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Lightning effects on distribution transformers and reliability of power distribution systems in Colombia

Efecto de los rayos sobre transformadores de distribución y confiabilidad de sistemas de distribución de energía en Colombia

D. Aranguren[1], C. Tovar[2], J. Inampués[3], J. López[4], E. Soto[5], and H. Torres[6]

ABSTRACT

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 geographical coordinates of 251,024 power transformers in a vast area in Central Colombia. An important portion of transformers present failure 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 75 times higher than in normal weather conditions.

Keywords: Power reliability, lightning, weather reliability model, tropical zone.

RESUMEN

Las tasas de falla de sistemas rurales de distribución de energía en Colombia son estudiadas a partir de parámetros del rayo y un modelo de tiempo atmosférico de dos estados (normal y adverso). La información de rayos es correlacionada con la ubicación de 251,024 transformadores en una amplia zona en el centro de Colombia. Una parte importante de los transformadores presenta tasas de falla 45 veces mayor que lo normal y redes extensas de distribución muestran tasas de fallas 75 veces mayores a las esperadas en condiciones consideradas de tiempo normal.

Palabras clave: Confiabilidad de sistemas de distribución, rayos, modelo de confiabilidad de tiempo atmosférico, zona tropical.

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Introduction

Reliability levels of power distribution systems in Colombia are apparently low compared to those of developed countries, and are even lower than those of similar developing countries. The US National Research Council (2012) published a comparative study of SAIDI (System Average Interruption Duration Index) around the world. SAIDI in European countries, United States and Japan is in general lower than 300 min; in tropical countries such as Brazil and Indonesia SAIDI averages approximately 1000 min; whereas in Colombia SAIDI is 9480 min (158 h). That huge difference has several possible explanations; the first logical analysis is to focus on the levels of investment and technology use; however, the Colombian power regulation, based on an open market scheme, encourages power utilities to continuously improve their reliability indexes, so that even though the levels of investment are not high, these are not so different from other developing countries. In this sense, another explanation based on local conditions is required. Studies such as Tolbert et al (1995), Alvehag et al (2011) and others, carried out in United States and Sweden, reveal that severe weather is the most recurrent outage cause of power distribution systems, commonly with more than 50% of the cases, where wind and lightning are the two major externalities.

Several investigations have shown that one of the most lightning active areas in the world is located in Colombia. The lightning phenomenon has its maximum occurrence in tropical regions and its physical parameters present variations compared with those typically observed in other

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regions of the world (Torres et al, 1996; Torres 1998). One of the most lightning-active zones worldwide is the region that connects the Magdalena River Valley in Colombia with the Catatumbo in Venezuela. Besides the geographical location, the big mountains in this region represent very dense lightning locations, which are within the highest Ground Flash Densities - GFD reported (Aranguren et al, 2015). This paper investigates the effect of the lightning activity in Colombia on the reliability of power distribution systems and tries to state if lightning is responsible for the major portions of the value of reliability indexes such as SAIDI. Failure rates of medium voltage systems and their behavior along the year depend on the lightning incidence parameters which are described in sections below.

Lightning activity in Colombia

For decades, several investigations have been carried out in Colombia in order to characterize the lightning physical parameters. The Colombian Weather Service (HIMAT) and the National University of Colombia published the first Keraunic Level (Thunderstorm Days - TD) Map in 1990 (Torres, 1990), where some regions exposed more than 140 thunderstorm days per year. High values of TD were found in the Magdalena River Valley, Cauca River Valley, Catatumbo and others. Younes (Younes, 2002) presented the first Ground Flash Density map obtained from a lightning location network called RECMA (composed by six LPATS sensors and using baselines from 190 to 480 km). The historic dataset comprised five years from 1997 to 2001 and the used computing area was 3 x 3 km. According to previous described data, the above mentioned regions presented GFD values up to 34 cloud-to-ground flashes/km^{2}year. A new evaluation of Ground Flash Density was carried out in 2008 (Gallego, 2010) by using a dataset from 2007 to 2008 and the same computing area (3 × 3 km); the maximum GFD was higher than 60 CG-flashes/km^{2}year, almost twice the GFD values found in 2002.

The most recent and accurate lightning detection system was installed in 2011 based on VLF/LF LINET sensors, using baselines from 120 to 420 km. Aranguren et al (2014) studied the GFD by using a two-year database (2012 to 2013) and a computing area of 3 × 3 km. The map on Figure 1 gives the GFD for Colombia based on the LINET lightning data (study area corresponds to the approximate area of maximum Detection Efficiency of the Lightning Location System). Maximum values are close to 60 flashes/km^{2}year. Previous lightning detection systems did not have a good performance for lightning flashes with peak currents lower than 10 kA. In order to carry out comparisons with previous datasets, only CG flashes with peak currents higher than 10 kA were considered for the GFD computation for Figure 1. If the entire dataset is used, the maximum GFD is 92 (Aranguren 2014).

The Magdalena Medio region (Medium Magdalena River Valley) presents a Ground Flash Density - GFD close to 60 flahes/km^{2}year. The GFD map on Figure 1 also shows a clear dependence of the lightning incidence on the topography of the country. The highest altitude zones of the Central and Eastern branches of the Andean Mountains are coincident with very low values of GFD, less than 1 flash/km^{2}year or even 0 in many parts. On the other hand, the highest GFD values are found along foothills and lowlands.

The relationship between Keraunic Level – KL and Ground Flash Density – GFD is depicted in Figure 2 using 8152 areas of 10 x 10 km, approximately 71 % of the Colombian continental territory (Aranguren, 2014). GFD exponentially increases with KL, however in a wide dispersion range. For instance, if KL is 80 thunderstorm days, the GFD moves from 1.2 and 10.5 flashes/km^{2}year; if KL is 140 thunderstorm days, GFD varies from 6.5 to 51.5 flashes/km^{2}year. The maximum GFD matches a KL of 132, while the maximum KL is 218 thunderstorm days.

The most accepted equation that relates GFD (denoted as Ng) and KL (denoted as TD) was proposed by Anderson (1984), using five years of historic data from South Africa (1). That expression was adopted by standardization organizations such as CIGRE and IEEE. The range for TD was from 4 to 80 thunderstorm days, the range for Ng was 0.2 to 13 flashes/km^{2}year and the relation between both variables was almost linear. Unlike Anderson's equation, GFD and KL in Colombia present a much higher variation range and a non-linear relation. Torres (2003) adapted Anderson's equation to the Colombian historic data and obtained a non-linear relation (2) where the Ground Flash Density (N_g in Equation (2)) takes very high values when the Keraunic Level (T_D in Equation (2)) increases.

$$N_g = 0.04 T_D^{1.25} \quad (1)$$

$$N_g = 0.017 T_D^{1.56} \quad (2)$$

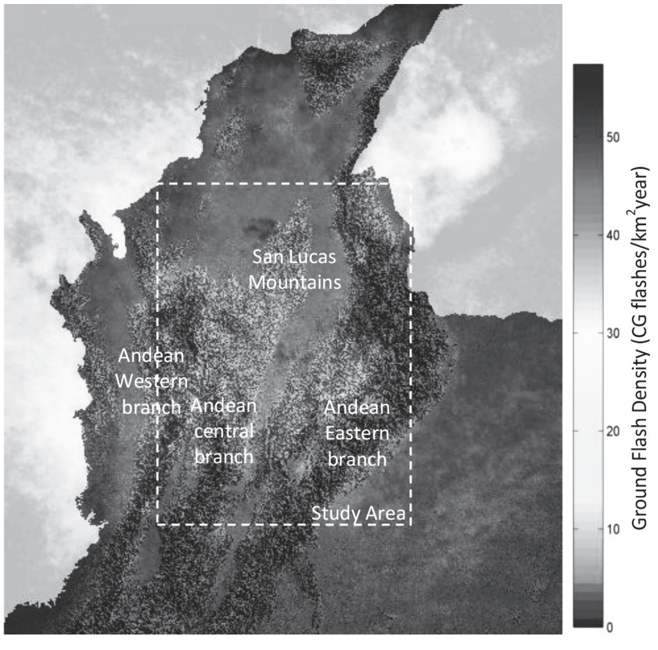

Figure 1. Ground Flash Density (CG flashes/km^{2}year) by Aranguren et al (2012) (Dataset: 2012 and 2013). Peak currents higher than 10 kA are used.

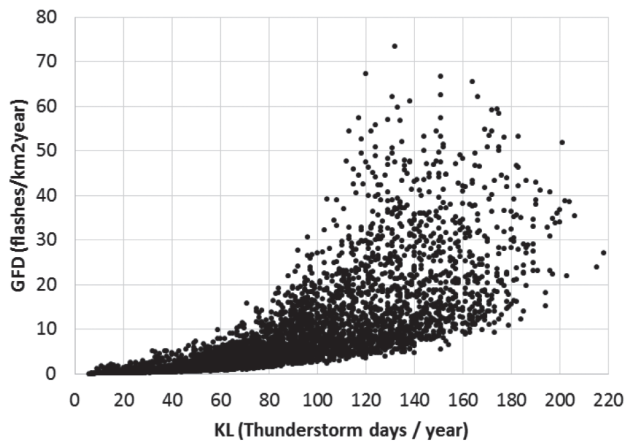

Figure 2. Ground Flash Density vs. Keraunic Level (2012-2013).

The number of CG flashes per month from 2012-2013 dataset is shown in Figure 3; in central Colombia a bimodal pattern is observed with maximum number of flashes in April to May and September to November, whereas in northern Colombia a monomodal behavior is clear with maximum activity during June, July and August. Figure 3 also gives the number of flashes detected as a function of the hour, in local time.

Most of the flashes are detected from 17 to 02 h. The minimum lightning incidence is observed from 08 to 13 h. Previous studies at tropical zone, such as Pinto et al (2003) in Southeastern Brazil, showed that the lightning activity is commonly observed from 12 to 24 h in local time, with a maximum of number of flashes at 17 h. Colombian datasets expose that not only during the afternoon but also during night and down the thunderstorms are very active, which partially explains the very high GFD values (Aranguren 2014).

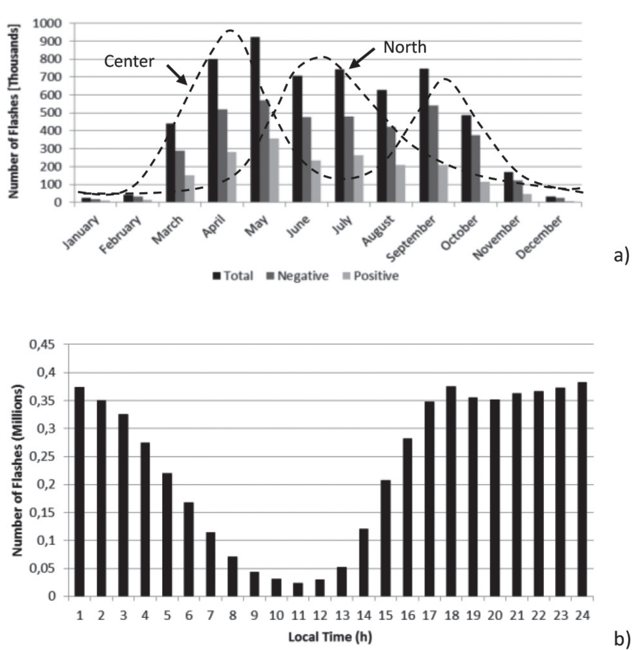

Figure 3. Lightning behavior in time. a) Monthly variation of the number of flashes. b) Hourly variations of the number of flashes.

Colombian Power Distribution System

The Colombian Power Distribution System (*Sistema Interconectado Nacional* - SIN) general features are stored at the SUI (*Sistema Único de Información*) database, managed by the CREG (*Comisión de Regulación de Energía y Gas*). The most important parameters related to the reliability of the system were studied by Keraunos and CREG (GREG, 2013). SIN is currently composed by 208,244 km of 11.4, 13.2 and 34.5 kV power lines, with 5,079 circuits and 496,908 power distribution transformers. Nearly 70 % of the circuits are located in urban areas, with an average length per circuit of 12.5 km and average rated load of urban power transformers of 112.5 kVA. On the other hand, the remaining 30 % are rural circuits with lengths from 50 to more than 500 km and an average rated load of 15 kVA for rural power transformers; as a consequence, the very long rural power distribution circuits represent approximately 75 % of the total length of the Colombian Power Distribution System.

The last results show that Colombia presents a strong urban-rural dichotomy, where very long medium voltage power networks in rural areas are used instead of higher voltage transmission systems. Consequently, medium voltage systems are more sensible to externalities such as lightning activity. Failure rates of rural systems (commonly higher than 0.5 failure/km year) are more than 30 times higher than in urban systems, and repair times (Mean Time To Repair - MTTR) considerably increase when the Rurality Level - RL (Index that measures the population density and distance to urban centers (UNPD, 2011)) increases. Figure 4 presents the MTTR for power distribution transformers as a function of Rurality Level in Colombia (CREG, 2013). Big urban centers have an RL of 1, intermediate populated regions have an RL of 2 and 3, and an RL of 4 and 5 applies for very remote areas. Note that MTTR for urban centers is approximately 0.5 days whereas in intermediate populated areas it is close to 2.5 days, and in very remote areas it is close to 4 days.

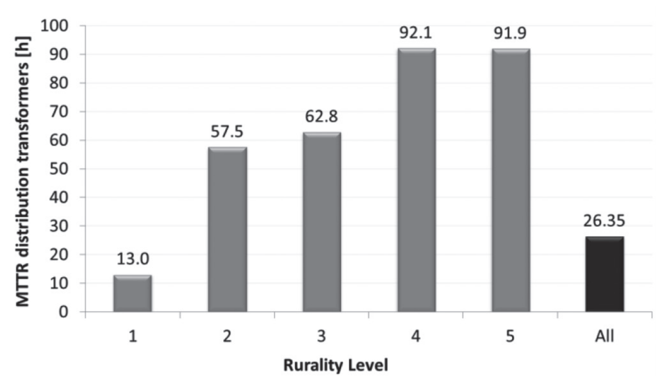

Figure 4. Mean Time To Repair – MTTR for power distributions transformers in Colombia, according to the Rurality Level – RL (1: Urban centers, 2, 3: intermediate populated areas, 4,5: very remote areas (UNPD, 2011)).

Lightning and failure Rates

Weather effects on power reliability can be considered by using a two-state weather model including at least two weather environment conditions (IEEE 346): normal and adverse. Failure rate in normal environment conditions (λ_0) is generally related to fire weather and failure rate for adverse weather (λ') is commonly related to severe weather, including lightning and intense winds (Figure 5). An average value of failure rate (λ) can be derived from λ_0 and λ', according to the time periods *S* and *N* in Figure 4, as described in Equation (3).

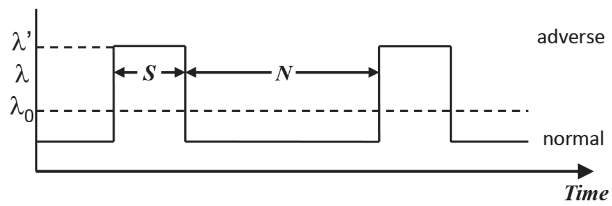

Figure 5. Failure rate in a two-state weather model.

$$\lambda = \frac{N}{N+S}\lambda_0 + \frac{S}{N+S}\lambda' \qquad (3)$$

Commonly, power distribution systems present short periods of severe weather conditions, that is to say *S* is many times shorter than *N*, and therefore the average failure rate λ in a calendar year is close to the normal failure rate λ_0.

The Colombian case may present a different situation. The Keraunic Level in Colombia, as described in Figure 2, is higher than 100 thunderstorm days per year in several regions; from Figure 3 it may be noted that lighting activity can also extend throughout much of the day. Thereby, *S* becomes comparable to *N* and, in some few areas, where the Keraunic Level is close to 200, *S* may be considered even higher than *N*; hence, the average failure rate λ in a calendar year could be closer to the severe weather failure rate λ' than to the normal failure rate λ_0.

Lightning failure rate during severe weather λ' for power overhead distribution lines is estimated by considering direct strikes and indirect induced overvoltages (IEEE1410). Equation (4) gives the number of lightning strikes per km N_s according to the Ground Flash Density N_g, the height *h* and width *b* of the line.

$$N_S = N_g\left(\frac{28h^{0.6}+b}{10}\right) \qquad (4)$$

Lightning induced overvoltages have a much more complex computation; this involves a lightning channel model, electromagnetic coupling and a model for electromagnetic transients on the overhead power lines. Studies such as Torres (2003) have shown that close to 90% of the failure rates of rural overhead lines are produced by indirect lightning induced overvoltages.

Lightning-caused failures rates in transformers and overhead lines

Current power distribution systems within the study area in Figure 1 (area of maximum detection efficiency of the Lightning Location System) have a total of 251,024 distribution transformers. Figure 7 gives a more detailed description of a smaller area corresponding to the most lightning active area in Colombia: the Magdalena River Valley and nearby mountain areas. Several very dense lightning zones are identified at some localities such as Samaná, Puerto Berrío, Nechí, Guarandá and others.

Black dots in Figure 7 illustrate the location of power distribution transformers along medium voltages power systems. Geographical coordinates of each transformer were matched with the GFD values computed by using 3×3 km^2 cells and the 2012-2013 cloud-to-ground lightning dataset. Approximately, 66,380 power distribution transformers are located in the high lightning active area in Figure 6, with a GFD higher than 8 flashes/km^{2}year; this number is slightly higher than the total number of transformers in the most populated city in Colombia (Bogotá, approx. 8 million people). On the other hand, 5,898 transformers matched extremely high lightning dense areas with a GFD higher than 25 flashes/km^{2}year.

Cumulative probability distribution of Ground Flash Density that matches the precise coordinates of the 251,024 power distribution transformers in the study area is given in Figure 6. The average GFD for the total 251,024 transformer's coordinates is 6.8 flashes/km^{2}year. Transformers in the high lightning active areas (GFD>8 flashes/km^{2}year) represent 26.4% of the total number of power transformers installed within the studied area.

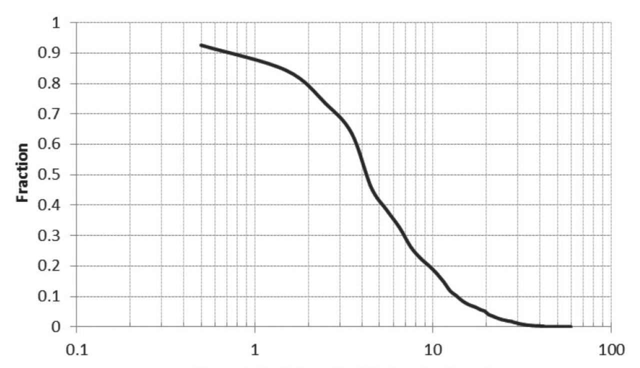

Figure 6. Cumulative distribution of Ground Flash Density (flashes/km^{2}year) for 251,024 power distributions transformers within the study area.

Torres (1996) studied the failure of power distribution transformers in Colombia and found the cumulative distribution of lifetime given in Figure 8. In low risk areas (risk given as a function of GFD) the mean lifetime was higher than 8 years, in medium risk zones it was 5 years and in high risk the lifetime was close to 1.5 years. Data from Torres (1996) shows that approximately 65 % of the transformer fails occur in the lightning active seasons.

Combining results from Torres (1996) and the cumulative distribution given in Figure 5, it is possible to estimate that approximately 66,380 power transformers in the area of Figure 6 could have a mean lifecycle of 5 years, and 5,898 may have a mean lifecycle of 1.5 years.

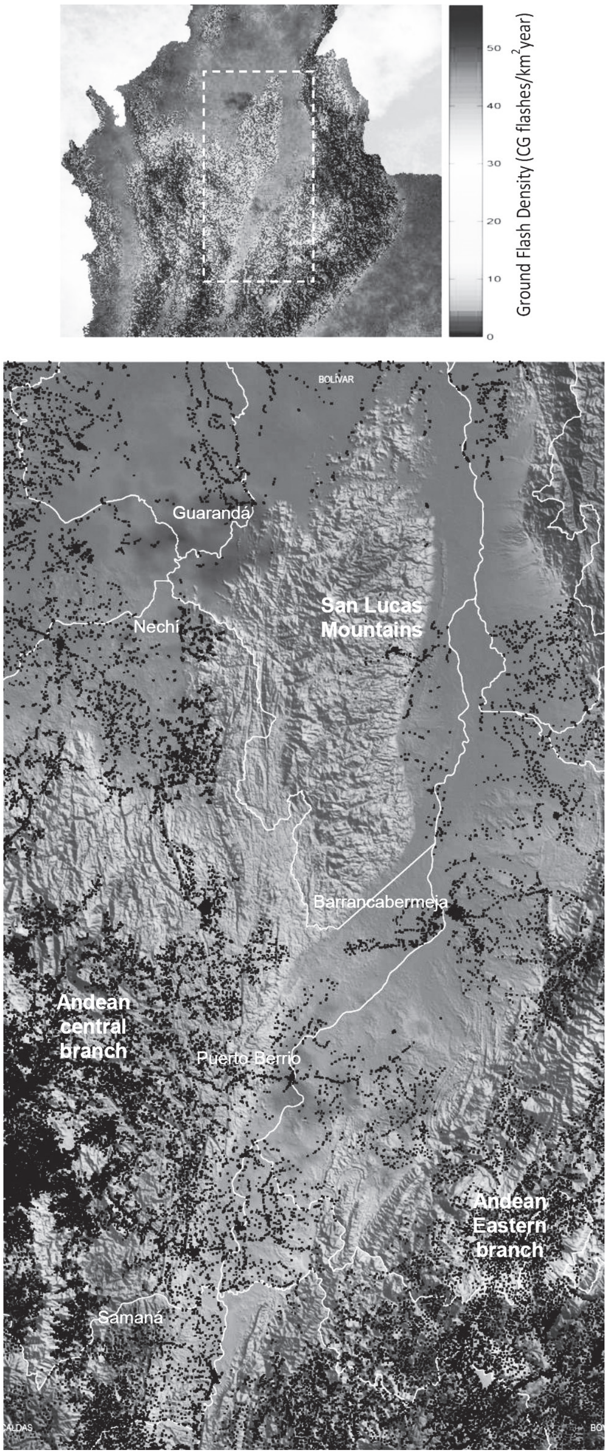

Figure 7. Ground Flash Density (flashes/km^{2}year) along the Magdalena River Valley, the most lightning active area in Colombia (Dataset: 2012 and 2013) and location of power distribution transformers (black dots).

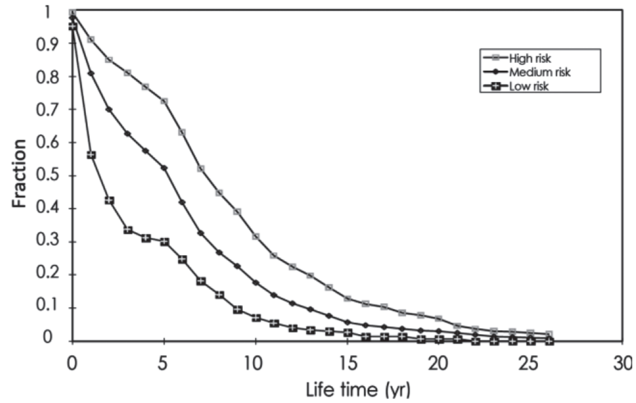

Figure 8. Life cycle for power distribution transformers in Colombia, according to the risk level. Adapted from (Torres, 1996)).

Table 1 gives the estimation of failure rates for power distribution transformers and overhead medium voltage lines, using a two-state weather model and taking into account statistic results previously described for lightning activity. Risk levels were defined as normal (GFD<8 flashes/km^{2}yr), high (8<GFD<25 flashes/km^{2}yr), and very high (GFD>25 flashes/km^{2}yr). Adverse weather period time *S* was defined as a function of the Keraunic Level computed based on the model described in Figure 2 (Aranguren, 2014), therefore average KL for the risk levels is 70, 115, 150 thunderstorm days, for normal, high and very high risk levels respectively. Assuming that one thunderstorm day correspond to an adverse weather day, *S* is equal to 0.19, 0.31 and 0.41 in the same normal, high and very high risk levels, over a calendar year.

Table 1. Failure rates in normal (λ_0), adverse weather (λ') and average (λ), for power distribution transformers and overhead distribution lines in the study area, according to the lightning activity.

Element	Number (%)	Avg. GFD (Flashes/ km^{2}yr)	Failure rates (yr-1)		
			λ_0	λ'	λ
Power distribution transformers	5,898 (2.3 %)	30.33	0.015	1.61	0.67
	60,482 (24.1 %)	12.28	0.015	0.60	0.2
	184,644 (73.6 %)	4.06	0.015	0.52	0.125
Total	251.024 (100 %)				
			Failure rates (km-1yr-1)		
			λ_0	λ'	λ
Medium voltage power lines		30.33	0.02	8.49	3.50
		12.28	0.02	4.62	1.47
		4.06	0.02	2.31	0.46

Failure rate in normal environment conditions (λ_0) was taken from IEEE (IEEE493). Failure rate in adverse weather conditions (λ') depends on the number of failures and the adverse weather period *S*. Failures of power distribution transformers during adverse weather can be estimated by using the life cycle statistics (Torres, 1996); on the other hand, failures of overhead lines can be estimated based on the standard IEEE 1410.

Both failures rates of distribution transformers and overhead lines are dependent on the GFD. Table 1 summarizes failure rates in normal and adverse weather conditions for distribution transformers and overhead networks by considering the normal, high and very high risk levels given by the lightning activity. Average failure rate in very high risk condition for power transformers (λ=0.67) is 45 times higher than the failure rate in normal conditions (λ_0=0.015). In the case of overhead lines in very high risk level, the average failure rate (λ=3.5) is 175 times higher than that in normal conditions (λ_0=0.02).

Reliability indexes such as SAIDI and SAIFI depend on the failure rates and repair times (MTTR) of the most important elements of power distribution systems. Results on Table 1 shows that 2.3% of the transformers have failure rates 45 times higher than those in normal conditions, and 24,1% have failure rates 13.3 times higher than normal. In the case of overhead power lines, the highest risk condition presents failure rates 175 times higher than normal: however, unlike the case of the transformers, extremely large rural medium voltage circuits represent the major portion of the total system length. Current available information does not allow to precisely state the total length of overhead lines that match the high and very high lightning risk areas; nonetheless, is it possible to state that those represent more than 40% of the total system length.

Conclusions

This paper presents new information that supports that reliability indexes in Colombia, which present very high values when compared with international references, are in part due to the local weather conditions affected by a high lightning activity. Time periods of adverse weather in Colombia are longer than those typically observed in other countries, and become comparable in some cases to the normal weather periods; as a consequence, average failure rates in a calendar year are closer to the adverse weather failure rates than to the normal weather ones. After studying a vast area in Central Colombia, it was found that 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 risk) and 45 (very high risk) times higher than what is considered a normal weather condition. Extremely large power overhead lines reach failure rates 175 higher than normal.

Taking into account that transformers and overhead lines are the most important elements of the power distribution system, their failures rates and restoration times define the final SAIDI and SAIFI indexes; therefore, if failure rates in those elements are much higher than those in the considered normal weather conditions, SAIDI and SAIFI should present similar differences with respect to the considered normal reference in other countries.

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