where the data exchange between the YALUK code and ATP is realized in the following way each time step: the inducing sources \( Ur_i^n \) and \( Ur_{k_{max}}^n \) at the terminal nodes, computed by the YALUK code are input to the ATP via voltage controlled sources (type TAC 60), and the voltages calculated by the ATP are input to the modified YALUK code reading total voltage at the termination (see figure 7).

The YALUK code is developed as a dynamic library separately from ATP and is linked to it using foreign MODELS in ATP.

In this proposed methodology the great majority of calculation is made with the FDTD method, hence, it is possible to calculate the non-linearities on the line such as corona effect and the ground transient impedance.
2.2 Calculation Methodology 2

The methodology described here is the basis of the LIV software proposed by Hoidalen [7;11-13] and implemented in MODELS of ATP.

This code uses the TL model in order to take advantage of an analytical solution of the lightning-electromagnetic field for a lossless ground following the approach proposed by Rusck [49]. The analytical calculation of the inducing terms is made assuming a step function to describe the channel base lightning current waveform. For other kind of channel base lightning current waveforms a convolution integral may be done.

Assuming a lossless line and neglecting the transient ground resistance, the LIV-ATP program represents the LEMP-to-transmission line coupling by means of a modified Bergeron line, using the characteristic method, which includes controlled generators representing the induced voltages (see figure). 

\[
\begin{align*}
Z_0 &+ v_{\text{L}}(t) \quad Z' + v_{\text{ind L}}(t) \quad -v_{\text{r 0}}(t) \\
&+ i_L(t) \quad -i_L(t) \quad \text{figure}\end{align*}
\]

Concerning the case considering ground conductivity it is used the formulation approach of Cooray-Rubinstein. The inducing terms are calculated from the solution of the electromagnetic fields described above and could be written as following.

\[
\begin{align*}
v_{r 0}(t) &= v_{\text{ind 0}}(t) + v_L(t - t) + Z' i_L(t - t) \\
v_{r L}(t) &= v_{\text{ind L}}(t) + v_L(t - t) + Z' i_0(t - t) \quad (2.11)
\end{align*}
\]

where,
\[v_{\text{ind 0/ L}}\] : induction term in the line
\[Z'\] : Surge impedance of the line
\[ v_{\text{ind}}(x,y) = \int_{x_0}^{x_L} E_x^y(x,t) \, dx - \int_{0}^{h} \left( E_z(x_0,z,t) - E_z(x_L,z,t-t) \right) \, dz \]
\[ + g_0 * \int_{x_0}^{x_L} B_x^y(x,t) \, dx \]  
\[ (2.12) \]

\[ v_{\text{ind}}(x,y) = g_1(t) * v_{\text{inf}}(x,y) + g_1(t) * g_0 * v_{Dx}(x,y) \]  
\[ (2.13) \]

Where,
- \( v_{\text{ind}} \): inducing source
- \( v_{\text{inf}} \): Inducing source for a lossless ground
- \( g_1 \) : Function representing the current wave shape
- \(*\) : Denotes convolution
- \( v_{Dx} = \int B_x^y(x,t) \, dx \) : Inducing source in order to take into account the ground conductivity

When it is considered the ground conductivity it is necessary to calculate a double convolution, one used in order to include the ground conductivity influence, and the other one in order to take into account the current wave shape.

In order to simplify this computation it is assumed for lossy ground a triangular wave shape which allows solving analytically the Cooray-Rubinstein approach. The analytical solution involves the Bessel integrals which are calculated using a large approximation argument (2.14). In figure ¡Error! No hay texto con el estilo especificado en el documento.-9 is shown the comparison of the exact solution and the approximation of the Bessel solution.

\[ f = \frac{1}{2p} \times a \times t \]  
\[ (2.14) \]

Where,
\[ a = \frac{s}{2 \times e \times e_0} \]  
\[ (2.15) \]

![Figure](image)

It is noted that the function produces reasonable results when \( a \times t \geq \frac{1}{2p} \), this causes as restriction that \( \Delta t \) may be larger than \( Dr \geq \frac{1}{2p \times a} \).
2.2.1 Link between LIV and ATP

The LIV calculate the total voltages of the Bergeron line including the inducing terms; this value is sent by means of the ATP-MODELS using a TAC-source Type 60 in the ATP, then with this source the ATP solves the circuit, for each time step, the LIV code reads the voltage value at the end of the surge impedance and calculates the total voltages of the Bergeron line for the next time step (see figure).

![Network diagram](image)

2.3 Numerical comparison between LIOV-EMTP, LIV-ATP and YALUK-ATP programs

The numerical comparison of the three programs is here presented for different cases of single-conductor and multi-conductor straight line and complex distribution systems, considering different positions for the stroke location and different values for the ground conductivity. Additionally it is make a validation of the LIV-ATP and YALUK-ATP with the results of the scaled circuit made by Piantini [8;9].

2.3.1 Results for Straight line

The geometry adopted for the single-conductor line above both ideal and lossy ground cases is represented in figure. The line is supposed to be matched at its both ends. In order to perform a comparison between three different software, the Transmission Line (TL) model has been adopted for the description of the return stroke current distribution. The cases considering a lossless ground it is assumed a double Heidler type waveform with an amplitude of 12kA and \( \frac{dI}{dt} = 40 \text{ kA/µs} \). The cases with ground conductivity a triangular waveform of the channel base current has been adopted with an amplitude equal to 12 kA and a 1.2/50 µs waveform.
Simulation Results for single-conductor line over a perfectly conductive ground

Simulation Results for 1 km multi-conductor line over a finite ground of 0.001S/m without considering transient ground impedance

Comparison between the LIOV-EMTP, LIV-ATP and YALUK-ATP for a 1 km overhead single conductor line; lightning current with Heidler function of 12 kA amplitude and 40 kA/µs maximum time derivative, infinite ground conductivity, observation point placed at line terminations (a) stroke location 500 m from right side of the line, (b) stroke location 500 m from the center of the line

Comparison between the LIOV-EMTP, LIV-ATP and YALUK-ATP for a 1 km overhead multi-conductor line; lightning current with triangular function 1.2/50 µs of 12 kA amplitude, ground conductivity 0.001 S/m, observation point placed at line terminations; conductor in the middle (a) stroke location 50 m from the center of the line, (b) stroke location 50 m from the right side of the line
Simulation results for 5 km single-conductor line over a finite ground of 0.001 S/m considering transient ground impedance

Simulation results for complex distribution network (figure 15) with several power system components connected to it (figure 16); over a finite ground of 0.001 S/m considering transient ground impedance

figure: Comparison between the LIOV-EMTP, LIV-ATP and YALUK-ATP for a 5 km overhead single-conductor line; lightning current with triangular function 1.2/50 μs of 12 kA amplitude, ground conductivity 0.001 S/m, observation point placed at line terminations; conductor in the middle (a) stroke location 50 m from left side of the line

Simulation results for complex distribution network (figure 15) with several power system components connected to it (figure 16); over a finite ground of 0.001 S/m considering transient ground impedance

figure: Distribution network with one main feeder and two branches

figure: Vertical configuration for the network of figure 15 and power system components features
2.3.2 Comparison for complex network

Regarding with the effect of the link implementation of the LIOV and YALUK with the transient program it was made calculated the induced voltages for two cases: the first one for a single conductor straight line of 500m and the second one for 1km line composed by two lines of 500m. in order to take into account the reflections it was considered matched with a capacitance of 453 pF in series with a resistance of 15 ohm which represent a transformer. The stroke location was assumed 50 m from one side of the line. For the current was used a double Heidler type waveform with an amplitude of 12kA and $\frac{dI}{dt} = 40$ kA/µs. The simulations varied from two simulation step, 0.01 µs and 0.03 µs; results are shown in figure 18 and figure 19.
2.3.3 Discussion of the Simulation Results

In general terms for perfectly conducting ground all codes calculate the nearly the same results. When finite ground conductivity is considered, the differences between codes are lower than 10% for short lines lower than 1km. LIV-ATP results show slightly smaller peak values compared to those predicted by LIOV-EMTP and YALUK-ATP. On the other hand, for longer lines, the omission of ground transient resistance in LIV-ATP can result, in some cases, in an overestimation of lightning-induced voltage peaks.

The major difference between the codes are mainly in the solution of the Cooray-Rubinstein approach, where LIV-ATP replace the Bessel integrals by means of a large approximation argument, meanwhile, the other two codes solve this formulation using a piecewise approximation.

Regarding the LIOV and YALUK implementation it could be concluded that in general terms the addition of a short lossless line in the case of LIOV produces a delay on the reflected wave which is associated directly with the time step assumed. The time delay on the reflected line is $4dt$ for each line simulated and it increments meanwhile more reflections occur. For the case of a simulation step time of 0.01 $\mu$s the difference are negligible for window simulation time lower than 30 $\mu$s; on the other hand for simulation step time of 0.03 $\mu$s the errors on the maximum amplitude could be more than 5%.

2.3.4 Validation with reduce scaled model

The measurements have been performed on reduced scale models set up at the University of Sao Paulo in Brazil; this network reproduces a typical overhead distribution system (main feeder plus branches) including surge arresters, neutral grounding, T-junctions (between line branches) and shunt capacitors aimed at modeling distribution transformers. The surge arresters are simulated by means of a combination of diodes and resistances.

This system has previously compared with the LIOV-EMTP96 program [9;82], using the TL model and neglecting the ground conductivity. This comparison had a good agreement between simulations and measurements.
Using the LIV-ATP and YALUK-ATP, it was compared the test results for two cases on a two conductors system. The system was composed by 39 branches which finished in transformers which were simulated as capacitances. The neutral conductor was connected to earth by means of a resistance and inductance in order to simulate the groundings.

The lightning current waveform on the base channel could be approximated to a triangular shape type, where its peak occurs at 2 µs and a half time equal is at 85 µs. For all cases the lightning return stroke velocity is, in the real scale, equal to 0.33 x10^8 m/s, the lightning channel height is 600 m. For each case different value for the lightning peak current is considered.

Case A

The system configuration showed in figure 18 and connections showed in figure 19 were used to simulate the induced voltage produced by a lightning strike 70m far from the line with amplitude of 70 kA for the maximum peak at 2 µs and 35 kA at the 85 µs. In figure 20 is shown the comparison between the measurement and the three programs.
Case B

The system configuration showed in figure 21 Components Termination Types for two conductors system, adopted from [82] were used to simulate the induced voltage produced by a lightning strike 70m far from the line with amplitude of 50 kA for the maximum peak at 2 μs and 25 kA at the 85 μs. In figure 24 is shown the comparison between the measurement and the three programs.
For the cases analyzed here the three programs estimate reasonably the induced voltages measured on the scale model. The differences between the different software are mainly due to the time delay of the signal; however, for these cases this error could be negligible.

Some other validations for the LIOV-EMTP code have been achieved in different sceneries, laboratory [17;82] and in real systems with triggered lightning [83-85]. The LIOV-code simulations present good agreement with the measurements.

2.4 Contributions made on the induced voltage modeling

The main contribution made in this PhD Thesis and presented in this chapter is the innovation on the new linking with a transient program methodology which allows simulating lines without introducing delays on the traveling time that could produce errors greater than 5%. This new implementation permits make simulations to extensive networks more accurately.

The comparison between different software and the study of the methodology on induced voltages yield to have the tools to develop new software which include the link methodology proposed. This new software was implemented as a dynamic library (dll) which is linked with ATP by means of foreign MOLDES.

- The comparison of the three different software (LIV, LIOV y YALUK) made on the different sceneries allows to determine the features of each software and its possible
application. The LIV-ATP is suitable for the calculations on single and multi-conductor lines with any number of branches over a perfectly conductive ground. In the case of lossy ground, this software is useful for lines lowers than 2km, due to the transient ground impedance is not considered.

- The LIOV-EMTP and YALUK-ATP compute the induced voltages with difference between them lower than 5%. The YALUK-ATP code has the advantage of estimating properly the wave traveling time, making a good estimation of the induced voltages for network simulated with a great number of single lines. The error on the delay could be neglected for LIOV-EMTP if the simulation time step is lower than 0.01 μs.

Some other differences on the LIOV-ETMP and YALUK-ATP are due to the different numerical routines and tolerances assumed for each one.

The different features of the three programs are summarized and compare in table ¡Error! No hay texto con el estilo especificado en el documento.-1 of the software.
<table>
<thead>
<tr>
<th>Description</th>
<th>LIV-ATP</th>
<th>LIOV-EMTP</th>
<th>YALUK-ATP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel-base current representation</td>
<td>Case of perfectly conductive ground, any analytical waveform is possible, what requires a convolution integral. Considering finite ground conductivity just triangular waveform</td>
<td>Any waveform is possible</td>
<td>Any waveform is possible</td>
</tr>
<tr>
<td>Vertical Electric Field Computation</td>
<td>Analytical solution assuming a perfectly conducting ground</td>
<td>Numerical solution assuming a perfectly-conducting ground.</td>
<td>Numerical solution assuming a perfectly-conducting ground.</td>
</tr>
<tr>
<td>Horizontal Electric Field Computation</td>
<td>Cooray-Rubinstein Formula [45;46], solved by means of large argument approximation for Bessel function and requires convolution</td>
<td>Cooray-Rubinstein Formula [45;46], solved by means of piecewise method using convolution method.</td>
<td>Cooray-Rubinstein Formula [45;46], solved by means of piecewise method using convolution method.</td>
</tr>
<tr>
<td>Ground Transient Resistance</td>
<td>Neglected</td>
<td>Rachidi et al. [56]</td>
<td>Rachidi et al. [56]</td>
</tr>
<tr>
<td>Non linearity along the line, such as corona effect.</td>
<td>Non treated</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Implementation and link with EMTP-ATP</td>
<td>ATP-MODELS environment (characteristic method)</td>
<td>EMTP-TACS environment FDTD solutions of field-to-line coupling equations, interfaced with EMTP for boundary. (link made with a short lossless line)</td>
<td>ATP-Foreign MODELS environment FDTD solutions of field-to-line coupling equations, interfaced with EMTP for boundary. (link made with characteristic method)</td>
</tr>
<tr>
<td>Engineering applications</td>
<td>Useful for multi-conductors lines on complex and branched networks of any length for perfectly conductive ground. Considering ground conductivity maximum 2 km</td>
<td>Useful for multi-conductors lines on complex and branched networks of any length over any ground conductivity. For branched lines it must be taken into account the delay on the reflections in order to choose a lower $\Delta t$</td>
<td>Useful for multi-conductors lines on complex and branched networks of any length over any ground conductivity.</td>
</tr>
<tr>
<td>Calculation time for a simple case. Base time from LIV-ATP(^a)</td>
<td>1</td>
<td>5-10</td>
<td>2-3</td>
</tr>
</tbody>
</table>

\(^a\) Time evaluated for 1km line with a stroke location 50m from one side of the line, ground conductivity 0.001S/m. For LIV-ATP it was assumed triangular waveform and the line is composed by four lines of 250m, for LIOV y YALUK was assumed Heidler function with $\Delta t = 0.01\mu s$, $\Delta x = 5m$.

\(^b\) This time depends on the number of nodes and the parameters $\Delta t \ y \ \Delta x$.
Chapter 3: Induced Voltages for Different Topologies

3.1 Introduction

In this chapter is described the four subjects: first the influence of branches on the calculation of induced voltages; second, the simplification of the network by means of non-illuminated lines, third the effect of the topology and some power system components on the distribution line performance and finally is described an application for locating surge arresters against lightning induced voltages.

3.2 Influence of Network Topology on The Response to Indirect Lightning Events

The preliminary analysis of the influence of the presence of branches on the calculation of lightning-induced voltages covered 6 cases, all based on the H-shaped network configuration and shown in figure. This H-shaped network represents case 1; it is composed by five 10 m high, 500 m long single-conductor lines. The other cases are obtained by removing one or more branches from the network of case 1, as described in table.

Lightning-induced voltages are observed at points P1 and P2, because generally these are assumed to be the more critical ones. At those branches that are not connected to any other branch, the network lines for all the 6 cases are terminated with a resistance equal to its surge impedance, in order to avoid reflections. The current waveform was assumed as 1.2/50 μs triangular waveshape with amplitude of 12 kA. The simulations were made for perfectly conductive ground and finite ground with a value of 0.001 S/m.
3.2.1 Perfectly conductive ground

The results relevant to perfectly conductive ground on stroke location S1 and S2, for observation point P1 and P2 are shown from figure -26 and figure -27: we can infer that the induced voltage waveform is strongly influenced by the network configuration, mainly for the asymmetric stroke location S1.

<table>
<thead>
<tr>
<th>Case</th>
<th>Network Configuration</th>
<th>Relevant shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A, B, C, D, E</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>A, B, C</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>A, B</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>A, D, E</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>A, D</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>A</td>
<td></td>
</tr>
</tbody>
</table>
3.2.2 Finite Conductivity

The results relevant to ground conductivity of 0.001 S/m on stroke location S1 and S2, for observation point P1 and P2 are shown from figure 28 and figure 29: we can infer that the induced voltage waveform is strongly influenced by the network configuration, mainly for the asymmetric stroke location S1.
We can conclude that for any stroke locations, either 'external' or 'internal' to the network (S1 or S2 respectively) it is fundamental to take into account the presence of the branches which are closest to the stroke location, because they are important both from the point of view of the induction on the network and on that of the equivalent impedance 'seen' at the observation point.

3.3 Simplification of the network by means of “non-illuminated lines”

This methodology is pretended to be use on complex and long distribution network where the time calculation is very high. This section describes the effect of replacing of illuminated lines for surge impedances or not illuminated lines.

In order to describe this effect it is consider a simple T network shape configuration composed by three branches, two branches of 1 km and one of 500m. The T-shaped network is terminated at the end of each line with a transformers (Z) modeled as a 453 pF capacitance in series with a 10 Ω resistance. The seven cases that we have simulated are reported in table 3 Network topology composed by three single conductor overhead lines (height: 10 m, conductor diameter: 1 cm).

TABLE 3: NETWORK TOPOLOGY CONFIGURATIONS

---

7 Non illuminated line: line which is not considered the interaction with the lightning electromagnetic field.
Different simulations were made considering two types of conductivity, first a perfectly conductive ground and second a ground conductivity of 0.001 S/m.

Regarding with a perfectly conductive ground the results for the most representative observations points are shown in figure 3-7, 3-8, and 3-9. Here is shown that replacing with a non-illuminated line produce a good estimation of the induced voltages for those cases where the stroke location is in S1 or S2 for the observation points in P1 and P2. On the other hand it is obtained that for the stroke locations S1 and S2, it could be a good approach the replacement of illuminated lines with surge impedances if the window time is set somehow it is not expected reflections coming from the replaced line.
Induced voltages for the observation point P1 and stroke location S2 (figure 3-30). Perfectly conductive ground; lightning current with triangular waveshape $1.2/50\,\mu s$ and 12 kA amplitude,
a) observation point P1; b) observation point P3

Regarding with a finite ground of 0.001 S/m, the most significative points are shown in figure 3-10, 3-11, and 3-12. In this case the ground conductivity produces that far lines have considerable contribution on the total induced voltages. The replacing with non-illuminated lines estimates reasonably the induced voltages for stroke locations S1 and S2, for the observation points in P1 and P2. However, the differences shown for this case are higher than the case with perfect ground conductivity. For the stroke locations S1 and S2, it could be a good approach the replacement of illuminated lines with surge impedances if the window time is set somehow is not expected reflections coming from the replaced line.
3.3.1 Considerations for the using of non-illuminated lines or surge impedances

One can draw the following conclusions from the obtained simulation results:

- Once the simulation time window has been fixed (e.g. 15 µs), a preliminary rather simple evaluation on traveling times of the induced surges, enables a clear evaluation of the portion of the network to be considered in the simulations.
• It is quite inappropriate to neglect the illumination of a branch of a network when such a branch is part of a T-junction and close to the stroke location, independently of the observation point and of the temporal window one is choosing for his analysis;

• One can replace an illuminated branch of a network with a non-illuminated one, only provided the stroke location is far from a T-junction and that the observation point is close to the stroke location. On the other hand, the value of ground conductivity is one of the main factors to take into account when choosing which lines could be replaced. For example for cases where the stroke location is lower than 200m from the line, for perfectly ground conductivity, it is possible to have reasonably results replacing lines which are at more than 1 or 2 km far from the striking point; and for cases with a ground conductivity 0.001 S/m, the replacements must be done for lines which are more than 3-5 km

• In general, it is appropriate to replace illuminated lines with surge impedance, only if stroke locations and observation points are very close to each other.

• The parameters that mostly affect the lightning-induced transient are certainly the distance between the stroke location and the line and the ground resistivity.

3.4 Effects of the power system devices and the network topology on the calculation of lightning-induced voltage performance on distribution networks

In this section is shown the differences on the calculation of the line performance taking into account different kina of terminations, such as open circuit, transformers, surge impedance or surge arresters. It is also shown the influence of the topology in the lightning induced voltages performance on distribution networks.

For this study it was chosen a complex line that makes part of a real distribution network located in Samana Colombia which was used as experimental energized line when induced voltages were measured (Chapter 4). This line consists in a main feeder of 4 km with three branches of different longitudes as it is shown in figure. The line is composed with 20 nodes with horizontal configuration, where the conductors are separated 1.3m and its mean height is 10m.

For the calculation of induced voltage – line performance, it was used the Monte Carlo method in a similar way as Paolone and Borghetti [91;92] did. In those studies more than 10,000 cases were simulated in order to have accurate results. However, due to the chosen line is quite complex and long it was reduced the number of simulations. According to Cogan [96] in the Monte Carlo method meanwhile the number of cases rises the results tend to be constant with small variations. Using these assumptions it was plot the tendency of the mean value of the
maximum voltage with is standard deviation achieving that for 1000 cases it is possible to have reasonably results.

The area chosen for the strokes location was 700 m far from the extremal points of the line and the locations were located randomly (see figure -39). The amplitude and he front time were calculated randomly from the probability distribution achieved from the direct lightning measurements made in Brazil [97;98]. The parameters of the log-normal curves for current amplitude and front time are shown below.

- Amplitude mean value : 45.3 kA and Standard deviation $s_{log} = 0.39$
- Front time mean value: 5.6 $s_{log} = 0.36$
- Correlation factor between amplitude and front time: 0.47

The ground conductivity was assumed as 0.001 S/m. The parameters used to calculate the number of faults /100 km - year are shown in table -4. The longitude is assumed as the sum of the longitude of all branches.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitude of the network</td>
<td>7 km</td>
</tr>
<tr>
<td>Ground Flash Density</td>
<td>1 rayo/km·año</td>
</tr>
<tr>
<td>Selected Area</td>
<td>25 km²</td>
</tr>
<tr>
<td>Number of cases</td>
<td>1000</td>
</tr>
<tr>
<td>Number of Years to complete 1000 flashes in the selected Area</td>
<td>40</td>
</tr>
</tbody>
</table>

3.4.1 Effect of the Power Devices on the calculation of lightning-Induced Voltages Performance on Distribution Networks

Generally the lightning-induced voltages performance on distribution networks is made using surge impedances as terminations [88;90;100]. Recently some studies are made using surge arresters along the line [91;92]. Here is presented some other cases on the terminations such as, open circuit, transformers, surge impedance and surge arresters.

All the terminations are considered connected to the three-phase line as it is shown in figure 3.4.1: Power devices connected on the termination of the line.

Regarding with a nodal analysis (see figure 3.4.2: Power devices connected on the termination of the line), it is shown that the mean value of the maximum induced voltages are obtained for the cases with transformers and open circuit as terminations where the most critical nodes for this two cases are the terminations ones (nodes 1, 14, 19 and 20). On the other hand, for the cases with surge impedance and surge arresters as terminations the mean induced voltages are lower than 50% for the other two cases, and in contrast, the most critical values are on the middle of the line (nodes 6, 7 and 8).
Analyzing the number of failures/100 km - year, it is obtained that the most critical case is when a transformer or open circuit termination is considered, where the number of failures for a Critical Flash over (CFO) could be greater than two times. The best lightning-induced performance is obtained for surge arresters when the CFO is lower than 200 kV.

3.4.2 Effect of the network topology on the lightning-induced voltage performance

Previously was analyzed the influence of a network induced voltages for a different stroke location and ground conductivity; here is presented the effect of the network topology on the calculation of the lightning-induced performance of the line. In figure ¡Error! No hay texto con el estilo especificado en el documento.-43 are shown the 4 configurations used for this analysis based on the distribution network of figure ¡Error! No hay texto con el estilo especificado en el documento.-39, where the ground conductivity was assumed 0.001 S/m. Two different terminations were used in this analysis, open circuit and surge impedance.
Regarding with nodal analysis for open circuit termination, it is obtained that mean value of the maximum amplitude is enhanced when the network branches are incremented (see figure \textit{Error! No hay texto con el estilo especificado en el documento.-39}). On the other hand, when surge impedance is assumed for terminations it is obtained the opposite, where the mean value of the maximum voltages is reduced when the number of branches is incremented (see figure \textit{Error! No hay texto con el estilo especificado en el documento.-44}). This could be explained due to the "seen" impedance of the line is reduced on the junction, when a branch is added, producing a reduction on the induced voltages.
The lightning-induced voltage performance on the distribution network was analyzed from the number of failures/100 km-year allowing to have the same scale for all cases. The scaling factors depend mainly in the total length of the line due to the area and ground flash density is the same for all cases (see table).

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Parameter</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main feeder</td>
<td>Total network longitude</td>
<td>4.25 km</td>
</tr>
<tr>
<td></td>
<td>Conversion Factor for failures per 100km-year</td>
<td>0.594</td>
</tr>
<tr>
<td>Main feeder + Line 1</td>
<td>Total network longitude</td>
<td>5.5 km</td>
</tr>
<tr>
<td></td>
<td>Conversion Factor for failures per 100km-year</td>
<td>0.455</td>
</tr>
<tr>
<td>Main feeder + Line 1 and 2</td>
<td>Total network longitude</td>
<td>6.3 km</td>
</tr>
<tr>
<td></td>
<td>Conversion Factor for failures per 100km-year</td>
<td>0.398</td>
</tr>
<tr>
<td>Complete network</td>
<td>Total network longitude</td>
<td>7 km</td>
</tr>
<tr>
<td></td>
<td>Conversion Factor for failures per 100km-year</td>
<td>0.357</td>
</tr>
</tbody>
</table>

Analyzing the results concerning with the lightning induced voltage performance of the distribution network, it is obtained that for the surge impedance used as termination the performance of the line is slightly worse for the case where is just the main feeder, however, the values are similar for all cases between a CFO of 100 kV and 200 kV (see figure).
For the case using open circuit on the termination, the results show that the number of failures/100 km-year is the same for the 4 analyzed cases on a CFO range between 70 and 220 kV (see figure).  

### 3.5 Engineering Applications

The use of surge arresters on distribution network has shown that it diminishes the number of failures on a line due to lightning induced voltage [91]. The reduction on the failures is related with the number of surge arrester used and the location of them [92]. In general those studies have been made for straight lines, with exception of Piantini et al [8;93] who experimented on branched networks.

The ideal case on the reduction of number of failures on a line is when surge impedance is located in every pole, however, this could be not useful due to economical and maintenance management restrictions, if a extensive distribution network is considered such as the one used to measure induced voltages described on chapter 4.

Using the YALUK-ATP software it was made a novel tool based on genetic algorithm which is intended to locate optimally the location of a certain number of surge arresters on a distribution network in order to reduce the number of failures of the line. This tool combines the YALUK ATP and the genetic algorithm library called UNGenetico Ver. 2.0 [102] developed in C++ in the National University of Colombia.
3.5.1 Genetic Algorithm Implemented

The tool made in this PhD thesis perform the following steps: first calculate randomly a location for the each surge arrester for each case or individual, then, is modified the ATP file updating the location of each surge arrester. As third step is run the YALUK-ATP for the modified ATP file for a determined number of strokes, calculating the maximum induced voltages on all nodes for all cases. The maximum voltages are processed in order to obtain the fitness function and assign a survival probability. In the next step new individuals are generated from the genetic information of the parents and the fitness function is evaluated again. The results of the new individuals are compared with their parents choosing the best ones. This process is made continuously until the finishing criterion is achieved.

The codification of the chromosome of each individual is made as following: First is determined the number of genes which represent the number of surge arresters that will be evaluated on the distribution network. Each gene represents by means of an integer the location node for each surge arrester. Thus, the codification of the chromosome of each individual is $C_i = \{g_1, g_2, K, g_n\}$ where $g_i$ identifies the node location for the surge arrester $i$ and $n$ identifies the number of genes used or surge arresters.

3.5.1.1 Evaluation and Selection Process

For the evaluation and selecting process it was assigned a survival probability proportional to the values of the fitness function. The selection of the individuals for obtain new individuals is made as a roulette where the individual who has higher probability will be more easily selected.

3.5.1.2 Crossover and Mutation Process

The crossover is made between two chosen individuals by jeans of and integer operator. This process computes a random integer value between the values of two genes. For example if are combined two individuals where the gene one of the individual A is $g_i = 5$ and the gene one of the
individual B is $g_{1} = 18$, this operator will obtain a value between 5 and 18. For every combination of two individuals it could be obtained a mutation gene where its value is assigned randomly. The probability for this event is set in 0.5% and it could be enhanced in 0.5% up to 10% if the mean value of the fitness function of the best individuals on the last five generations varies less than 10%.

### 3.5.1.3 Fitness Function

Maybe one of the most important tasks on the using the genetic algorithms are the properly chosen of the fitness function. In this procedure three different functions were evaluated.

*Root Mean Square (RMS) value of the Maximum Induced Voltages plus the Maximum Value*

Using the function (1.1) it is taking into account two main aspects, one it is aimed to reduce the maximum induced voltages in all nodes giving more importance to those which have higher values and the maximum induced voltage in the system

$$V_{\text{media}} = \frac{\sqrt{V_{1}^2 + V_{2}^2 + K + V_{\text{max}}^2}}{n} + V_{\text{max}}$$

(1.1)

where:

- $V_{i}$: is the maximum induced voltage in the node $i$
- $n$: is the number of nodes

*Percentile distribution curve for induced maximum voltages*

Here is obtained two different fitness functions from the cumulative probability distribution curve, one associated to the percentile 90 and the other to the 60 (see figure 49 Cumulative distribution probability. (percentile 90 blue curve), (percentile 60 red curve))

![Percentile distribution curve for induced maximum voltages](image)

### 3.5.2 Example

As example it was used the distribution network shown in figure which is composed by one main feeder with three branches and represented by 20 nodes. In this example is attempted to locate optimally four surge arresters in the distribution network. In this case are evaluated the different fitness functions shown above. The surge arrester curve is shown in figure.
\[ R_{nl} \]

\[ R = 15\Omega \]

\[ L = 22\mu\text{H} \]

<table>
<thead>
<tr>
<th>( R_{nl} \rightarrow I_r \text{[A]} )</th>
<th>( V_r \text{[kV]} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>36</td>
<td>27.0</td>
</tr>
<tr>
<td>54</td>
<td>27.9</td>
</tr>
<tr>
<td>360</td>
<td>29.7</td>
</tr>
<tr>
<td>1620</td>
<td>32.22</td>
</tr>
</tbody>
</table>

3.5.2.1 Number of flashes for each individual

Each individual which has the information of the location of the four arrester must be evaluated somehow it could be determined the line performance of the line and then it is able to evaluate if it is a good option or nod by means of the fitness function. However, this procedure is two time expensive due to for each individual it is need to calculate at least 1000 cases with different stroke information as was shown in section 3.4.

In order to reduce the time calculation, it was enhance the \( dt \) and \( dx \) considerable assuming that the error will be lower than 5% on the induced voltage estimation. The number of strokes are also diminished and three different test were made to obtain a properly value. The two first test were made choosing 20 and 40 strokes selected from those who produced the maximum voltages in the system in the case of open circuit. For the third test it was chosen 100 strokes randomly from those who produced maximum induced voltages greater than 100 kV.

3.5.3 Results

The results obtained for the different fitness function and for different number of lightning were compared with a case with random location of the surge arresters and a case without surge arrester and open circuit on the terminations. The comparison was made using the curve for the number of failures/100 km - year calculated by means of the procedure described on 3.4.

The first evaluated case was made for the group of 20 flashes and the fitness function (1.1), in this case, as it is shown in figure figure ¡Error! No hay texto con el estilo especificado en el documento.-50: Surge Arrester Configuration and curve value the results are worse for the random case if the CFO is greater than 200kV, for CFO lower the results is slightly better.
Using 40 flashes and the fitness function calculated from the percentile 60 and 90 the number of failures/100 km-year are lower for CFO greater than 110 kV. The best performance is obtained for the results obtained with the fitness function of the percentile 60.

Finally it is used the group of 100 flashes with the fitness function based on the percentile 60. In the figure it is shown that the curve improves its performance for CFO values lower than 120 kV and greater than 270 kV.
The surge arresters location obtained for every case is shown in Table 6.

<table>
<thead>
<tr>
<th>Surge Arrester Location</th>
<th>Random Case</th>
<th>20 flashes RMS + max</th>
<th>40 flashes percentile 90</th>
<th>40 flashes percentile 60</th>
<th>100 flashes percentile 60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge Arrester 1</td>
<td>2</td>
<td>14</td>
<td>9</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Surge Arrester 2</td>
<td>10</td>
<td>3</td>
<td>4</td>
<td>18</td>
<td>13</td>
</tr>
<tr>
<td>Surge Arrester 3</td>
<td>9</td>
<td>7</td>
<td>14</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>Surge Arrester 4</td>
<td>6</td>
<td>20</td>
<td>2</td>
<td>8</td>
<td>16</td>
</tr>
</tbody>
</table>

This tool allows to find a “good” solution but not always this is the best one, however, for this case were just 4 surge arresters were located it was obtained a reduction of the number of failures/100 km –year compared with the case without surge arrester and with a random surge arrester location.

3.6 Contributions made in the modeling of Induced Voltages

In this chapter are described several analysis made to different network topology using software suitable for this purpose.

By means of the analysis of the effects of the branches on the lines it was proposed simplify a complex network by means of “non-illuminated” lines without scarify considerably the accuracy on the results. In order to obtain errors lower than 10%, it is possible to replace lines which are farther than 1 km for perfect ground conductivity and more than 3 km for ground conductivity around 3 km.

Regarding with the number of failures per 100 km year on a branched line, it is obtained that the effect is different depending on the type of termination, being more critical when are considered high impedance on the terminations, such as transformers or open circuits.

On engineering applications it is proposed that the distribution networks terminations be always connected whether surge arrester or impedance with values near the surge impedance of the line. This recommendation is also valid for those locations were a switch is dividing a circuit, due to if the switch is open it remains and open circuit which will enhance the chances of failure on the distribution line.
Finally in this chapter it is developed a tool based on genetic algorithm which search a good location of surge arrester to improve the performance of complex line against lightning induced voltages.
Chapter 4: Study of Induced Voltages Measurements in Colombia, Comparison between Theoretical and Experimental results

4.1 Introduction

Several studies on experimental networks have been carried out around the world with the purpose to have better knowledge of this phenomenon. In this PhD thesis it has been gathered the measurements made in a lightning induced voltage measurement system located in Colombia [65]. Additionally a new system was built in order to have better more reliable data, able to be used for validating theoretical studies.

4.2 Lightning – Induced Voltages Measurements systems in Colombia

4.2.1 Experimental Measurements on a Colombian Distribution Network located in “Samana”

The distribution network, where the measurement system was installed, has reported a great number of faults. It has a large number of branches, covering a surface of approximately 200 km² on a region of a ground flash density around 30 flashes/ km²-year [103]. The measurements were made using three capacitive dividers, described next, located in the network and separated approximately 1 km from each other. The lightning stroke location and the lightning current amplitude estimation were carried out by using the Colombian lightning location system (LLS) [1].

The overhead distribution line evaluated is an 11.4 kV three phase line with neutral conductor and horizontal configuration as it is shown in. The line is composed by 4 conductors ACSR 2/0 AWG type (12 mm diameter), with metallic pole, porcelain insulators and a mean height of 10 m. This line has connected one, two and three phase transformer and each transformer is protected with surge arresters on the phases it is connected and the neutral conductor is grounded on each transformer location; furthermore the line has several neutral grounding connections along the line different to the transformer ones. The single line diagram of the whole network is shown in figure ¡Error! No hay texto con el estilo especificado en el documento.-54. The ground conductivity measured a magnitude of .001 s/m approximately.
4.2.1.1 Measurement System

The voltage transients were recorded by means of three measurement systems located in the network, as shown in Fig. 1, and separated approximately 1 km from each other. Each measurement unit, see Fig. 2, is composed by an oil immersed Pearson capacitive dividers (Model VD305A) with 300 kV maximum voltage range, 4MHz bandwidth and 18 pF total capacitance; and a digital Fluke oscilloscopes with 25MHz bandwidth.

The capacitive divider was linked to oscilloscope with a 10 m shielded RG58 coaxial cable, grounded at the entrance terminal, provided with an additional external shield.
4.2.2 Description of the designing and construction of a new measurement system located

In 2005 was designed a new lightning-induced voltage measurement system and built in other Colombian zone, called Puerto Olaya, with high ground strokes density\(^8\) de 15 strokes/km\(^2\)-año

4.2.2.1 Line Configuration

The distribution line is located in a petroleum facility. The overhead distribution line is a three-phase one with two shielding wires with a longitude of 1 km approximately. The conductors are ACSR 2/0 AWG type (12mm diameter) on metallic poles, porcelain insulators and a mean height of 11 m. This distribution network is located 100 m far away from the Colombian direct lightning measurement station (see figure ¡Error! No hay texto con el estilo especificado en el documento.-57).

\(^8\) Obtained from data of the Colombian Lightning Location System
4.2.2.2 Design and Device Construction

Focusing mainly on the electromagnetic interference, it was decided to reduce the coaxial cable at the minimum longitude and was used fiber optic to send on the signal up to 1 km. The scheme used for the measurement system is shown in figure ¡Error! No hay texto con el estilo especificado en el documento.-58, where the high voltage measurement is made with a capacitive divider (Pearson model VD305A) with the same features described above. The signal from the capacitive divider low voltage output is attenuated in 20 times by means of a compensate capacitive divider, constructed in this thesis, in order to reduce the voltage from 250kV to 2.5 V, which is the maximum amplitude for the fiber optic transducer. The signal is passed through a voltage follower in order to keep the bandwidth. The transducers are supply by means of two batteries charged by means of two solar panels [112].

![Diagram of the induced voltage measurement system](image1.png)

**20x Attenuator**

The attenuator constructed for this purposes is a compensated resistive divider which is suitable for working in the range of frequencies of 60 Hz to 10 MHz. The schematic and a photo of the divider is shown in figure ¡Error! No hay texto con el estilo especificado en el documento.-59 and figure ¡Error! No hay texto con el estilo especificado en el documento.-60.
**Voltage Follower**

The voltage follower has an output impedance of 50 ohm and is suitable for working from DC up to 5 MHz.

**Fiber Optic Transducers**

The transducers are composed by one transmitter and one receptor produced by Analog Modules (model T-732), this devices convert an electrical signal in optical one and is suitable for working between DC and 10Mhz. this transducer uses a 62.5/125µm multimode fiber up to 1km.

**Battery Charger**

In order to reduce the electromagnetic interference on the measurement system due to disturbances on the main, the transducer supply is made isolated by means of a couple of batteries charged by two solar panels (see figure [Error! No hay texto con el estilo especificado en el documento].61).
4.2.2.3 Devices Calibration

The devices were calibrating in order to determine the transformation rate and the bandwidth of each device and the whole system. Moreover, it was calculated the Basic Insulation Level (BIL) by means of several test done in the National University high-voltage generator located in Bogota-Colombia.

The BIL of the system for Bogota altitude was calculated by means of the Up and Down test and it was obtained 143 kV for positive polarity and 154 kV for negative. The critical values was corrected for the altitude where the system will be installed obtaining 200kV for positive polarity and 215 kV for negative polarity.

The transformation rate for the whole system was calculated on 122,000:1 with a bandwidth around 1Mhz. The test was done individually (see diagrams bode in figure ¡Error! No hay texto con el estilo especificado en el documento.-62) and for the whole system (see figure ¡Error! No hay texto con el estilo especificado en el documento.-63) obtaining consistent values.
4.3  Induced Voltage Measurement Analysis

Nowadays, the measurement systems in Colombia described above have registered more than 200 signals. In this section are described and analyzed them.

The signals measured were filtered for those greater than 2 kV, reducing the number of registers to 160. Due to the measurements were measured in an energized system with power systems components connected to it, all signals present reflections. These reflections in several cases produced that the maximum peak yields on the subsequent ones and its time duration be more than several hundreds of microseconds.

There were seen three distinctive type of signals as are shown in figure ¡Error! No hay texto con el estilo especificado en el documento.-64.
Measurements made in Samana measurement system for different types of signals:

- **Type A**
- **Type B**
- **Type C**

Figure shows:

- Voltage vs. Time for different signal types.
The maximum amplitude registered was 47 kV; on table ¡Error! No hay texto con el estilo especificado en el documento.-7 are described the measurements made. The great majority of the signals are classified on type A and 72% of the signals have positive maximum peak.

The mean value of the measurements is 11.4 kV and its probability frequency distribution could be adjusted to a log-normal one. On other hand, the mean value of the first peak of the induced voltages is 8 µs.
4.4 Comparison between measurements and theoretical calculations of Lightning-Induced Overvoltages

It was compared a pair of measurements made on the measurement system of Samana with simulations made with LIOV/EMTP. This comparison let apply the results obtained on chapter 3 and establish the different contributions that could have a real complex network.

The comparison was made with a pair of measurements made simultaneously in two different points (A and B) and were correlated with the lightning Location System, see figure ¡Error! No hay texto con el estilo especificado en el documento.-68.
4.4.1 Simulation Description

Taking into account the analysis of the chapter 3, we attempted the representation of the distribution system of figure 4.4.1 by means of a reduced equivalent network, shown in figure 4.4.1. As the ground conductivity is about 0.001 S/m, we have simulated the distribution network including branches that are located within a distance of at least 3 km from the stroke location. Concerning the rest of the network, those branches who are close to the observation point, at a distance larger than 3 km from the stroke location, have been replaced with non-illuminated lines. In case no transformer was connected to them, distant branches were replaced by surge impedances. The transformers, when present, were simulated as a lumped capacitance of 450 pF for each phase. The neutral conductor groundings are simulated with a lumped resistance of 20 Ω. The presence of the capacitive voltage dividers is also taken into account as lumped capacitances of 18 pF.
The lightning current amplitude and strike location were obtained from the Colombian Lightning Location System (LLS), which uses LPATS technology antennas. Several studies have shown the limits of the estimation accuracy of the current amplitude and the stroke location [2;104;105].

As we are interested in comparing a specific measurement with the relevant calculation, this accuracy uncertainty in the estimation of lightning parameters suggested us to perform a sensitivity analysis of the return stroke current magnitude and stroke location, in order to infer the values for which we obtain the best agreement between simulation results and experimental measurements. Also the value of the ground conductivity has been varied, as was inferred by a measurement in a small part of the entire considered region.

The network topology was set with all the switches closed as in Fig. 1. However, this rural network is not equipped a system providing real-time data relevant to switches operation information: this means that, in principle, during the considered measurement period, the network may have a (slight) different topology, e.g. because of the intervention of fault protections.

On the LIOV/EMTP, the simulation time step was set in 0.01 $\mu$s in order to neglect the influence of the time delay in the propagation. The TL model was assumed to describe the return stroke with a triangular current waveform on the channel base; the ground conductivity was assumed constant along the line with a value of 0.001 S/m.

4.4.2 Sensitivity to the stroke Location

The strike location point was varied from the LLS location data within a radius of 600m in order to find the most approximate location of the lightning. The striking points were located on 5 several circles separated 100m each one, and were chosen 25 (figure ¡Error! No hay texto con el estilo especificado en el documento.-71) initial points to make the calculations.
The sensitivity analysis consisted of the simulation more than 100 cases. The best agreement between measurements and calculation results, shown in figure 71: Lightning Striking Point variation

The network is simulated without the branch highlighted in figure 73, which was supposed to be disconnected when the measurements were carried out.

figure 72: Comparison between LIOV-EMTP simulations and the measurement for point A with a stroke location 50m near the line. Lightning current amplitude of 30 kA, \(\frac{di}{dt}\) 10 kA/\(\mu s\). The branch highlighted on figure 73 is dismissed for this simulation a) Point A, b) point B.
It could be conclude from this analysis that despite the LLS are very useful for a lot of engineering applications, for the induced voltage calculation the accuracy of this data, around 500 m, is not suitable for get reasonably results. For this reason it is recommended when using LLS data perform a sensitivity analysis in order to achieve more reliable results [5;106].

It was compared a lightning-induced measurement made on an extensive and complex rural distribution network in Colombia, with simulations obtained by means of the LIOV-EMTP code. Such comparison does not pretend neither to validate the simulation program nor the measurements carried out, in view of the several approximations introduced, but has been presented essentially as an application of the findings that we have presented in the first part of

4.5 Contributions on Experimentation

One of the main contributions on experimentation was the building of a new measurement system on energized distribution network. The network is located 100m far away from the lightning direct measurement station. This new system was build using fiber optic and solar energy technology.

Several measurements were analyzed in finding some features of its maximum peak and occurrence time of the first peak.
Chapter 5: Conclusions and Future Work

In this PhD thesis is done a work on the modeling of the lightning induced voltages with applications focused on complex distribution network. The main contributions made are done in three areas: first, the induced voltage modeling, second, experimentation on energized distribution network and third engineering applications.

**Induced Voltages Modeling**

One of the main contributions on this PhD thesis was the development of a new lightning induced voltages software based on the most well known methodology and including a novel methodology for the link with the ATP. This new scheme in the induced voltage calculation combines two methods, one, the finite difference method and second, the characteristic method. This implementation allows calculating the interaction of the induced voltage along the line including non linearities with the calculation of the boundaries conditions in ATP. This methodology improves the one proposed for LIOV-EMTP due to it doesn't introduce an additional delay on the propagation time.

Worldwide several equations have been made to calculate the induced voltages on distribution lines, however, despite their use is easy, they are just valid for very simple cases. However for accurate results it is necessary to use more sophisticated codes. On the basis of the three software comparative studies (LIV-ATP, LIOV-EMTP and YALUK-ATP), it could be infer the suitable of each software depending on the complexity of the system and the ground conductivity.

- The LIV-ATP is suitable for the calculations on single and multi-conductor lines with any number of branches over a perfectly conductive ground. In the case of lossy ground, this software is useful for lines lowers than 2km, due to the transient ground impedance is not considered.

- The LIOV-EMTP and YALUK-ATP compute the induced voltages with difference between them lower than 5%. The YALUK-ATP code has the advantage of estimating properly the wave traveling time, making a good estimation of the induced voltages for network simulated with a great number of single lines. The error on the delay could be neglected for LIOV-EMTP if the simulation time step is lower than 0.01 μs.

Regarding with the network topology analysis, it could be concluded that the topology has a great influence on the induced voltage calculation. This effect is seen mainly on a single stroke analysis where it is shown that the ground conductivity and the stroke location are part of the contributions on the branches being most influential ones those near to the stroke location. On a statistical analysis the influence of the topology depends on the devices connected at the line terminations, where transformers and open circuits are those which produce higher induced voltages amplitudes. Here it could be concluded that for real networks at the lines terminations must be connected surge arresters.

Additionally it is proposed to simplify a extensive circuit (greater than 2km) by means of non illuminated lines. This is made in order to reduce the calculation time of the induced voltages
maintaining a reasonably accuracy. Some considerations must be taking into account to evaluate this.

- Once the simulation time window has been fixed (e.g. 15 µs), a preliminary rather simple evaluation on traveling times of the induced surges, enables a clear evaluation of the portion of the network to be considered in the simulations.

- It is quite inappropriate to neglect the illumination of a branch of a network when such a branch is part of a T-junction and close to the stroke location, independently of the observation point and of the temporal window one is choosing for his analysis;

- One can replace an illuminated branch of a network with a non-illuminated one, only provided the stroke location is far from a T-junction and that the observation point is close to the stroke location. On the other hand, the value of ground conductivity is one of the main factors to take into account when choosing which lines could be replaced. For example for cases where the stroke location is lower than 200m from the line, for perfectly ground conductivity, it is possible to have reasonably results replacing lines which are at more than 1 or 2 km far from the striking point; and for cases with a ground conductivity 0.001 S/m, the replacements must be done for lines which are more than 3-5 km

- The parameters that mostly affect the lightning-induced transient are certainly the distance between the stroke location and the line and the ground resistivity.

**Experimental**

In this area it is made a contribution on the design and construction of a new induced voltage measurement system on an energized distribution network. This system is located near the Colombian direct lightning measurement station, which allows to obtain more induced voltage measurements including the lightning current on the channel base. This new measurements will be useful to make more comparisons with simulations with software as YALUK.

The measurements made in two measurement systems in Colombia were gathered obtaining more than 200 registers. These signals were analyzed establishing features such as, mean maximum magnitude and front time. It was also compared a lightning-induced measurement made on an extensive and complex rural distribution network, with simulations obtained by means of the LIOV-EMTP code. The LLS accuracy is not always enough to have reasonably results on the calculation of induced voltages, thus, it is necessary to perform a sensitivity analysis to improve them.

**Engineering Applications**

Concerning with the distribution line performance it was developed a tool based on genetic algorithms and the software YALUK-ATP. This software is intended to search and optimal solution for the location of surge arresters con complex distribution network. At this point this tool has its limitations due to the calculation time, for this reason is necessary to improve the calculation speed for YALUK-ATP.

**Future Work**

From the knowledge acquired on this thesis and the development of an induced voltages calculation software, it is obtained major autonomy for the proposition and developing on applications concerning with lightning on distribution networks. In this same way it is possible to integrate somehow other results for induced voltaje calculations such as the PhD thesis of Herrera [29].

The measurement system built near the lightning experimental measurement station will allow to make more comparative studies on natural lightning. Having more comparative studies will allow to adjust better the theoretical calculations for engineering applications.
The new tool developed using genetic algorithms could be improved mainly on the fitness function, calculation time and the number of variables included to be optimized.
References


