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Analysis of Leakage Current on Polluted Polymeric Insulator Using Finite Element Method

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Abstract: **This paper develops a Finite Element Model (FEM) for a 138 kV High Temperature Vulcanized (HTV) Silicone Rubber (SiR) transmission insulator in which, in a first step, leakage current is calculated for different non-uniform continuous and discontinuous pollution deposits and then features based on the phase shift between the leakage current and the applied voltage are extracted for each kind of pollution layer to identify the existence of dry bands on the insulator surface. A phase shift of 84.75° lag between the leakage current and applied voltage was found for a pollution layer with dry bands inserted. This results evidence that the phase angle can be used to detect the dry band formation by measuring the leakage current and its phase angle.**

Resumo: **Este trabalho desenvolve um Modelo de Elementos Finitos (FEM) para um isolador de transmissão de 138 kV Vulcanizado em Alta Temperatura (VTA) de Borracha de Silicone (BS) para o qual, em uma primeira etapa, a corrente de fuga é calculada para diferentes depósitos de poluição contínua e descontínua não uniformes e em seguida, são extraídas características baseadas no deslocamento de fase entre a corrente de fuga e a tensão aplicada para cada tipo de camada de poluição para identificar a existência de bandas secas na superfície do isolador. Um deslocamento de fase de 84,75° de atraso entre a corrente de fuga e a tensão aplicada foi encontrado para uma camada de poluição com bandas secas inseridas. Esses resultados evidenciam que o ângulo de fase pode ser usado para detectar a formação de banda seca através da medição da corrente de fuga e seu ângulo de fase.**

Keywords: Insulator; High Voltage; Leakage Current; Simulation; Finite Element Method.

Palavras-chaves: Isolador; Alta Tensão; Corrente de Fuga; Simulação; Método dos Elementos Finitos.

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1. INTRODUCTION

A reliable power system is a great concern for power utilities whether on transmission or distribution. Insulator discharges poses a threat on power system reliability due to unplanned outages caused by the protection system action taken to clear such faults. An annual report of the Brazilian National Electrical Energy Agency (ANEEL) showed that in 2018 from 3768 outages occurring in transmission lines and equipment from July 1st of 2016 to June 30th of 2017, 75.6% were originated on transmission lines (ANEEL, 2018). Gomes et al. (2020) inform that 98% of the interruptions were caused in transmission lines mainly due to insulators failures. A survey conducted by CIGRÉ showed that annual average of outages in transmission lines under 230 kV is caused by insulators (Garcia and Santos, 2003).

Polluted environment menaces reliable transmission or distribution line operation whether by long term processes such as corrosion rates of end fittings and insulating polymer components or by depleting power system performance in short term processes like flashover and faults on insulators Farzaneh (2009). A research program was developed in South Africa on 2000s to compare the performance of different insulator materials subjected to severe marine pollution (Vosloo, 2002). Pollution under rainforest environment was assessed in one research carried out in (De Mello et al., 2008) in which studies were conducted to look for solutions to mitigate problems caused by typical contaminants found in Amazon region, such as: slimes, moss, lime, lichen, etc.

In order to understand the insulator flashover process, several studies to model insulator flashover were conducted since 1958 when Obenaus developed a model to describe flashover under DC conditions for a pollution layer with uniform resistance. Later, on the 1970s, Claverie studied the arc development on a flat surface considering that the arc series resistance, a reignition condition to foresee the flashover by measuring only the leakage current (Claverie, 1971), then Riszk and Rezazada (1997) improved the Obenaus model by adding the combined effect of humidity and reduced air density on the leakage current and flashover voltage. Further enhancement was added to take into account the pollution effects on insulator surface. The nonuniformity of pollution taken into account in (Ahmadi-Joneidi et al., 2017) by two methods to simulate the leakage current: one considering the circuit theory and the other using the Finite Element Method. The random characteristic of the arc flashover was approached by the development of a statistical model to evaluate the effect of suspended water particles on insulator flashover probability (He et al., 2017). The behavior of polluted insulator and the influence of pollution configuration, voltage polarity and the resistivity of the pollutant on the flashover voltage and leakage current was treated on (Dhahabi-Megriche et al., 2016) by the development of a multi-arc model. The flashover prediction was assessed in (Palangar et al., 2020) by the improved analytical calculation of arc parameters based on an extended equivalent electric circuit of the polluted insulator.

This paper develops a Finite Element Model (FEM) of a 138 kV SiR-HTV transmission insulator in which, in a first step, leakage current is calculated for different non-uniform continuous and discontinuous pollution deposits and then features based on the phase shift between the leakage current and the applied voltage are extracted for each kind of pollution layer to identify the existence of dry bands on the insulator surface. The work is structured in the following way: Section II has a brief explanation of leakage current behavior on polluted insulators. Next, Section III describes the methodology used to model the insulator, Section IV discusses the simulation results and at last, the conclusions are deployed on Section V.

2. LEAKAGE CURRENT AND FLASHOVER OF POLLUTED INSULATORS

In the following subsections some aspects concerning to pollution deposit on high voltage insulators, the flashover process on polymeric polluted surface and the influence of leakage current value on the breakdown voltage are treated.

2.1 Pollution on High Voltage Insulators

The pollution deposit on insulator surfaces creates a dust layer composed of materials that ranges from marine salt, coal from power plants, inert dust from quarries and cement factories, fertilizers from agricultural environment and lime from rainforest environment (Farzaneh, 2009). When this layer is wetted, a leakage current begins to flow leading to dry band arching and finally to the insulator flashover. The knowledge of flashover process on polluted insulator is a target for many studies. The pollution that settles down over the insulator surface is composed of salts near coastal areas that are regarded as soluble deposits and non-soluble deposits like fly-ash and cement dust on inland areas and in conjunction with wet and fog reduce the surface resistance of polymeric insulators leading to an increase of leakage current (Ahamadi-Joneidi et al., 2017).

2.2 Breakdown Process on Contaminated Polymeric Surface

The flashover mechanism of a non-ceramic surface is different from the one that happens on hydrophilic surfaces like those found in glass insulators. The wetting produced by the environment creates droplets instead of a continuous electrolyte. The polymeric material suffers degradation of its properties due to aging; the housing material is sensitive to its local environmental condition and degrades over the time which leads to a temporary loss of hydrophobicity resulting in frequent flashover under fog or moist conditions (Verma and Suba, 2018).

2.3 Influence of leakage current on flashover voltage

The breakdown of an insulator was first modeled by Obenaus (Farzaneh, 2009) as a partial arc that bridges a dry zone (dry band) and a resistor in series with the dry band representing the resistance of the pollution layer. Equation (1) represents the Obenaus model.

$$U = xAI^{-n} + (L - x)R_pI \tag{1}$$

In Equation (1) xAI^{-n} is the stress in the arc and $(L - x)R_pI$ is the stress across the pollution layer, x is the arc length, L is insulator leakage path, R_p is the resistance of the pollution layer per unit length and I is the leakage current and A and n are arc constants. Analysing Equation (1) one can observe that the voltage across the dry band is inversely proportional to the leakage current, so as the leakage current increases the voltage across the gap formed by the dry band decreases until the system voltage is totally applied over the pollution layer resistance. If the breakdown voltage of the gap formed by the distance between the point where the arc touches the insulator surface after bridging the dry band and the tower $(L - x)$ is attained, a flashover is stablished. Therefore, as the insulator is subjected to the system voltage and the pollution and arc resistances are small compared to the insulator impedance, a short-circuit is stablished and the line will be taken out of service by the protection system.

3. INSULATOR MODEL

The modelled insulator belongs to the 138 kV HTV-SiR class, whose dimensions and components are established in Table 1. The layer of pollutant residues was drawn with 1 mm thick over the SiR surface, as suggested by Ahmadi-Joneidi et al.(2017). This layer represents the accumulation of saline particles from rain, dust and fog, which in sufficient humidity dissociate forming an ionic conductive path, through which a leakage current flow. The studies by Farzaneh et al.(2009), Ahmadi-Joneidi et al.(2017) and norm IEC/TS – 60815 point to a difference in conductivity between the pollutant layers at the top and bottom of each polymeric disc, resulting from the pollutant deposition accumulation rate (T/B) in those respective locations. Over time, this deposit can assume different rates, being adopted 4 rates for analysis in this study. The dry band modeling follows the one adopted by Muniraj et al.(2011), which consists of a 1 cm cut in the polluting layer. The FEM model designed for the equipment with polluting layer and dry band is shown in figure 1.

Table 1. Dimensions and components of the Insulator

Height (mm)	1175
Core Diameter (mm)	27
SiR Thickness (mm)	3
Number of Sheds	43
Leakage Distance (mm)	3735
Shed Diameter (mm)	220/190
Voltage Class (kV)	138

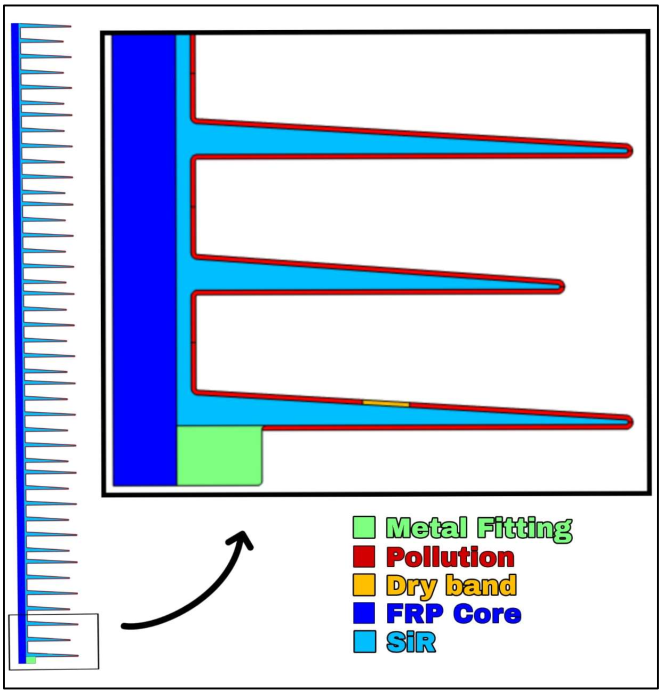

Fig. 1 FEM model with polluted layer and dry band.

This work studies the profile of the leakage current in a polymeric insulator of 138 kV (60Hz) in 3 different cases and their sub-groups, to then compare them, being them

Case A: No pollution (clean).
Case B: Layer continuous pollution on the surface.
  B.1 pollution rate (T/B) = 1 (uniform).
  B.2 pollution rate (T/B) = 1/2.
  B.3 pollution rate (T/B) = 1/5.
  B.4 pollution rate (T/B) = 1/10.
Case C: Dry band inserted in polluted disk.
  C.1 pollution rate (T/B) = 1 (uniform).
  C.2 pollution rate (T/B) = 1/2.
  C.3 pollution rate (T/B) = 1/5.
  C.4 pollution rate (T/B) = 1/10.

Table 2 includes each component and its adopted material property. The Table 3 establishes the conductivity of the polluted layer according to the T/B deposition rate.

Table 2. Material property

Material	Conductivity σ (S/m)	Relative Permittivity (ε)
Silicone Rubber	$1\mathrm{x}10^{-12}$	4
FRP Core	$1\mathrm{x}10^{-14}$	6,5
Pollution on Top Shed	-	80
Pollution on Bottom Shed	-	80
End Fittings	$5{,}9\mathrm{x}10^{7}$	1
Air	$1\mathrm{x}10^{-20}$	1

Table 3. Conductivity of polluted layers (S/m)

T/B	1	1/2	1/5	1/10
Pollution on Top of the Shed	$9{,}64\ \mathrm{x}10^{-3}$	$6{,}42\ \mathrm{x}10^{-3}$	$3{,}21\ \mathrm{x}10^{-3}$	$1{,}73\ \mathrm{x}10^{-3}$
Pollution on Bottom of the Shed	$9{,}64\ \mathrm{x}10^{-3}$	$1{,}29\ \mathrm{x}10^{-2}$	$1{,}61\ \mathrm{x}10^{-2}$	$1{,}75\ \mathrm{x}10^{-2}$

4. RESULTS AND DISCUSSION

The leakage current calculated for the insulator when it is in clean conditions (case A) is quantified in Figure 2 over the first 60 ms of high voltage excitation with 60Hz, in which an RMS current of 123 μA is obtained. It can be seen that the current is out phase with the applied voltage of 90° lag, resembling a capacitive circuit in view of the absence of a conductive path.

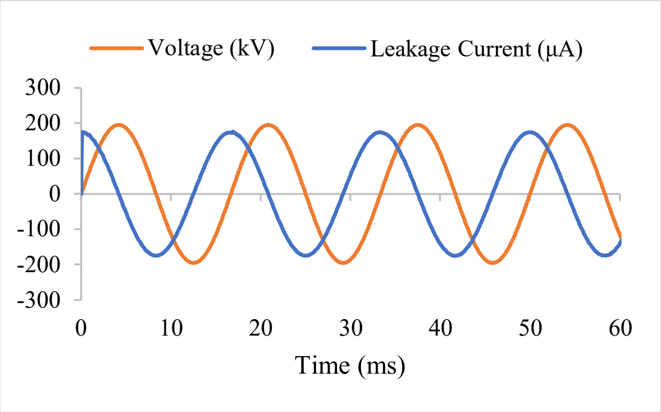

Fig. 2 Voltage and leakage current on clean insulator (case A).

On the other hand, for a continuous pollution layer covering the insulator surface (case B), the leakage current increases considerably, to a few hundred milliamps as shown in figure 3 and table 4, the amplitude being different for these signals due to the conductivity attributed to the different rates deposition of pollution on insulating surfaces.

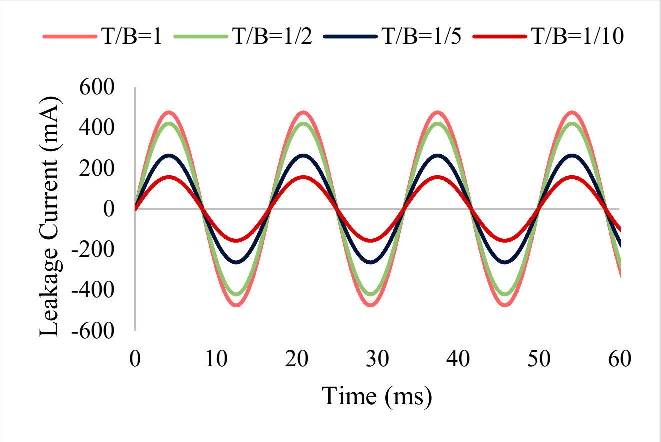

Fig. 3 leakage current in the insulator with continuous pollution (case B).

Table 4. RMS current in continuous polluted case

T/B	1	1/2	1/5	1/10
Leakage current RMS (mA)	336,06	297,5	186,21	110,7

In Figure 4, the voltage at the device terminals is compared with the current in the case of continuous and uniform pollution (T/B = 1). It is verified that for this group the phase shift between current and voltage is minimal, showing that the capacitive effect decreased on the insulator. This happens because the pollution layer creates a leakage path with a finite resistivity in a differing from the situation where the equipment is in clean conditions. Since a resistive path was constituted by the polluting residues, the lag between the currents of this group for different T/B is also minimal.

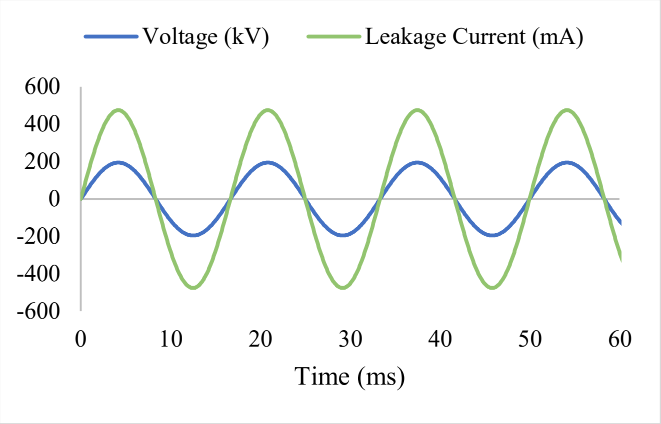

Fig. 4 Current and voltage in the continuous and uniform case (T/B=1).

When we add a dry band, the leakage current suffers an attenuation as the proportion of deposited residues is changed, shown in figure 5. On the other hand, there is an increase in the phase shift in relation to the voltage (see Table 5) as the pollutant layer tends to be uniform over the surface after the dry band.

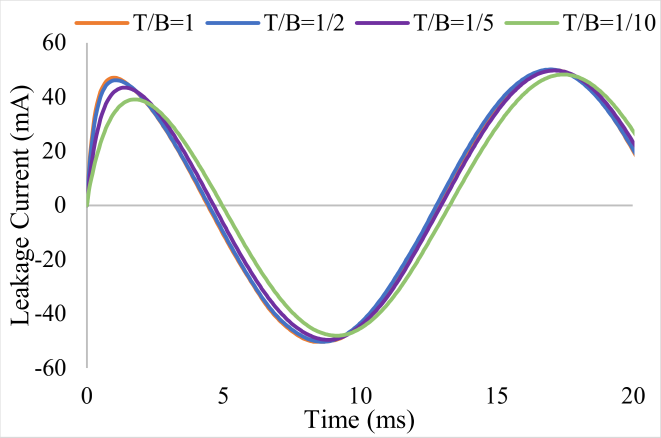

Fig. 5 Leakage current in insulator with dry band (case C).

Table 5. Lag with the presence of dry band

T/B	1	1/2	1/5	1/10
Lag in degrees	84,24°	84,24°	79,92°	73,44°

After the analysis, it is possible to assimilate each case and its variants to specific types of circuit, outlined in figure 6. for case A, the absence of pollution and, therefore, of a conductive path, makes the set a capacitive circuit, proven by the almost perfect phase shift between current and voltage, so the insulator is analogous to a capacitor. For case B, the continuous pollutant layer on the polymeric surface forms a conductor in parallel with the insulator, allowing the flow of a resistive current proportional to the concentration of residues deposited in the equipment, such that voltage and current occur in phase. and finally, case C, which, when a dry band is inserted in the middle of the polluting conductive path, it produces an effect similar to that of a capacitor, influencing the total impedance of the circuit and displacing the voltage current. The provoked angular lag can be used to detect the existence of dry bands. The loss tangent can also be another way to check.

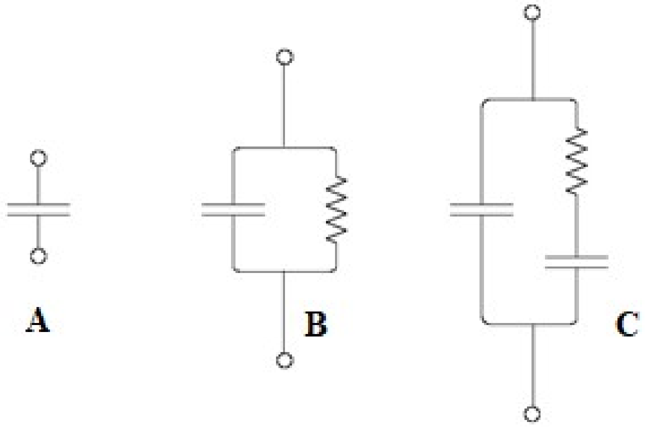

Fig. 6 Approximate circuits for cases A, B and C.

5. CONCLUSION

This work, in addition to verifying the modeling of polymeric insulators and their operating conditions using FEM, performs an analysis of the leakage currents of this equipment in three environmental conditions: clean, continuously polluted and polluted with dry band. Also adding different deposition rates for the pollution layer. It was found that the current manifests itself in a typical way for each case and capable of approaching the phenomenon of a schematized electrical circuit. In each situation it was possible to distinguish intensity and lag, being useful in the detection of dry bands in the equipment by measuring the leakage current, and measuring the phase angle between the leakage current and the applied voltage and also making it possible to estimate the non-uniformity of the pollutant layer. Determining the presence of dry bands as soon as possible is essential to delay the aging process of the insulator housing, given that they stimulate frequent partial discharges on the insulating material. Over time, the intensification of this phenomenon permanently damages the insulation and can lead the insulator to a major failure, such as a breakdown.

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