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ASSESSMENT OF THE RISK OF FAILURE OF HIGH VOLTAGE SUBSTATIONS DUE TO ENVIRONMENTAL CONDITIONS AND POLLUTION ON INSULATORS

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ABSTRACT

Pollution on electrical insulators is one of the greatest causes of failure of substations subjected to high levels of salinity and environmental pollution. Considering leakage current as the main indicator of pollution on insulators, this paper focus on establishing the effect of the environmental conditions on the risk of failure due to pollution on insulators and determining the significant change in the magnitude of the pollution on the insulators during dry and humid periods. Hierarchical segmentation analysis was used to establish the effect of environmental conditions on the risk of failure due to pollution on insulators. The Kruskal-Wallis test was utilized to determine the significant changes in the magnitude of the pollution due to climate periods. An important result was the discovery that leakage current was more common on insulators during dry periods than humid ones. There was also a higher risk of failure due to pollution during dry periods. During the humid period, various temperatures and wind directions produced a small change in the risk of failure. As a technical result, operators of electrical substations can now identify the cause of an increase in risk of failure due to pollution in the area. The research provides a contribution towards the behaviour of the leakage current under conditions similar to those of the Colombian Caribbean coast and how they affect the risk of failure of the substation due to pollution.

KEYWORDS

Reliability, risk of failure, atmospheric pollution, leakage current, insulator, electric power substations.

1. INTRODUCTION

Electrical insulators used in outdoor substations are exposed to several pollutants, such as dust, chemicals, vehicular emissions, mineral salts, and others. All these contaminants get stacked on the surface and while it is dry, the effect of dirtiness on the insulator's performance is negligible (Departamento técnico Gamma – Aisladores Corona 2007). However, the presence of humidity in the surroundings, such as drizzles and mist, establishes certain conditions that produce a conductive solution on the dirty insulator's surface, causing a decrease in its dielectric properties (Castillo Sierra et al. 2014) and increasing the probability of failure due to the nearby pollution (Li et al. 2010; Zhou et al. 2009).

Pollution is one of the greatest problems for the reliability of power systems (Li et al. 2010) and is becoming one of the most common causes of failure in electrical networks (Gorur 2005). It is extremely important to study the phenomenon of electric arc to earth due to the layer of contaminants present on the insulators for external use and how atmospheric factors influence the increase in the risk of failure.
According to Li J.Y. et al. (Li et al. 2009), some factors that significantly influence the failure of insulators are the atmospheric pollution, the operating voltage, and weather conditions. Some studies have reported this phenomenon through the relation between operating voltage and the severity of the atmospheric pollution. Additionally, the effects of the environmental conditions on the performance of insulators have been reported,

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while other research studies have shown how environmental pollution increases the risk of failure for insulators.

In (Obenaus 1958), Obenaus considered the operating voltage and the severity of the pollution as important parameters. He was the first one to propose a shock model based on the pollution on ceramic insulators (Venkataraman and Gorur 2006). The failure process was modelled as a shock in series with a resistor. Based and guided on Obenaus' proposed model, there have been several particular models, which depend on the physical characteristics of the studied isolator (material and dimensions), severity of the pollution and operating voltage (Venkataraman and Gorur 2006).

Based on Obenaus' theory, (Venkataraman and Gorur 2006) the model for non-ceramic insulators was developed taking into account values of ESDD (Equivalent Salt Deposit Density) between 0.8 to 0.34 mg/cm2, with the sole purpose of measuring the failure voltage and the resistance of the insulator's surface. For instance (Yang et al. 2012), considering that Obenaus models the failure process through a physical-mathematical analysis, the use of the voltage gradient criteria ((dE_ion)⁄dx>0) is proposed to exemplify the spread of the arc over the insulator's surface. Likewise, (Gençoğlu and Cebeci 2008) developed a dynamic model for the behaviour of the electric arc present in the failure of the polluted insulators. Alternately, the research performed by (Kontargyri et al. 2007) deducts, through the use of neuronal networks, the flashover voltage of the insulators based on the physical characteristics of the insulators string, weight, diameter, leakage distance, shape factor, and severity of the pollution on the environment, measured in mg/cm2.

Taking into account that the others factors that influence the failure process are environmental conditions, recent studies have focused on relative humidity as the main factor that enables the conditions for failure to ground in polluted insulators. Research performed by (Zhou et al. 2009), (Mao et al. 2007; Meyer et al. 2011; Montoya et al. 2004) show the effect that humidity and pollution have on the magnitude and the number of pulses of leakage current, measured in mg/cm2 (ESDD). It is concluded that the number of pulses are directly proportional to the degree of humidity and ESDD.

Finally, other studies make special emphasis on defining pollution and relating it to the risk of failure for insulators. For example, (Li et al. 2010) and (Li et al. 2009) analyse the leakage current, taking into account RMS current, waveforms and power spectral density, aiming to establish the behaviour that leads from negligible current values to the specific time when the failure occurs to identify the progressive increase of current to prevent an imminent failure. Alternately, (Boudissa et al. 2013) establishes a possible relation between the process of failure for half-voltage insulators, measured via fault voltage, with types of non-uniform pollution, such as cross, longitudinal, and periodic, and compares them with the process of failure due to uniform pollution. It was concluded by the study that, facing non-uniform cross pollution, insulators had better performance, and the fault voltage was 21% higher than the one given by the uniformly polluted insulators. In contrast, facing longitudinal and periodic pollution, insulators experienced a decrease in their performance with a reduction in the fault voltage approximately 42% and 30%, respectively. Finally, in (Mei et al. 2010), different values of ESDD, NSDD (Non Soluble Deposit Density), CaSO4, and NaCl concentrations, acting like conductive compounds in the humid environment, were used with the leakage current to predict the fault voltage through a non-linear regression model.

Studies about the risk of failure for outer insulators are diversified. Nonetheless, most of them are very similar, with many having the same base point being they were developed from Obenaus' theory. Some studies have focused on the effect of weather conditions on the risk of failure, but they are fairly limited as they consider humidity as the only influential factor. In addition, all of the studies conducted on this topic have been established on regions such as China and India, among others, i.e., areas where the weather conditions differ greatly to the ones present at the north Colombian coast, which is characterized by a dry and humid period (Hermelin 2007).

The aim of this study is to investigate the effect of weather conditions on the risk of failure on outer 220 kV insulators, specifically, establishing significant differences in the climate variables and leakage current between dry and humid periods. Furthermore, this study focuses on determining the effects of weather conditions on the risk of failure due to the pollution on insulators, measured by the leakage current.

2. MATERIALS AND METHODS

Based on observational data, this paper focused on determining the effect of the environmental conditions on the risk of failure due to pollution on insulators. All statistical analyses presented in this research were performed using SPSS statistical software (version 19.0; SPSS, Inc., Chicago). Kruskal-Wallis test and hierarchical segmentation analysis were used to verify if the dry and humid periods cause a significant difference on the weather variables and to evaluate the effects of them over the risk of failure due to pollution respectively.

2.1 Location

The electric power substation Nueva Barranquilla is located in the city of Barranquilla, Colombia. The substation is at a distance of approximately 7 km from the Caribbean Sea and 6 km from the Magdalena River. The city of Barranquilla is filled with highly polluted atmosphere (mostly by marine salts), and, as a seaport, it experiences important industrial activity and high vehicular traffic and shipping, increasing the concentration of pollutants in the atmosphere. The study performed by (Aponte et al. 2009; Castro et al. 2006) shows that the zone where the substation is located has a high level of pollution according to the scale in IEC 60071-2, with an equivalent salt deposit of 0.45 mg/cm^2.

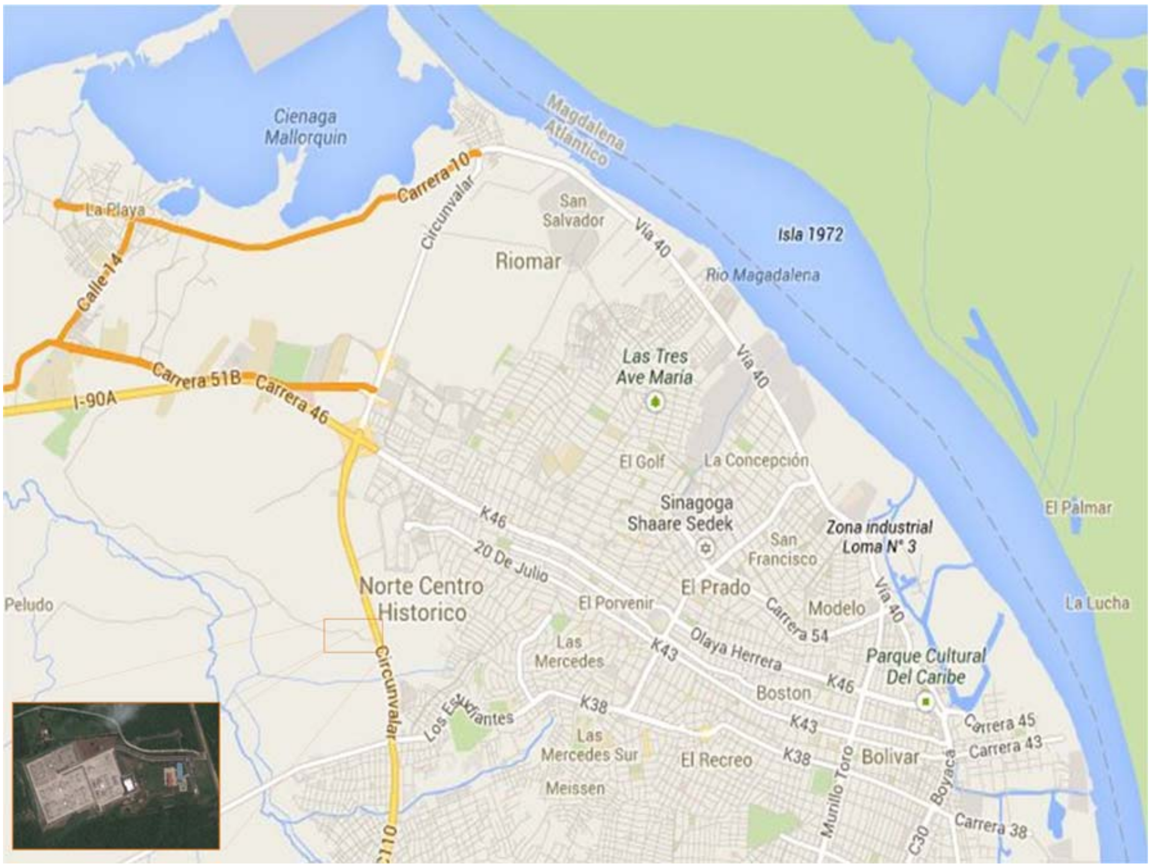


Fig. 1 Location of the Nueva Barranquilla Substation

2.2 Data collection

Leakage current measures were taken with a current clamp (brand KYORITSU, model 2432) with scales of 4 mA, 40 mA and 100 A. The resolution of the current clamp is 0.001 mA. Furthermore, the current clamp has an accuracy of ±1% for the scales of 4 mA and from 0 to 80 A and an accuracy of ±5% for the scales of 40 mA and from 80.1 to 100 A. Measures of ambient temperature, relative humidity, atmospheric pressure, solar radiation, wind direction, and speed were taken by a meteorological station located inside the substation.

Leakage current measures were taken every twenty-four hours on the insulators of 220 kV power transformers due to the ease of measurement, as shown in Figure 2. The leakage current was measured by using the induction of a wire surrounding the insulator. Climate variables were measured using a weather station, located at the substation, with sample frequencies of 2 to 10 minutes. Consequently, there was a crossing of the database of the measurements of leakage current and the database of the climate variables.

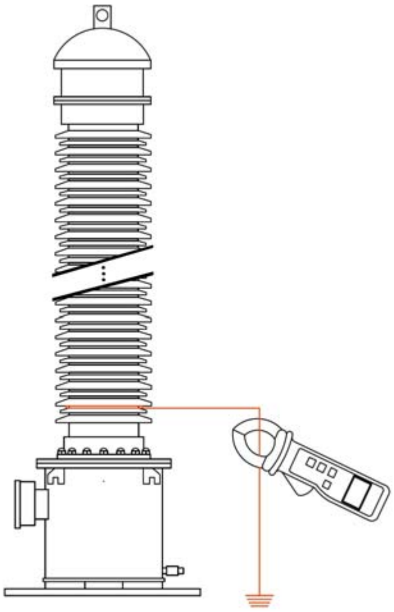
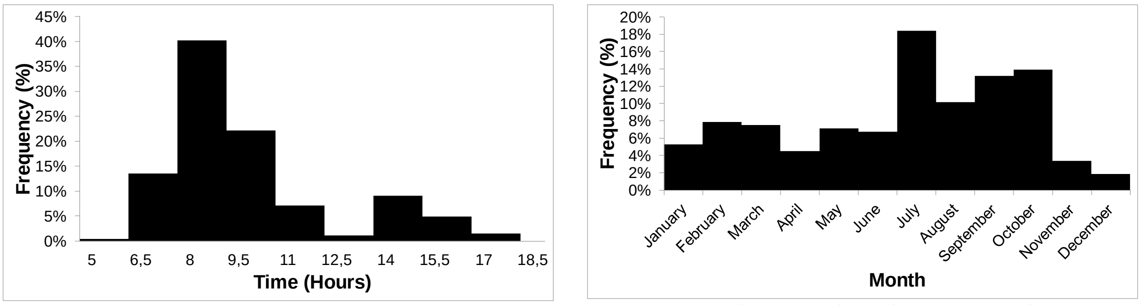


Fig. 2 Measurement of the leakage current

2.3 Samples

Porcelain insulators located on 220 kV potential transformers of the Nueva Barranquilla substation were used for the test. Historical data about the magnitude of the leakage current, ambient temperature, relative humidity, atmospheric pressure, solar radiation, level of precipitation, and wind direction and speed from December 2011 to December 2012 were considered to analyse the behaviour of the insulators.

Figure 3a shows the distribution of time in which samples were taken. It is observed that more than 80% of the samples were taken between 6:30 AM and 12:30 PM. Figure 3b shows the number of samples taken per month to perform the correlation of atmospheric variables and leakage current. The average number of samples per month was 22 with a standard deviation (SD) of 13.



(a) Samples taken per hour

(b) Samples taken per month

Fig. 3 Samples taken in the study

2.4 Analysis

2.4.1 Analysis of variance

The Kruskal-Wallis test was used to determine whether there existed statistically significant differences. This test was used as a way to check the null hypothesis that the levels are identical against the alternative hypothesis that some levels generate observations that are greater than others. Due to the procedure being designed to be sensitive to differences of averages, on occasion it is convenient to consider it as a test of the average levels. This test is a non-parametric alternative to the usual analysis of variance (ANOVA) (Montgomery 2010). The statistical test of "H" used by Kruskal-Wallis is shown in (1).

$$H = \frac{1}{S^2}\left[\sum_{i=1}^{a}\frac{R_{i.}^2}{n_i} - \frac{N(N+1)^2}{4}\right] \tag{1}$$

where ni is the number of samples of the i-th level, N is the total of the samples, Ri. is the sum of the ranges of the i-th level and S^2 is expressed in (2).

$$S^2 = \frac{1}{N-1}\left[\sum_{i=1}^{a}\sum_{j=1}^{n_i} R_{ij}^2 - \frac{N(N+1)^2}{4}\right] \tag{2}$$

The rejection of the null hypothesis is achieved when the statistical test H is greater than the value chi-square or when the critical P-value is less than the alpha value.

2.4.2 Hierarchical segmentation analysis

Hierarchical segmentation analysis was used to analyse the effect of the atmospheric conditions on the risk of failure of a substation due to excessive leakage currents on isolators. This analysis belongs to a family of non-parametric methods that uses a recursive partition to find patterns on large databases (Medina-Borja and Pasupathy 2007). Its non-parametric nature enables it to overcome limitations that usually appear in relation to linearity in model construction, and this allows for a greater quantity of applications. Basically, all of the automatic tree methods follow the same algorithm that divides the variables in nodes and builds the model through ramification growth. The main node contains the total population (N=266), and every remaining node in the lower part (child nodes) contains a portion of the population located immediately above (parent nodes).

This methodology is known and used specifically to make predictions and classify and detect interactions between variables. It enables the hierarchical division of a determined population in segments that differ in the function of a variable or defined criteria. In this case, the objective of the implementation of this classification tree was to find the risk of failure due to atmospheric pollution represented by leakage current given by a group of climate variables.

For modelling, a data mining algorithm called CHAID (Chi-Squared Automatic Interaction Detector), designed by (Kass 1980), which allows the growth of a tree through sequential combination and the division on the basis of a statistical test of Chi, was utilized. The CHAID technique divides the population into two or more groups based on the categories of the dependent variable (in this case, the leakage current categorized) and then divides each one of these groups into smaller subgroups on the basis of other predictive variables (climate variables). The process ends when there are no more variables that produce significant new segments. The initial variables included in the model were ambient temperature (°C), relative humidity (%), solar radiation (W/m2), wind speed (m/s), wind direction (°) and climate period (dry/humid).

3. RESULTS

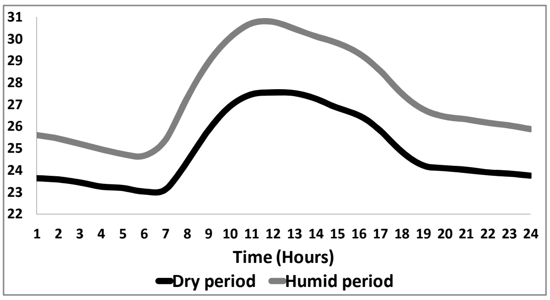
3.1 Periodic variations of the weather

Average, minimum, maximum, and standard deviation of the climate variables are shown in Table 1. It is observed that ambient temperature and wind direction during humid periods present higher values than those given by dry periods, being approximately 10% in temperature increase and 39% in wind direction. In contrast, relative humidity and wind speed during humid periods presented lower values than those during dry periods. For relative humidity, the decrease was approximately 7.3% and, for wind speed, 60.8%.

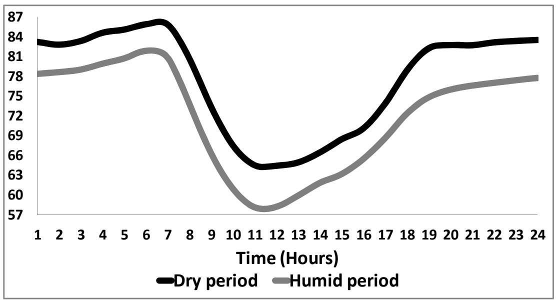
Table 1. Description of the climate variables during dry and humid periods

Variable	Period	Average	Stand. Dev.	Minimum	Maximum
Ambient temperature (°C)	Dry	24.9	1.6	23.0	27.6
	Humid	27.4	2.1	24.7	30.8
Relative humidity (%)	Dry	77.6	7.9	64.4	85.9
	Humid	72.0	8.1	58.1	81.9
Wind speed (m/s)	Dry	9.2	1.6	6.3	11.6
	Humid	3.7	0.9	2.0	5.1
Wind direction (°)	Dry	110.8	4.9	102.9	119.1
	Humid	153.9	5.6	147.6	166.0
Solar radiation (W/m^2)	n/a	217.2	282.3	0.1	734.0

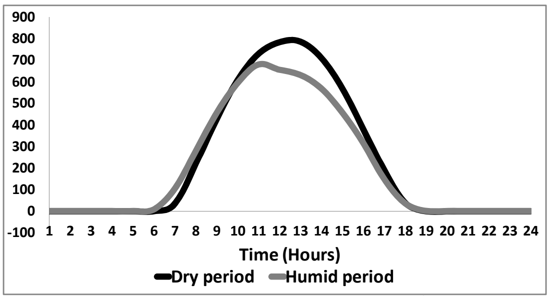
Figure 4 shows the average behaviour of the climate variables for the dry and humid periods. There are some differences in the magnitudes of each variable during the dry and humid periods. Through the Kruskal-Wallis, test it was possible to verify formally that the dry and humid periods significantly influence the climate variables.



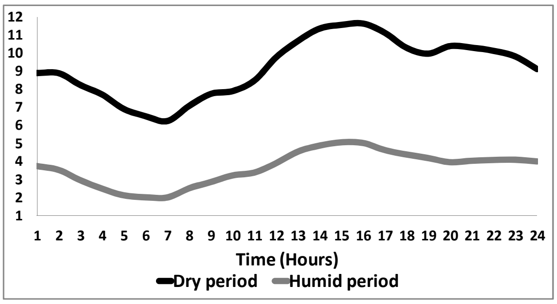
(a) Temperature (°C)



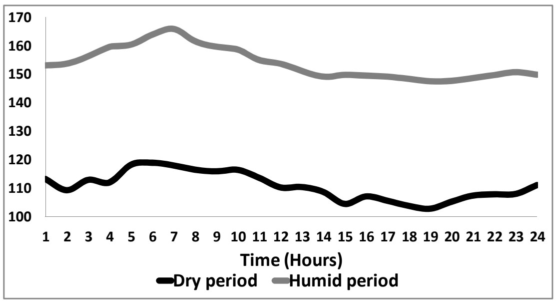
(b) Humidity (%)



(c) Solar radiation (W/m^2)



(d) Wind speed (m/s)



(e) Wind direction (°)

Fig. 4 Influence of dry and humid periods on the climate variables

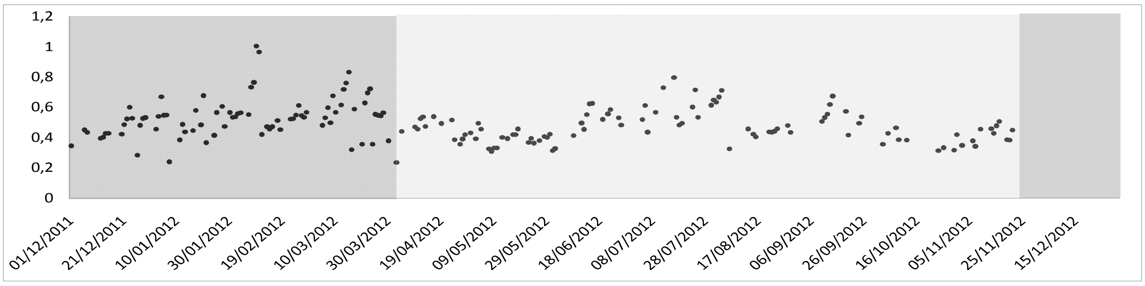
The design factor to consider in the test was 'climate period'. The category was defined using two levels: level zero was the dry period, and level one was the humid period. The response variables are each of the climate factors measured, ambient temperature, relative humidity, solar radiation, and wind speed and direction. The hypothesis test to be taken into account for each climate variable was:

Ho: The averages of the levels of the climate period are identical.
H1: At least a pair of the averages of the levels of the climate period are different.

The results of the Kruskal-Wallis test show that the P-value of the ambient temperature, relative humidity, and wind speed and direction are less than the value of the used alpha (α=0,05). Therefore, it can be concluded that there is a significant difference between the averages of the levels of the factor 'climate period'. The P-value obtained in the test of the solar radiation (P-value=0.36) is greater than the value of alpha used, thus it can be concluded that there is no significant difference between the averages of the levels of the factor 'climate period'.

3.2 Leakage current during humid and dry periods

The Kruskal-Wallis test was also used to evaluate the effect of the factor 'climate period' on the magnitude of the leakage current. The P-value of the test returned a value of 0.04, and, given that the value of alpha is 0.05, this rejects the null hypothesis; therefore, it can be concluded that there is a significant difference in the averages of the leakage current between dry and humid periods.



Dark grey area: dry period. Grey region: wet period

Fig. 5 Leakage current measurements (mA)

As seen in Figure 5, the dry period has current values higher than those presented during the humid period. On average, the leakage current in dry periods has a value of 0.97 mA, in contrast with the 0.65 mA obtained during the humid period. The limits of the current measurements during the dry period are between 0.6 and 1.28 mA, and during the humid periods, they are between 0.28 and 1.03 mA.

3.3 Leakage current

As mentioned previously, for the configuration of the climate variables associated with the risk of failure of insulators due to the leakage current, the hierarchical segmentation analysis using the CHAID technique algorithm (Kass 1980) was used.

Leakage current was used as a dependent variable that was later transformed into a categorical variable. For leakage current under 0.5 mA, the number 1 was used to indicate a safe level or no risk of failure. For leakage current over 0.5 mA, the number 0 was used to indicate an alert level or risk of failure.

In terms of the independent variables for the model, we used the climate variables, ambient temperature, relative humidity, solar radiation, and wind speed and direction. As additional variables, the dry and humid periods were used. The final variables included in the model were the climate period, the atmospheric temperature, and the wind direction. The rest of the variables were excluded due to the insignificant results for the hierarchical segmentation of the dependent variable.

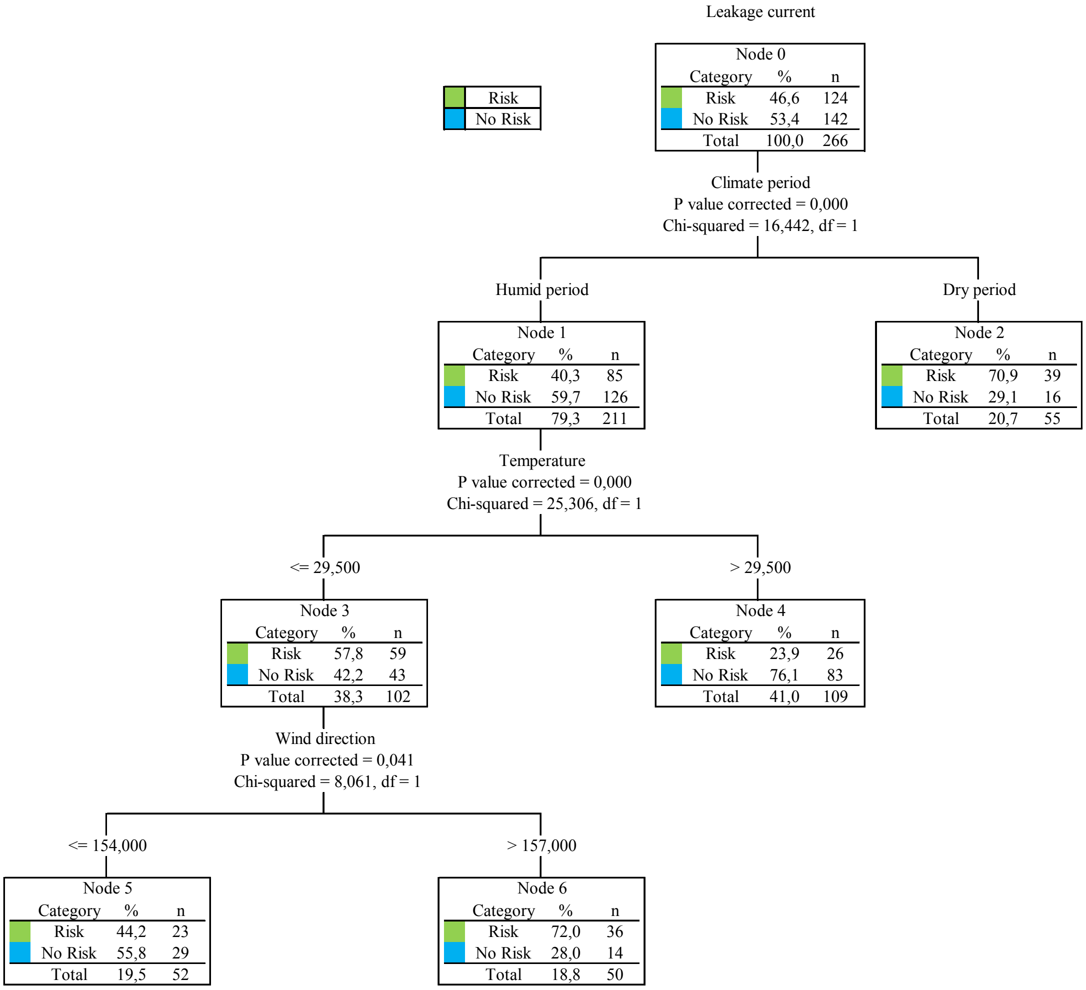


Fig. 6 Classification tree of risk of failure

The resulting tree, shown in Figure 6, is set on three levels. The first level includes the climate period. The second level consists of the ambient temperature. Finally, the third level includes the direction of the wind. The tree correctly predicts 70.3% of all cases, including the variable leakage current categorized (Table 2). The quality of the fit of the model proposed is confirmed because the P-value was below 0.041 in all divisions for the tree.

Table 2. Percentage of cases correctly predicted

Observed	Predicted		
	Risk	No Risk	Correct percentage
Risk	75	49	60,5%
No Risk	30	112	78,9%
Global percentage	39,5%	60,5%	70,3%

Growing method: CHAID

In terms of the variable included in the first level, the climate period (Chi-square=25.306, p<0.01), 70.9% of the measurements of leakage current taken in the dry period are in a state of risk compared to 40.3% of the measurements of leakage current in the humid period.

For the measurement of the leakage current taken in the humid period, the ambient temperature variable is the next best predictor of the model (Chi-square=16.441, p<0.01). The results indicated that 57.8% of the measurements are at risk for temperature values less than or equal to 29.5°C. In contrast, for temperatures greater than 29.5°C, 23.9% of the measurements were at risk.

Finally, in the case that the ambient temperature is below 29.5°C, the wind direction is the best predictor of the final model (Chi-square=8.061, p=0.041). For values greater than 154°, 72% of the measurements are in a state of risk compared to only 44.2% present in the values of wind direction less than or equal to 154°.

4. DISCUSSION

This study focused mainly on modelling of the relationship between climate variables and the risk of failure associated with the leakage current present in polluted insulators. This analysis is of great importance because it provides information about what conditions of ambient temperature, relative humidity, solar radiation, and wind speed and direction present a greater risk of failure due to the contamination present in the pollutants. Taking this information into consideration, the increase in the risk of failure is known in time to take corrective actions.

There is a clear difference in the magnitude of the climate variables in the dry period in comparison to those in the humid period. The Kruskal-Wallis test showed that all variables except solar radiation change with the climate period variation. The ambient temperature in the dry period is approximately 10% higher than what is presented during the rainy season. The relative humidity, in contrast, suffers from a decrease of approximately 7.3% from the dry period to the humid period. The wind speed, as well as the relative humidity, shows a clear decrease of approximately 60.8%, from an average speed of 9.2 m/s in the dry period to 3.7 m/s in the humid one.

The wind direction presented an increase of 39%, from a direction of 110.8° during the dry period to a direction of 153.9° during the humid period. Finally, the solar radiation showed no significant differences between climate periods. In terms of leakage current, a clear difference is observed between the magnitude in the dry period and that in the humid period. On average, leakage current in the humid period was 33% lower than that in the dry period.

In the study of the risk of failure, it can be clearly identified that, during the dry period, there will always be the risk of failure due to the leakage current present in the insulators (as mentioned above, the leakage current in this period is, on average, higher than in the humid period), regardless of the value that the climate variables take during this period. In contrast, during the humid period, the risk of failure decreases substantially, allowing these periods to be considered secure. Only under certain atmospheric conditions during this period can a hazardous condition occur.

If the ambient temperature is above 29.5 °C during this period, the state of security can be maintained; however, if the temperature is below this limit, and, in addition, the wind direction is greater than 154°, the secure status during the humid period changes to the risk status. On average, the ambient temperature during the period of rain was below 29.5 °C between 1 and 9 pm and between 16 and 24 hours. Furthermore, the direction of the wind was above 154° between 3 and 11 hours. Across these time periods, it can be concluded that, daily, between 3 and 9 pm, there will be a risk status of failure in the insulators due to the leakage current.

In previous studies, (Mao et al. 2007; Meyer et al. 2011; Montoya et al. 2004; Zhou et al. 2009), relative humidity has been taken as the only variable influential on the risk of failure. In these studies, there have not been similar conclusions because there were not consideration of climate variables according to each season and the effects on the risk of failure due to the pollution.

In analyzing the data the main limitation was due to failure to take into account the time variable in the model of hierarchical segmentation. Failure to include this variable in the analysis due to the historical database used did not provide enough for it to be included in the study information. Considering the results and improving raised above limitations; future, research will focus on the prediction of the behavior of the leakage current versus time, in order to improve the planning process of laundering activity insulators of a substation or transmission line and/or distribution.

5. CONCLUSIONS

This article studied the effects of the weather conditions on the risk of failure for outer insulators of 220 kV. First of all, we established the effects of weather conditions on the risk of failure due to pollution on insulators, and, second, we determined whether there exists a significant change in the magnitude of the presented pollution on insulators due to the climate periods typical of the north Colombian Coast (humid and dry periods).

Through hierarchical segmentation analysis, it was possible to determine that, during dry periods, there was a higher risk of failure due to the pollution on insulators. In contrast, in humid periods, there was no such risk of failure, except if certain conditions of temperature and wind direction were met. While the results of the analysis of segmentation model cannot be generalized to any substation because each geographic area that has its own climate and natural and artificial pollution characteristics. However, the methodology of how to build the model is fully generalizable, you must select the climatic variables to consider in the model, taking into account the specific seasons of the geographical area of study and the extent of pollution (ESDD, NSDD, leakage current, etc).

By the Kruskal-Wallis test, the goal of understanding the reason why there is a higher chance of risk of failure during the dry period due to pollution in the area was accomplished. This occurs because the leakage current during this period is significantly higher than that of the humid period. An elevated leakage current was related to the decrease of the dielectric property of the chain of insulators, causing shock to the ground through the insulator’s surface. The relation between the climate periods, leakage current and the risk of failure due to pollution have now been determined for the Colombian Caribbean coast, which represents a remarkable contribution towards the scientific community owing to the requirements for the identification of the impacts that pollution brings to electric insulators.

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