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Technological innovation due to Lightning effects on the reliability of Power Distribution Systems in Colombia

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Featured Application: The technological innovation presented in this paper can be implemented in any power distribution system that is located in an area of high lightning activity.

ABSTRACT

The failure of distribution transformers, mainly in rural areas of very high lightning activity, has been a constant problem for the reliability of Power Distribution Systems in Colombia in recent decades. Research centers and consulting firms have carried out particular diagnostic work and specific solutions. However, to date, the problem persists, with costs that exceed million dollars per year. An important portion of transformers present failures rates 45 times higher than normal and very large overhead lines, representing a high portion of the total system, present very high failure rates over 70 times higher than in normal weather conditions. Initially, a theoretical and laboratory study was carried out with models of distribution transformers and later a systematic study was carried out in the field. The main contribution of this paper is to present a technological innovation in the design, manufacture and installation of prototype transformers that operate satisfactorily in areas of high lightning activity, thus improving the reliability of electrical power systems.

Keywords: *Lightning, tropical region, reliability, technological innovation, distribution transformer*

I. Introduction

It is estimated that at any one time there are about 2000 electrical storms on the earth, generating about 100 lightning strikes per second. The highest incidence occurs in the three areas with the highest deep tropical convection [1, 2]: Tropical South America, Central Africa and the maritime continent.

Colombia, located in the intertropical confluence zone (Tropical South America), has one of the highest atmospheric activities in the world, with a number of lightning strikes per year in excess of ten million. Although the lightning protection methods developed by researchers worldwide apply in Colombia, the parameters estimated in other latitudes are not necessarily applicable in tropical region [3, 4, 5].

The economic and social costs that Colombia currently assumes due to this risk factor represent incalculable losses in human lives, livestock, trees, facilities and equipment; and for the power energy companies, it is the biggest cause of outages and low reliability.

In particular, regarding the failures in distribution transformers in rural areas, and the consequent losses, in the Research Program on the Acquisition and Analysis of Signals (PAAS-UN) of the National University of Colombia, a direct observational correlation was be inferred between the areas of high risk due to lightning and the mortality of distribution transformers. In this way, in this program a specific alternative solution was proposed for this case.

Several investigations have shown that one of the most lightning active areas in the world is located in Colombia [6, 7]. The lightning phenomenon has its maximum occurrence in tropical regions and its physical parameters present variations compared with those typically observed in other regions of the world [4-24]. The most lightning-active zones worldwide is the region that connects the Magdalena River Valley in Colombia with the Catatumbo region in Venezuela [6].
Besides the geographical location, the big mountains in this region represent very lightning dense locations, which are within the highest Ground Flash Densities - GFD reported [5]. This last paper investigates the effect of the lightning activity in Colombia on the reliability of power distribution systems and tries to state whether lightning is responsible to the major portions of the value of reliability indexes such as system interruption duration index (SAIDI) [25].
In order to achieve that a solution to an engineering problem is efficient, adaptable, economical and thus improve the reliability of an electrical power system, it is necessary to guarantee three phases that must be integrally related:

- Comprehensive diagnosis of the problem,
- Technological alternatives and implementation of the solution,
- Control and monitoring of variables

A Comprehensive Diagnosis implies:

- Evaluation of the studies and previous solutions that have been carried out
- Analysis of the Causes of the problem and its Effects
- Characterization of the environment
- Technical and economic indices for evaluation After the Comprehensive Diagnosis of the problem, we proceed to propose technological alternatives for solving the problem.

Once these alternatives have been analyzed, one or more is chosen and the proposed solution is designed and implemented in a comprehensive manner. To do this, you must take into account:

- Mathematical modeling of each and every one of the system components
- On-site and laboratory measurements
- Appropriate designs, technically and economically feasible
- Adaptation and Improvement of variables: Networks, Equipment, Protections, Improvement of grounding.
- Proper handling and installation

Finally, a control, monitoring and maintenance of the implemented system (protections, grounding, equipment, network) is necessary, in such a way that solutions can be adjusted or improved, the implementation is maintained in optimal conditions and reliable conclusions can be inferred about the solution.
These three phases of the methodology can take several years and their costs are relatively high. But, in the face of a chronic problem, such as the failure of distribution transformers and the reliability of electrical power systems, this methodology is much more economical in the medium and long term than the short-term, conjunctural and punctual solution such as Generally, these types of engineering problems are attacked in Colombia.
The following describes how the proposed methodology was developed, implemented and applied in order to improve reliability and the solution to the problem of failure of distribution transformers for the Colombian Power Distribution Companies. This methodology can be implemented in any power distribution system that is located in an area of high lightning activity.

II. Materials and Methods

2.1 Applied Methodology

Based on the high mortality of distribution transformers, a continuous, systematic, methodological research project was proposed to a Colombian Electric Power Company, with the aim of contributing to find technical-economic solutions, on firm and objective scientific and technological bases to the high mortality of distribution transformers to improve their reliability.

In the first phase of this research project, an evaluation of the previous studies and the existing information was carried out, both on mortality of transformers and the environment (atmospheric electric discharges, easement, grounding, handling and installation) in order to carry out a comprehensive diagnosis and propose preliminary hypotheses to seek an objective solution to the problem.

In the second phase, the contingencies to which a rural distribution electrical system may be subjected were raised and the theoretical design, construction and laboratory tests of an appropriate transformer for areas of high lightning activity were developed. Subsequently, an Experimental Pilot Circuit EPC located in an area of high mortality of transformers and Severe Risk from lightning was selected, with the aim of implementing technological innovations found. During three continuous years the behavior of the EPC was monitored.

Complementary, the main variables that directly affect the failure of transformers were controlled, such as: growth of trees around the easement area, handling and installation of the transformer, electrical components of the network, protection elements, starting resistance ground and atmospheric electrical activity in the area. The latter was monitored through the Colombian Lightning Location Network. A control, monitoring and maintenance of the implemented system (protections, grounding, equipment, network), allow minor adjustments and keep the solution in optimal conditions.

The process of monitoring the variables that was carried out shows that, despite the more than 130 lightning strikes that have struck less than 100 m from the EPC in three years, the technological innovations implemented have responded satisfactorily.

2.2 Analysis cause – effect

The failure of a distribution transformer occurs due to the interaction of various factors, which deteriorate it to a greater or lesser degree, leading to its final failure [4]. One of the most useful analysis tools for processes of this type is the Cause - Effect diagram, also known as the Ishikawa diagram (see Figure 1), which allows observing the interactions between the different factors in-volved and giving guidance on technological alternatives from solution.

To develop the Cause - Effect diagram, the following steps were followed:

• All relevant factors were identified by consulting the existing bibliography and subsequent discussion with expert engineers on the subject.
• The component subsystems of the system involved in transformer failure (transformer, load, network and environment) were determined.
• A diagram was prepared, Figure 1, which characterizes each subsystem of the system.
• The elements of each subsystem were chosen, taking into account which ones are susceptible to technological innovation and which can only be monitored.

The electrical distribution system for analysis is broken down into:

The Transformer, which in turn breaks down into a subsystem that involves:

• Design (Coils, Core, Accessories, Tank, Insulation Level - BIL)
• Transformer construction process
• Operation and maintenance of the transformer

The Network, like the transformer, breaks down into design:

• Civil (Configuration, Route, Structures)
• Electrical: Protections (Surge Arresters, Circuit Breakers, etc.) Parameters (Power, Voltage, Regulation, etc.) Isolation Level (BIL) Grounding
• Construction process of previously designed elements (civil and electrical)
• Operation and maintenance of the network as a whole (Protections, structures and grounding)

The load, which is considered a subsystem composed of:

• Planning by the Energy Company, in which electrical parameters are taken into account (power, voltage, regulation)
• Operation by the user, being regulated by the energy supplier company.

The system environment, which is considered to be composed of:

• Natural phenomena that intervene in the fault (atmospheric electric discharges, wind, vegetation, etc.)
• Unnatural phenomena (pollution, human errors, vandalism).

An analysis of the Cause - Effect diagram and the 26 previous studies [4] related to distribution transformer failure, carried out in Colombia by consulting firms, energy companies and universities were analyzedand show that transformer failure has tried to be solved by modifying only the elements that make up the network, such as structures, protections, grounding, insulation, but not the transformer itself.
The 26 studies were classified into five groups as follows: Selection of protections; Analysis of Atmospheric Electric Discharges; Manufacture, selection and handling of transformers; Failure analysis, insulation coordination and Models.
A common aspect of the 26 studies is that none of them took into account the distribution transformer and its electromagnetic environment; raised the solution's supervision indexes and neither was a short- and medium-term follow-up, by monitoring and control of the proposed solution, nor cost / benefit ratio of the solution.
The failure of a distribution transformer occurs due to the interaction of various factors, which deteriorate it to a greater or lesser degree, leading to its final failure. One of the most useful analysis tools for processes of this type is the Cause - Effect diagram, also known as the Ishikawa diagram[26] (see Figure 1), which allows observing the interactions between the different factors involved and giving guidance on technological alternatives from solution.

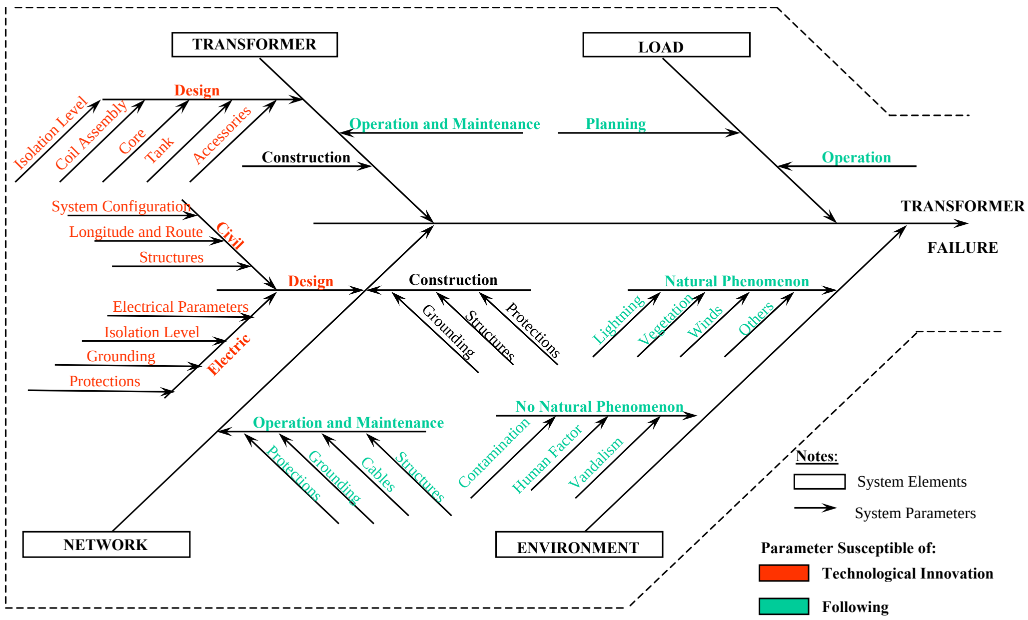

Figure 1. Diagram Cause-Effect for transformer failure analysis

To develop the Cause - Effect diagram, the following steps were followed:

- All relevant factors were identified by consulting the existing bibliography and subsequent discussion with expert engineers on the subject.
- The component subsystems of the system that intervene in transformer failure (transformer, load, network and environment) were determined.
- A diagram was prepared, Figure 1, which characterizes each subsystem of the system.
- The elements of each subsystem were chosen, taking into account which ones are susceptible to technological innovation and which can only be monitored.

2.3 Characterization of the environment

In studies on atmospheric electric discharges, carried out by the PAAS-UN Research Program, for more than 40 years, it has been found that Colombia, due to its geographical location in a tropical zone, presents variations in the magnitudes of the lightning parameters with respect to other latitudes [5], [6], [7].

Based on the multiannual data obtained from the Colombian Lightning Location Network for the Average Peak Current and the Ground Flash Density GFD, a Lightning Risk Factor matrix was elaborated [3] which indicates that there are areas in Colombia Severe, High, Moderate and Low Risk Level. See Figure 2.

The Lightning Risk Factor matrix was developed within the Colombian Technical Standard [3] based on the principle that the magnitude of the lightning current and the GFD, are the primary sources of damage. The 4 sources of damage and the 4 causes of damage were statistically analyzed, according to the methodology of the IEC 62305 Standard [26] and the multi-year data obtained with the Colombian Lightning Location Network [5].

LIGHTNING RISK FACTOR				
Ground Flash Density GFD [Flashes/km²- Year]	R_{iabs} R_{GFD}	Average absolute peak current [kA]		
		$40 \le I_{abs}$	$20 \le I_{abs} < 40$	$I_{abs} < 20$
30 ≤ GFD	1	1.000	0.895	0.790
15 ≤ GFD < 30	0.75	0.825	0.720	0.615
5 ≤ GFD < 15	0.50	0.650	0.545	0.440
GFD < 5	0.25	0.475	0.370	0.265

SEVERE HIGH

MODERATE LOW

Figure 2. Lightning Risk Factor

Figure 3 presents the Lightning Risk Factor Map of the Power Companyobtained based on Lightning Risk Factor. Its distribution, as can be seen, is not homogeneous, presenting areas of Severe Risk for Lightning in the Northwest, where an Experimental Pilot Circuit EPC waschosen to apply the proposed methodology.

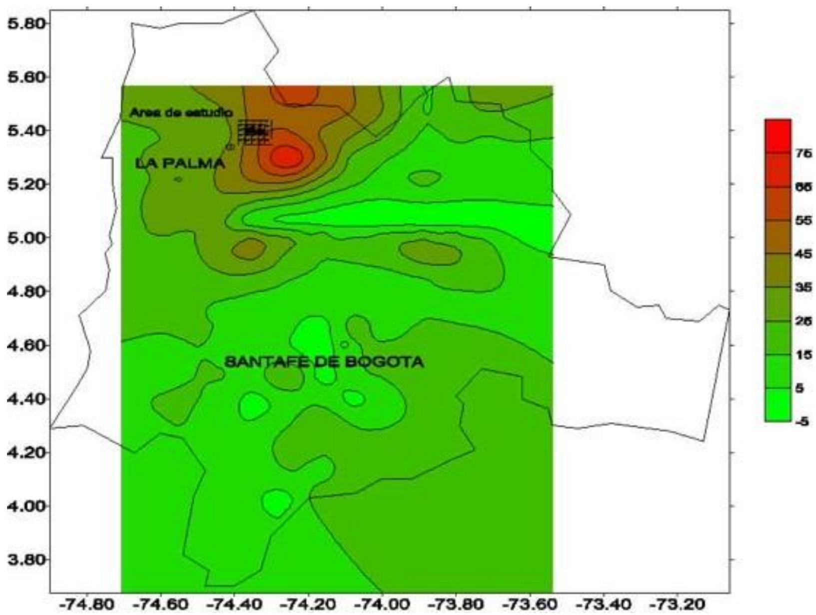

Figure 3. Lightning Risk Factor Map

An evaluation of the information available at the Electric Power Company on transformer failures shows highly correlated results between the areas of high mortality of transformers and Severe Risk from Lightning, as presented in the map of Figure 4 of Mortality of Transformers.

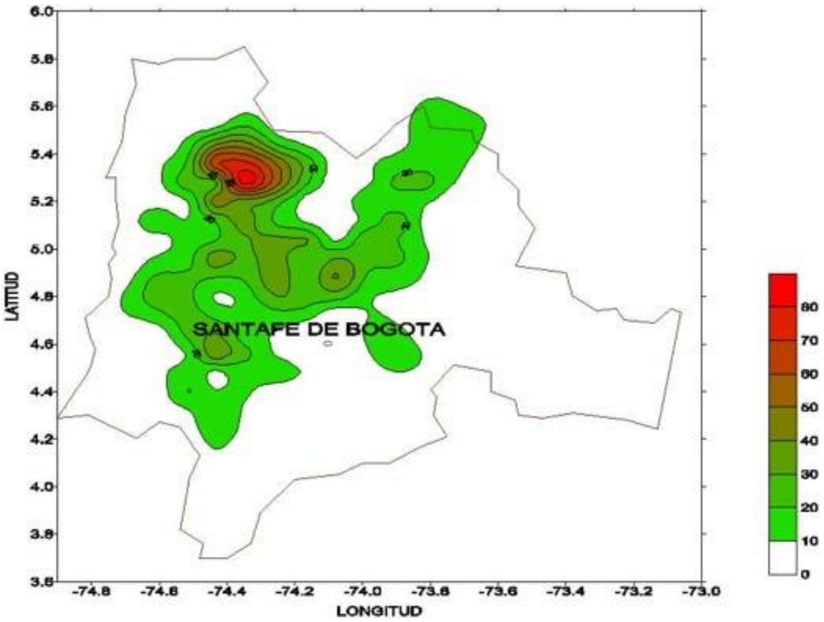

Figure 4. Distribution Transformer failure Map.

This observation raised the need to study in more depth the designs, modeling, maintenance, operation, handling and relationship of the transformer with the electromagnetic environment.
As an element of the diagnosis and follow-up, failure rates were studied for the transformers of the Power Distribution Electric Company, presented in Figure 5. The Useful Life Index was prepared with a sample of 2500 transformers. According to the Lightning Hazard Index, it was divided into three zones: Severe (81-100%), Moderate (41-80%) and Low Risk (0-40%).

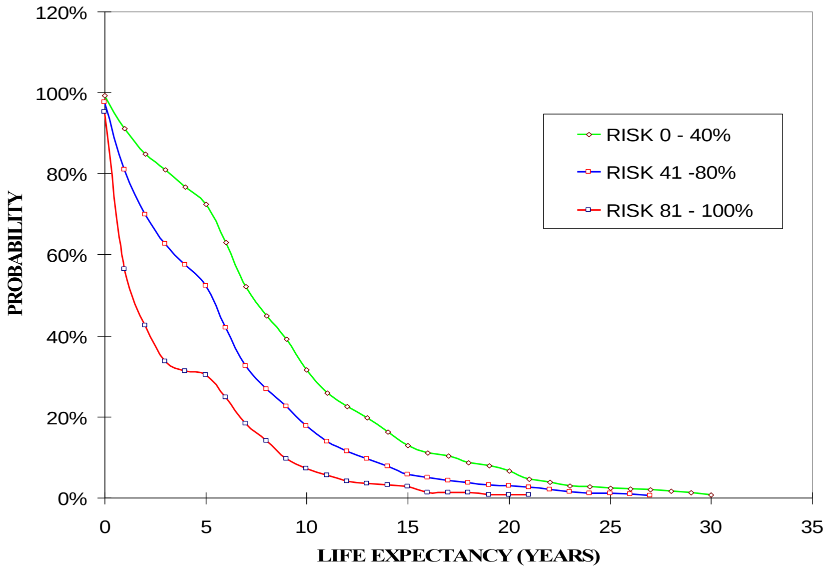

Figure 5. Probability of life expectancy [4],[5]

These curves show years of useful life of distribution transformers well below that guaranteed by the manufacturing companies, with values of 50% probable of 2 years for areas of Severerisk due to lightning, 6 years for Moderate risk and 8 years for areas of Low risk.

2.4 Electromagnetic Compatibility Zones (Lightning Risk Factor)

Reviewing the bibliography on the historical development of the measurements and estimates of the lightning parameters [4-24], a methodology was used that compared averages and characterized

regions. When researchers in lightning physics proceeded to classify the different regions of the earth, according to the different measured lightning parameters, they only took into account data from local measurements from northern latitudes and generalized them to the entire planet [8]. Thus, even today in the specialized literature (CIGRE) and in international technical standards (IEEE, IEC, NFPA) [27], [28], [29] there are probability distribution curves, for example, for the Lightning Return Current, measured in temperate latitudes. such as Europe, which are recommended to be used in lightning protection design, insulation design in electrical machines, shielding design in transmission lines, for any part of the world.
According to the IEC 801-3 [30] standard on Electromagnetic compatibility for industrial-process measurement and control equipment, the Electromagnetic Compatibility (EMC) is defined as the ability of electrical or electronic equipment or system to operate satisfactorily in its electromagnetic environment. Operating satisfactorily means not introducing intolerable disturbances in that environment or other equipment and withstanding those produced by the electromagnetic environment or other equipment or systems.
The design parameters of most electrical and electronic equipment have been estimated at non-tropical latitudes. However, on a local scale, in a tropical environment, their particular operating conditions do not always coincide with the conditions for which they were designed; that is, the electromagnetic environment in which they will operate is not taken into account. A better knowledge (characterization) of the requirements of the electromagnetic environment existing in the Colombian tropical environment can quantify the levels of disturbance and the interaction between sources and receivers (the environment and the equipment or systems).
Said characterization leads to the proposal of zoning the phenomenon of the disturbance of atmospheric electric discharges, determining Electromagnetic Compatibility Zones; being able to arrive at the proposal of changes in the design of equipment and in the construction standards of the Company, which can later be taken to national technical standards.
After the Comprehensive Diagnosis of the transformer failure problem, we proceed to propose technological alternatives to solve the problem. Once these alternatives have been analyzed, one or more is chosen and the proposed solution is designed and implemented in a comprehensive manner.

2.5 Modeling of capacities and inductances of distribution transformer

Normally the coils of standard distribution transformers of small rating powers (5-112.5 kVA) are manufactured in elliptical shape.
The ellipse is still a complicated geometry, therefore, to find the capacity between these two elements, the mathematical method of Conformal Transformation is used, or "Conformal Mapping", which allows the solution of problems with value at the border, within the theory of the potential calculation. With this, the transformation of a "complicated" region into a simpler one in the new plane is achieved, making use of the axiom: "The capacity is invariant under a conformal transformation".
The deduced expression starts from two elliptical elements of infinitesimal thickness, confocal and with greater radii R_1 and R_2. By doing two successive transformations to the region between these two ellipses, we arrive at the expression of the equation:

$$C = \frac{2.\pi.\varepsilon.l}{arcosh(R_2/c) - arcosh(R_1/c)} \qquad [F]$$

Where:

$\in = \in_0 \in_r$

$\in_0$ = Empty permittivity = 8.85*10-12 [F/m]

$\in_r$ = Relative permittivity of dielectric.

l = Winding height [m]

R_1 = Major semiaxis of curve 1 [m]

R_2 = Major semiaxis of curve 2 [m]

c = Coordinate of focus [m]

The inductance calculation expressions reported in the literature are applied to windings of circular section. When the winding geometry does not present a cylindrical symmetry, they do not allow to reliably evaluate the inductance value, being necessary to propose new expressions for its calculation. The starting point for the calculation is the Neumann equation [31], which expresses the mutual inductance between two circular elements in free space, separated by a distance (d) in space. Posing this equation in mathematical terms, using the equivalent radii r_1, r_2 of the parametrized ellipses as a function of an angle ψ, an expression is obtained that represents the mutual inductance between two elliptical elements.
Generalizing the equation found for two windings of lengths l_1 and l_2 with N_1 and N_2 turns respectively, with a separation distance between the two layers equal to zero (for coaxial coils), we find the equation:

$$M = \mu_0 N_1 N_2 \int_{-l_2}^{l_2} \int_{-l_1}^{l_1} \int_{0}^{\pi} \frac{r_1 r_2 \cos\psi' \, d\psi' \, dz_1 \, dz_2}{\sqrt{(z_1 - z_2)^2 + r_1^2 + r_2^2 - 2 r_1 r_2 \cos\psi'}}$$

Where:

N_1, N_2 = Number of turns per unit length of each winding in the axial direction.
ψ '= Angle of azimuth.

The parameters of each and every one of the designed and built transformers were measured in the laboratory and compared with the mathematical models developed for the EMTP / ATP digital program. The results of more than 50 transformers tested in the laboratory and modeled in the EMTP / ATP show a very good correlation between the values obtained with the mathematical model of the distribution transformer and those obtained in the measurement, with errors that did not exceed 10%.
A sample of these results of calculated and measured,at a frequency of 60 Hz, ofInductances and Capacities values is presented in Table 1.

Table 1. Arithmetic average value of capacitances and inductances measured at a frequency of 60 Hz.

Coil	C_g HV (pF)	C_g LV (pF)	C_{HV-LV} (pF)	L_{HV} (mH)	L_{LV} (mH)
Calculated value	471.2	621.8	897.1	662.9	305.8
Measured value	424.0	649.0	817.0	468.5	268.8

2.6Modeling in EMTP / ATP digital Program and evaluation of the Transferred Pulse
The digital program for the analysis of electromagnetic transients (EMTP / ATP) allows, with the help of an adequate modeling, the prediction of the behavior of electrical systems in steady state conditions or in transitory state conditions.
In this research, the EMTP / ATP was used to evaluate the behavior of the system in terms of overvoltage present in the network, transformers, surge arresters and load, when lightning impacts occur on the distribution network, depending on the different types of installed transformers.
Three models were developed for each transformer, each one of which allows representing its behavior for different frequency ranges, taking its constructive simplicity as a premise. The methodology used to derive these models has as its starting point the classical circuit network used to represent the behavior of transformers at 60 Hz, gradually adding the capacities and observing their behavior when different excitation waves are applied, simultaneously comparing with the experimental results.
The first of them corresponds to the low frequency model, which adequately represents the single-phase transformer up to a frequency of the order of 2 kHz, with any type of signal. The medium frequency model, for frequencies between 2 and 250 kHz and finally the high frequency model with which the behavior of transformers can be adequately represented before transient phenomena such

as the impact of lightning. Every model must comply with a general rule in which both its constructive simplicity and the degree of accuracy to be obtained are related.

The modeling was done using the TRANSFORMER subroutine, which allows modeling, in addition to the resistances and stray reactance of each of the windings, the magnetization branch through a resistance representative of the losses in the core, in parallel with a Non-linear element that corresponds to the magnetization characteristic of the material. The EMTP / ATP program has different sources to simulate different types of signals, sine waves, pulse, square etc.

With the help of the transformer model for high frequencies developed for the EMTP / ATP, the measurements carried out on the different types and powers of transformers and theoretical calculations, the mathematical models of each and every one of the types and transformer powers, in order to evaluate the phenomenon of voltages transferred between the high voltage winding and the low voltage winding and, in this way, analyze which is the best configuration for it.The main change in the design of the prototype PROT transformer was the placement of the High Voltage winding - core, that is, in contact and isolated from the core. With this change, the capacity between high and low voltage changes with respect to a standard design and the transferred pulse decreases. By placing the high voltage coil-core, the insulation must be increased and the BIL of the transformer increases.In section 3 of this paper the other characteristics of the prototype transformer PROT are presented.

The objective of the simulations presented below was to compare the behavior of the transformer that we have called New Design Prototype PROT with that of standard design transformers.

For this purpose, the following types of transformers were chosen:

- Standard design transformer, BIL 95 kV. Low vs. Core Construction. (to be called from now on TYPE 1: 95 BN).
- Standard design transformer, BIL 95 kV. High construction against core. (to be called from now on TYPE 2: 95 AN).
- Standard design transformer. BIL 150/45 kV. Low vs. Core Construction. (to be called from now on TYPE 3: 150 BN).
- Prototype transformer new design PROT. BIL 125/30 kV. High Voltage winding - core, that is, in contact and isolated from the core. (Called TYPE 4: PROT).

The simulations were performed by comparing the transformers separately, based on the pulse transferred from unit step and pulse waves, to a setup like the one shown in Figure 6.

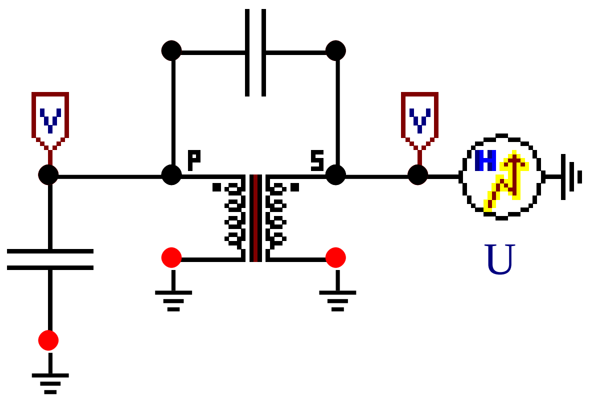

Figure 6. Transformer model in the EMTP / ATP for transferred pulse analysis

Figure 7 were obtained, for each of the four types of transformers. As can be easily observed, the New Design Prototype PROT transformer presents pulse voltage values transferred from Primary to Secondary 4 times lower than the standard manufacturing type with increased BIL and 6 times lower for standard type transformers.

After simulating each of the transformers individually, we proceeded to simulate each of the system components (surge arresters, grounding, lines) and completely the experimental circuit.
The characteristics of the Experimental Pilot Circuit EPC that were taken into account for the simulation were the following:

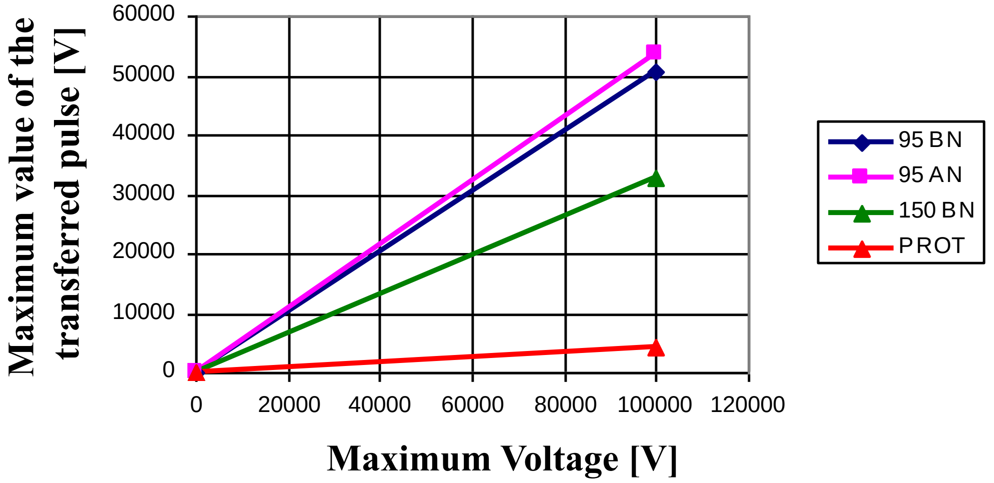

Figure 7. Pulse transferred for four types of transformers (lightning wave)

- Two simulations of the complete circuit were made calculating the parameters of the lines for high and low frequency using the JMarti model of variable parameters with frequency.
- The structures used are 12m high and have a 6m separation between high voltage conductors. In low voltage, single-phase lines of 100m in length and a separation of 40cm between the conductors were simulated.
- Soil resistivity was assumed to be constant 500 Ohm-m at all sites in the network.
- It was assumed that the loads connected to each of the phases were approximately balanced.
- The load connected to each of the transformers is the same as that placed in the simulations of the transferred pulse.

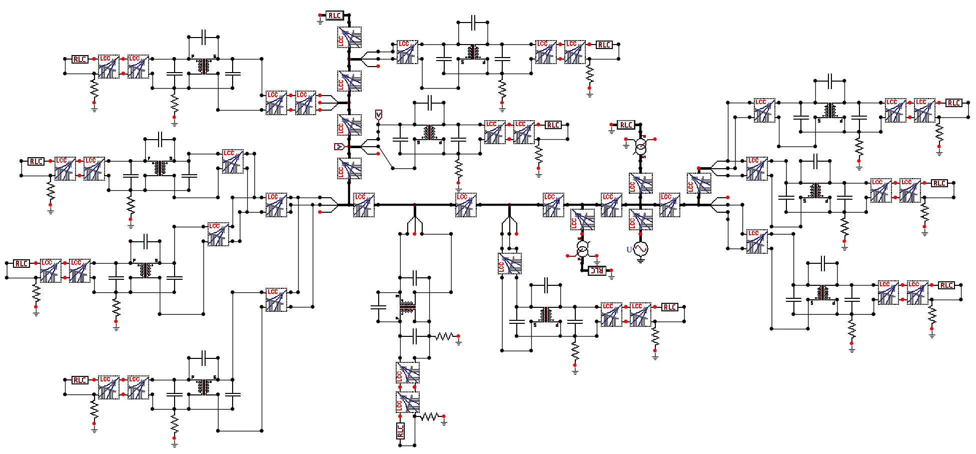

Figure 8. Experimental Pilot Circuit EPC mounted on the EMTP / ATPDraw digital program.

The simulations that were carried out are of typical events that occur in distribution networks in areas of high lightning activity.In the EMTP / ATP model of figure 8 lightning wave impacts were randomly modeled at different points in the network.

2. 7 Field implementations of the proposed solution

The EPC selected with the information on lightning activity for the last 5 years and an average useful life of the transformers of less than 2 years, is a rural three-phase medium voltage network, 13200 kV, with wooden poles and guard cable. 14 standard transformers of different nominal capacities (from 5 to 112.5 kVA) with their corresponding surge arresters.

The EPC circuit model where the Prototype New Design PROT transformers were installed corresponds to the one located in a rural municipality with high lightning activity (GFD greater than 10 lightning strikes / km2-year, see figure 3), whose single-line diagram is shown in Figure 9.The EPC has an approximate length of 7.5km and is comprised within a 6km x 3km area.

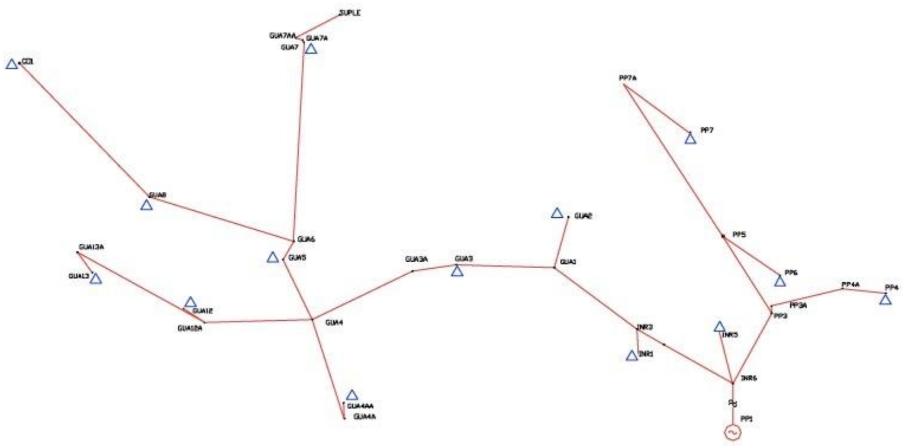

Figure 9. Experimental Pilot Circuit EPC

The 14 standard transformers were replaced by 14 PROT transformers. Continuous monitoring with the Colombian Lightning Location Network was carried out during the 3 years of the project in order to be able to evaluate the incidence of lightning and, in case of failure, if the origin was one of them. When conducting a 3-year temporal analysis of lightning activity with the Colombian Lightning Location Network.

A filtering was carried out to identify those discharges that impacted in a range of less than 100m, around the corridor of the line. The maximum current was –47.83kA and 46.02kA. Making a projection of the data taken for a whole year, the density of lightning strikes per square kilometer GFD would be approximately 19, which is consistent with the historical density maps of the area

Figure 10 shows as an example the lightning activity during the first year (58 lightning strikes) less than 100 meters from the electric power distribution network without presenting any failure of the 14 PROT transformers.It was found that storms occur probabilistically in the afternoon and part of the night.

In the three years of follow-up to the EPC, the result is similar to that modeled. It has been possible to reduce the failure rate of transformers in this circuit from 50% prior to the installation of the New Design Prototype transformers PROT to 0% in the first year, to 7% in the second year and 0% in the third year, with more than 130 discharges presented within 100 meters of the circuit, according to the Colombian Network of Lightning Detection.

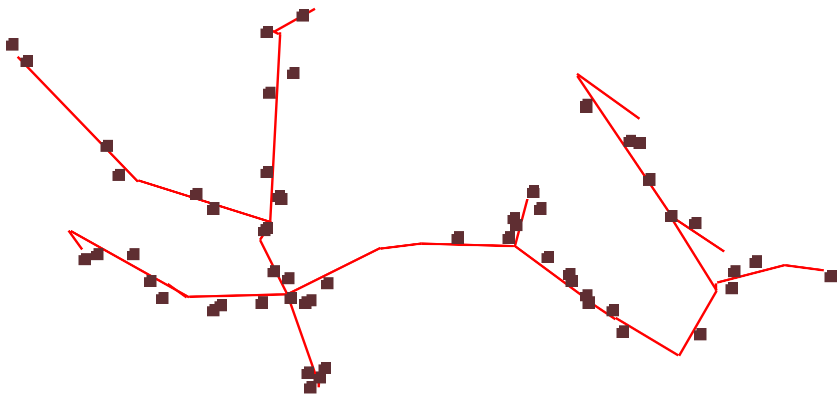

Figure 10. Atmospheric Electrical Activity (58 discharges) in a year, 100m around the EPC Experimental Pilot Circuit.

III. Results and Discussion

The most significant results of a systematic and successful theoretical-experimental investigation of more than 12 years have been presented in this paper, the purpose of which has been to contribute to the solution of the costly problem of the failure of distribution transformers installed in areas of highlightning activity, which affects the reliability of electric power companies in Colombiaand countries with high lightning activity.
Following the applied methodology and in conjunction with transformer manufacturing companies and an Electric Power Company, the design, construction and implementation of a technological innovation: New Design Prototype Transformer PROT, which iselectromagnetic compatible in zones of high lightning activity.
Prototype PROT transformers were designed and built with the high voltage winding-core, that is, in contact and isolated from the core, since according to the calculations and simulations carried out, the pulse transferred from high to low is lower due to having a higher high-low capacity than a conventional transformer. The individual cost of the PROT transformer may be higher, but if its probability of life expectancy is longer, its value to the customer will decrease.
As a result of the experiences with the Experimental Pilot Circuit EPC and the Lightning Measurement Experimental Station (Ilyapa) of the National University of Colombia, the following are, in summary, the eight Basic criteria to take into account for the optimal operation of the New Design Prototype Distribution Transformer PROT:

- Greater robustness: Increased transformer BIL 125/30 kV.
- Reduction of Transferred Pulse: Coil-Core Design. High voltage winding- core
- Easy handling: Modification of the mechanical supports for transport in hard-to-reach areas
- Improvement of Protections: HV and LV arresters, Self-protection (CSP), additional network protections if necessary
- Proper handling and installation: at least 24 hours of rest before energizing.
- Improvement of Grounds: Grounds of low ohmic value.
- Permanent monitoring and maintenance of the system - environment (Network, protections, transformer, grounding, vegetation)
- Evaluation of the cost / benefit ratio

A self-protected CSP transformer includes, from its design stage, protection elements against overvoltage, overloads and elements to isolate it from the network in case of internal or external failures.
Regarding the last criterion, we have evaluated the cost / benefit ratio for the transformers installed in the EPC. We have considered the worst case, that is, a New Design Prototype transformer PROT cost 1.5 times the cost of a standard transformer. Nowadays the cost of the New Design Prototype transformer depends on several aspects such as the manufacturer and the number of units to purchase, but it can have a cost equal to that of a standard. Additionally, having considered a cost of 1.5 times, it was

done on the basis of the construction of a single transformer; however, due to economies of scale, the cost will decrease as hundreds or thousands of them are built. The results obtained for the worst case are as follows:

A time horizon of 10 years was considered with a number of 100 transformers installed in year zero, an annual growth in demand of 2%. A unit value of 1000 in per unit (p.u) was estimated for a standard design transformer and 1500 in the case of the New Design Prototype transformer PROT, for an average power of 15kVA.

The costs of the New Design Prototype PROT (1500 p.u) include: manufacturing costs (CSP, low voltage protection, improved BIL in High and Low Voltage, tank adaptation, land improvement and easement cleaning). The cost of labor for changing the transformer is not taken into account. This cost would be in favor of the costs of the New Design Prototype PROT, since it would have a longer useful life, therefore fewer changes.

The EPC located in one of the two areas with the highest lightning activity in the world, show promising results for the solution to the problem of failure of distribution transformers in Colombia and improvement of the reliability in power systems. For example, after installing the New Design Prototype PROT transformers, the failure rate went from 50% for a period of 7 years, to 0% in year one, 7% in year 2 and 0% in year 3.

The effect of lowering the ground value for high (impulse) frequencies does not have a great impact on the surges received by the transformer, although a value less than 20 ohms is desirable, to guarantee a reliable operation of the surge arrester.

The transformer, once installed on the pole, must be allowed to stand for at least 24 hours, due to the shaking it experiences in transport to the installation site.The Colombian rural area is very mountainous with bridle paths. Handling a distribution transformer along these rough roads causes the insulating oil to easily form air bubbles that diminish its insulation and requires at least 24 hours of standing before energization

The research on the reliability in electric power systems is part of the theoretical and practical results of a research hypothesis and its applications, about the spatial and temporal variation in the magnitude of the lightning parameters that has been developed, published and tested in the last decades in lightning research in Colombia.

Through a process of interdisciplinary, rigorous, systematic and scientifically based research, it was possible to contribute to the knowledge of a natural phenomenon that due to its physical and meteorological characteristics is very different in the tropical latitude than in temperate latitudes, where this type of phenomenon generally develops research [4], [5], [7].

The hypothesis has been implicit in all the works that the author has carried out and directed in the PAAS-UN Research Program and has been demonstrated in papers of international academic arbitration.

The hypothesis is based on the scientific principles proposed by the English physicist Wilson in 1920 [1, 2], on the Global Electric Circuit and the dominant contribution, by a superposition of effects, of the three largest areas of Deep Tropical Convection on the planet: South America Tropical, Central Africa and South East Asia and Australia.

Although the areas of Deep Tropical Convection were identified at the beginning of the 20th century as having high atmospheric electrical activity, until a decade ago most of the information available on the characteristics and magnitudes of the lightnings was based on studies carried out in semi-tropical areas or temperate, but very few in tropical areas.

After studying a vast area in Central Colombia, it is found high lightning active areas agree with the location of important portions of the power overhead distribution lines and a high number of power distribution transformers. 26.4% of the total power transformers are located in high or very high lightning active areas and their failure rates increases to an average of 13 (high) and 45 (very high) times higher than to the considered normal weather condition. Extremely large power overhead lines reach failures rates 175 time higher than normal [5].

Torres [4], [5], [32] studied the failure of power distribution transformers in Colombia and found the cumulative distribution of lifetime given in Figure 5. In low-risk areas (risk given as a function of Ground

Flash Density GFD) the mean lifetime was higher than 8 years, in medium risk zones it was 5 years and in severe risk the life time was close to 1.5 years. Data from Torres [4] show that approx. 65% of the transformer fails occur in the lightning active seasons.
Failure rates of rural power systems are statistically studied based on lightning parameters and a two-state weather model (normal and adverse). Lightning information is matched with coordinates of 251.024 power transformers in a vast area in Central Colombia [25]. An important portion of transformers present failures rates 45 times higher than normal and very large overhead lines, representing a high portion of the total system, present very high failure rates over 70 times higher than in normal weather conditions [5].
These results show that a technological product such as an electric power distribution transformer has a different behavior in tropical zones with high lightning activity than in a temperate zone. Therefore, it is essential that these technological products have electromagnetically compatible designs with the environment and thus improve the reliability of electrical power systems.
It is advisable to continue with the monitoring and control phase for at least another five years and expand the comprehensive solution to other areas of high lightning activity.

IV. Conclusions

These technological innovations, after a comprehensive diagnosis such as the one presented here, can be applied to circuits located in high-risk lightning areas.These leads to the proposal of zoning the lightning phenomenon, determining Electromagnetic Compatibility Zones; being able to arrive at the proposal of changes in the design of equipment and in the construction standards of an electrical power company, which can later be taken to national technical standards.
Through the zoning found with the parameter "Lightning Risk Factor", three types of adaptation are proposed for the distribution systems (Low, Moderate and Severe), so that they are more in line with the surrounding conditions.
For severe-risk areas, the technological innovation New Design Prototype transformers PROT, new grounding designs and more robust protections would be installed; in low-risk regions, use standard design and for moderate risk regions implement a combination of new design and standard design.

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