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ORIGINAL ARTICLE

Modeling the Electrical Breakdown of High Voltage Insulators in Wet and Polluted Environments for Electrical, Energy, and Construction Engineering Applications

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ABSTRACT

High voltage insulators are crucial components in electrical transmission and distribution systems, responsible for maintaining the insulation between conductors and supporting structures. These insulators are exposed to diverse environmental conditions, including humidity and pollution, which significantly impact their performance. Long-term exposure to moisture and severe pollution reduces the surface resistance of insulators, leading to increased surface currents and the potential for electrical discharges. Such failures compromise network reliability and safety. This study examines the behavior of porcelain and glass insulators under polluted and humid conditions, presenting an electrical model for contaminated insulators in wet environments. The simulation results reveal that the parameters of electrical arcs depend on the insulator profile and pollution severity, indicating that these factors are variable and dynamic. This paper contributes to the field of electrical and energy engineering by providing insights into the performance of insulators in challenging environments, highlighting the need for adaptive strategies in insulator design and maintenance.

Keywords: *Insulation, Pollution, Humidity, Leakage current, Critical conditions, Electric arc*

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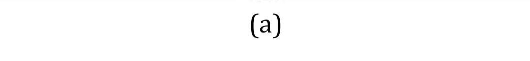
INTRODUCTION

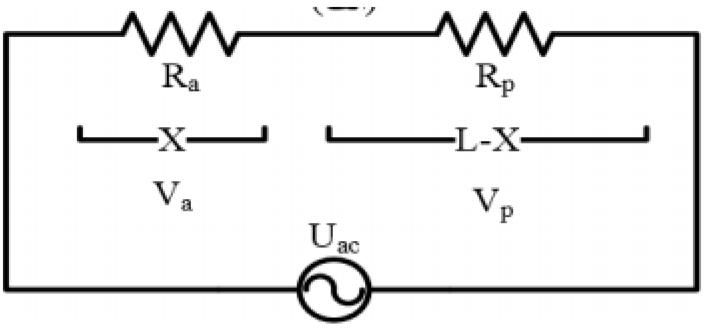
High voltage insulators are essential in power transmission lines, serving to support conductors and ensure electrical insulation. Chain insulators, which consist of multiple insulator units connected in series, are commonly used in high voltage overhead lines due to their mechanical strength, ease of installation, and cost-effectiveness. The performance and reliability of these insulators are critical for ensuring system safety and uninterrupted power supply [1-2]. Insulators in overhead lines are continuously exposed to the elements, including various environmental and weather conditions. One major challenge is the effect of pollution, which, when combined with moisture, can lead to a significant reduction in the surface resistance of insulators. This reduction increases the leakage current across the insulator surface, potentially causing heating, dry band formation, and ultimately, electrical discharges or arcs. These occurrences can degrade power quality and reduce network reliability [3]. The impact of pollution on insulator performance has been a subject of extensive research, given its importance in the design and operation of electrical systems [4-5]. This paper focuses on the behavior of porcelain and glass insulators under polluted and wet conditions, providing a detailed electrical model of contaminated insulators. The findings underscore the variability and dynamic nature of arc parameters, influenced by insulator design and pollution levels. This study's insights are vital for the field of electrical and energy engineering, particularly in the context of construction and maintenance of high voltage systems, where adaptive measures are essential to manage the effects of environmental stressors on insulators. The main cause of aging and destruction of most insulators is the creep current, one of the main factors of which is the reduction of the creep path of the insulator due to the establishment of pollution on its external surface. Among the types of pollutants, we can mention chemical, industrial, agricultural pollution, dust and even snow that sits on the surface of insulators in cold areas. In this condition, the increase of creep current on the surface of the insulator can cause unconventional electrical behavior of the insulator, surface failure and electric arc. Various electrical models for insulators have been proposed in scientific references and documents [6-11]. The electrical model of a clean insulator is different compared to a contaminated or snow-covered insulator. Most of these differences are in obtaining the electric arc constants that so far have been presented for different electrolytes such as salt [12-13]. The reason for this difference is due to the different mathematical method and type of insulator that each of them considered for their model. In all the conducted researches [14-21], there is a great agreement between the values obtained from the experiments and the results obtained from their mathematical model. The reason for obtaining the mathematical model for the performance of the contaminated insulator during an electric arc is to achieve the desired results in the fastest time and with the lowest cost. The pollution required for conducting experiments is done by two artificial methods, salt fog and solid layer, which have different concentrations. In IEC815, IEEE and CIGRE standards, in order to compare the intensity of pollution, pollution is divided into seven categories of non-polluted, very light, light, medium, heavy and very heavy pollution, whose unit of measurement is milligrams per square centimeter (mg/cm^2) [22-23]. The tests performed on the insulator covered with snow have shown that the snow acts as a non-linear resistance and its unit length resistance depends on various parameters such as the shape of the insulator and the leakage current passing through it has a non-linear relationship with the voltage applied to it. Also, depending on the conditions and amount of contamination and the geometric shape of the insulator, the contamination layer is modeled as a nonlinear resistance, which depends on the applied voltage in addition to the dimensions and geometry of the insulator. In addition, the temperature of the insulator surface and the temperature between the insulator and the pollution layer increases under the influence of current passing. This leads to an increase in the length of the dry band and increases the probability of electric arcing. These models can provide great help to researchers and power companies in checking the performance of insulators, improving the shape of insulators, designing system isolation, or predicting the probability of electric arc occurrence and studies of damages caused by weakness in insulators [24-25]. In this paper, the effect of parameters such as the amount and type of contamination, uniformity or non-uniformity of contamination on factors such as leakage current spectrum, voltage distribution and the occurrence of electrical discharges (corona) have been analyzed to monitor the performance of insulators. In this paper, the effect of the intensity of pollution on the shape of the leakage current and the amplitude of the critical voltage of porcelain and glass insulators in dry and wet conditions has been investigated using simulation experiments. Finally, an electrical and mathematical model has been presented for modeling insulation conditions in polluted and humid environments.

MATHEMATICAL MODEL

Identifying the behavior of electrical breakdown and arc propagation and their modeling has been of interest for a long time, and models have been presented and are currently being worked on them. An electric arc starts when the intensity of the electric field in the dry area of the insulator is greater than the intensity of the field in the wet area. This happens when the power injected into the electric arc through the source is greater than the loss power of the electric arc. In this case, the arc resistance drops sharply and the arc remains stable, and the arc current is limited only by the resistance of the wet layer. If the source power decreases, the arc resistance increases and the arc is extinguished. The equivalent circuit of the contaminated insulator is shown in Figure 1. According to this figure, the contaminated part and the dry band part of the contaminated insulator are modeled as two non-linear resistors in series. R_a and R_p are the electric arc resistance (electrical resistance of the dry band) and the resistance of the pollution layer in ohms, respectively. Also, L and x are the creepage length of the insulator and the creepage distance of the electric arc in centimeters, respectively.



(a)



(b)

Figure 1. (a) A view of the insulator with a dry band contamination layer and (b) the equivalent circuit of the contaminated insulator

The dry band voltage is defined according to Eq. 1:

$$V_a = r_a X I_a \tag{1}$$

In this regard, I_a is the leakage current and r_a is the linear resistance of the unit length of the dry band in ohms/cm. According to the electrical circuit in Figure 1, the voltage applied to the contaminated insulator is obtained from the Eq. 2:

$$U = V_a + R_p I_a \tag{2}$$

In this equation, R_p is the resistance of the contaminated layer in ohms and is expressed according to the Eq. 3:

$$R_p = r_p \left(L - X\right) \tag{3}$$

In which, r_p is the linear resistance of the unit length of the pollution layer in ohms/cm.
The electric field of the dry band is defined according to the Eq. 4:

$$E_a = \frac{V_a}{x} = N I_a^{-n} \tag{4}$$

In this equation, N and n are the electric arc constants. By replacing Eqs. 3 and 4 in Eq. 2, the voltage applied to the insulator can be written as follows:

$$U = xNI_a^{-n} + r_p \left(L - X\right) I_a \tag{5}$$

In critical conditions (critical conditions are one cycle before the occurrence of a complete electric arc in the insulator), the changes in voltage applied to the insulator relative to the leakage current and also the creep distance of the electric arc are zero. Therefore, in critical conditions, the following equations are established:

$$\frac{\partial U}{\partial X} = 0 \tag{6}$$

$$\frac{\partial U}{\partial I} = 0 \tag{7}$$

According to Eqs. 5 to 7, the critical parameters of the insulator will be as follows:

$$X_c = \frac{L}{n+1} \tag{8}$$

$$I_c = \left(\frac{N}{r_p}\right)^{\frac{1}{n+1}} \tag{9}$$

$$V_c = L\left(N\right)^{\frac{1}{n+1}} r_p^{\frac{n}{n+1}} \tag{10}$$

On the other hand, we have heat theory equations according to Fourier's thermal law:

$$P = E_a I_a = \frac{dQ}{dt} \tag{11}$$

Where Q is the amount of heat caused by the leakage current and E_a is the electric field of the dry band. On the other hand, the resulting temperature change rate per unit of time can be defined as follows:

$$\frac{dQ}{dt} = -\lambda A \frac{\partial T}{\partial r} \tag{12}$$

Where λ, A, r and T are thermal conductivity, cross section area, cross section radius and average surface temperature respectively. By comparing Eqs. 11 and 12, we will have:

$$E_a I_a = \pi \lambda_{ave} T \tag{13}$$

On the other hand, λ_{ave} is defined according to [26] with the following equation:

$$\lambda_{ave} = \sum_{i=a}^{v} \frac{\lambda_i}{\frac{A_i\left(1-v_i\right)}{v_i}} \tag{14}$$

In this equation, λ_i, A_i and v_i are thermal conductivity coefficient, kinetic gas coefficient and volume fraction for each component, respectively. The indices are related to air and water vapor respectively. It is assumed that the part of the discharge channel contains air and water vapor [26].

RESULT

For simulations, two types of composite insulators have been considered at voltage levels of 66 kV. The specifications of these insulators are given below. Also, the simulations were done with PDE toolbox of MATLAB software. The physical characteristic of the 66 KV insulator is given in Table 1.

Table 1. The physical characteristic of the 132 KV insulator

Parameter	Value
Rated voltage	66 KV
Shed No.	19
Section length	860 mm
Large shed diameter	140 mm
Small shed diameter	105 mm
Net weight	3.5 Kg
Lighting impulse withstand voltage	460 KV
60 Hz flashover power frequency withstand voltage	320 KV

The insulator considered for simulation is a 66 kV composite insulator that has 37 shutters. The coefficient of permeability of the polymer insulating core is between 5 and 6 and that of silicone rubber is between 3 and 5. In the simulations, the relative permeability coefficient of the insulator core (made of fiberglass) is 6, the relative permeability coefficient of the rods is 4, and the relative permeability coefficient of the air around the insulator is 1. The values related to the relative permeability coefficients are given in table 2.

The simulations have been carried out in a two-dimensional, axially symmetric manner to investigate the effect of air freezing around the insulator on potential distribution and electric field for the two types of insulators. For designed composite insulators and field control equipment, single-phase calculations, considering the appropriate geometric model for these equipments, provide sufficient accuracy.

Table 2. Relative permeability coefficients of different materials

Environment Type	ε_r
Air	1.0059
fiberglass	6
Silicone rubber (Polymer sheath)	4
Aluminum	1
Steel alloy	1
Ice	75

Normal Condition

The electric potential and electric field distribution of the 66 kV tensile insulator in normal weather conditions are shown in Figures 2 and 3, respectively. According to Figure 2, it can be seen that the electric potential is maximum at one end of the insulator and minimum at the other end. The behavior of the electric field is similar to the electric potential. In other words, the electric field and therefore the leakage current is maximum on one side of the insulator and minimum on the other side.

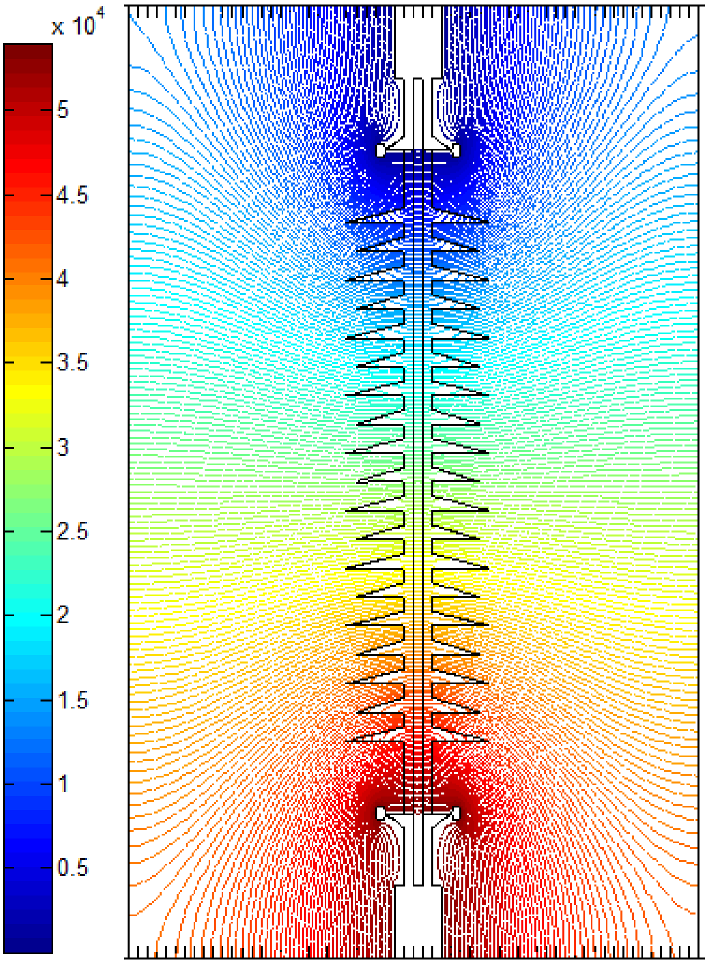


Figure 2. Distribution of equipotential lines around the 66 kV insulator in normal weather conditions

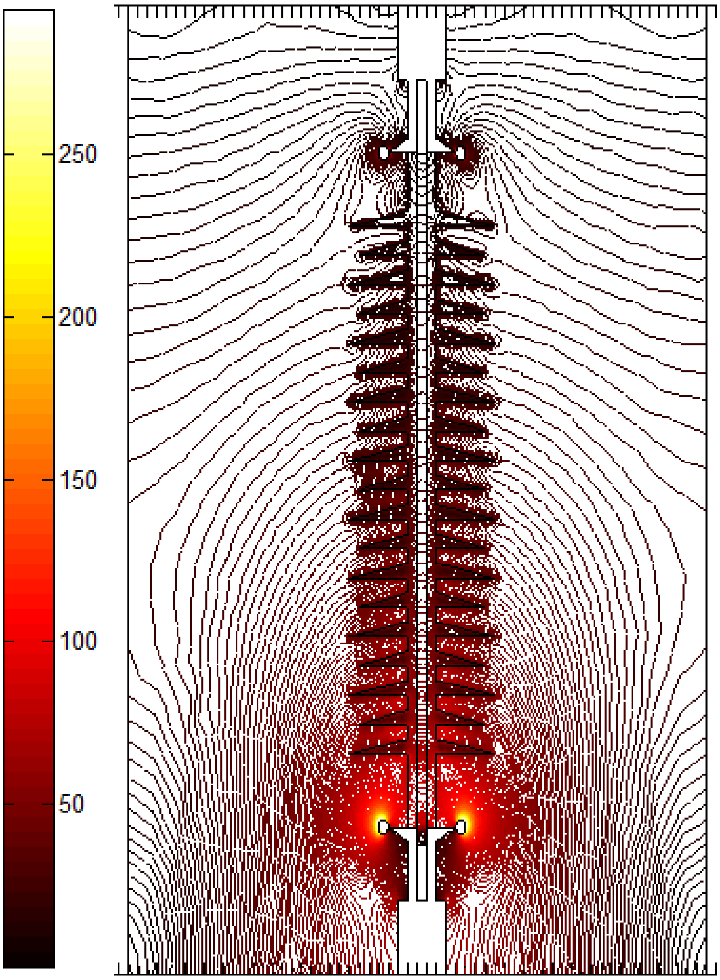


Figure 3. Distribution of electric field lines around the 66 kV insulator in normal weather conditions

Freezing Conditions

For this purpose, it is assumed that the entire surface of the insulator is frozen and the diameter and shape of the frosts are different in different parts of the insulator. The electric potential and electric field distribution of the 66 kV tensile insulator in freezing conditions are shown in Figures 4 and 5, respectively.

According to Figure 4, it can be seen that the electric potential is maximum at one end of the insulator and minimum at the other end. The behavior of the electric field is similar to the electric potential. In other words, the electric field and therefore the leakage current is maximum on one side of the insulator and minimum on the other side. Also, by comparing the amplitude of the electric field, or in other words, the leakage current between the two conditions of normal weather and freezing, it can be seen that the electric field has increased in the freezing condition, but the amplitude of the electric potential has not changed much.

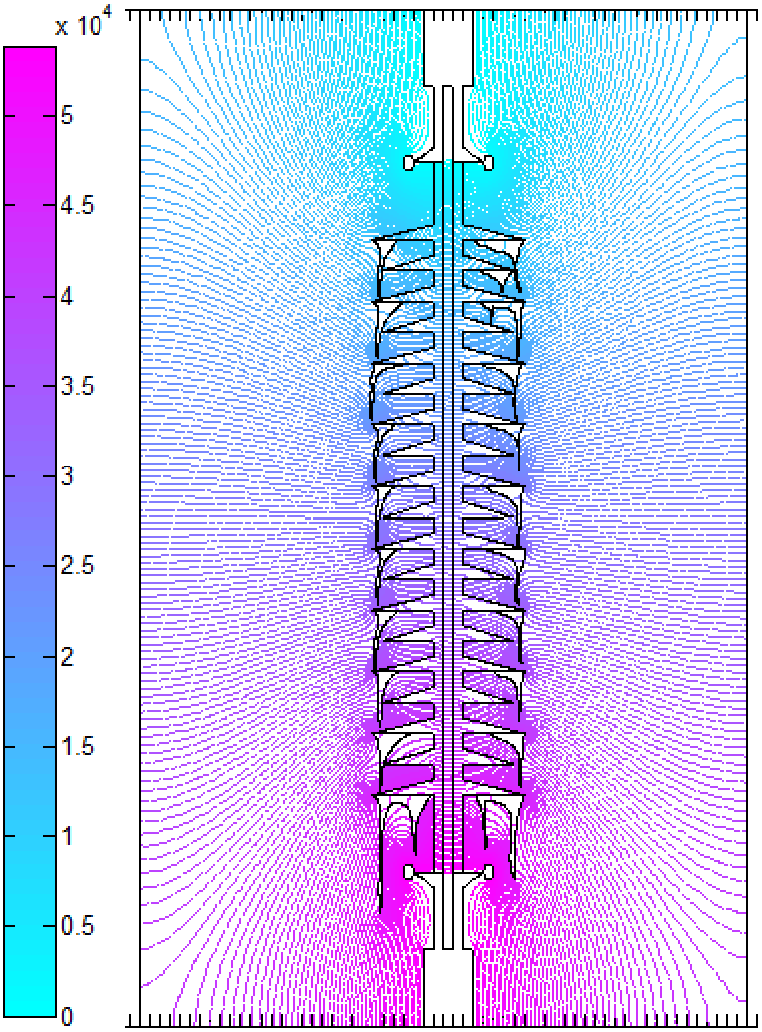


Figure 4. Distribution of equipotential lines around the 66 kV insulator in freezing conditions

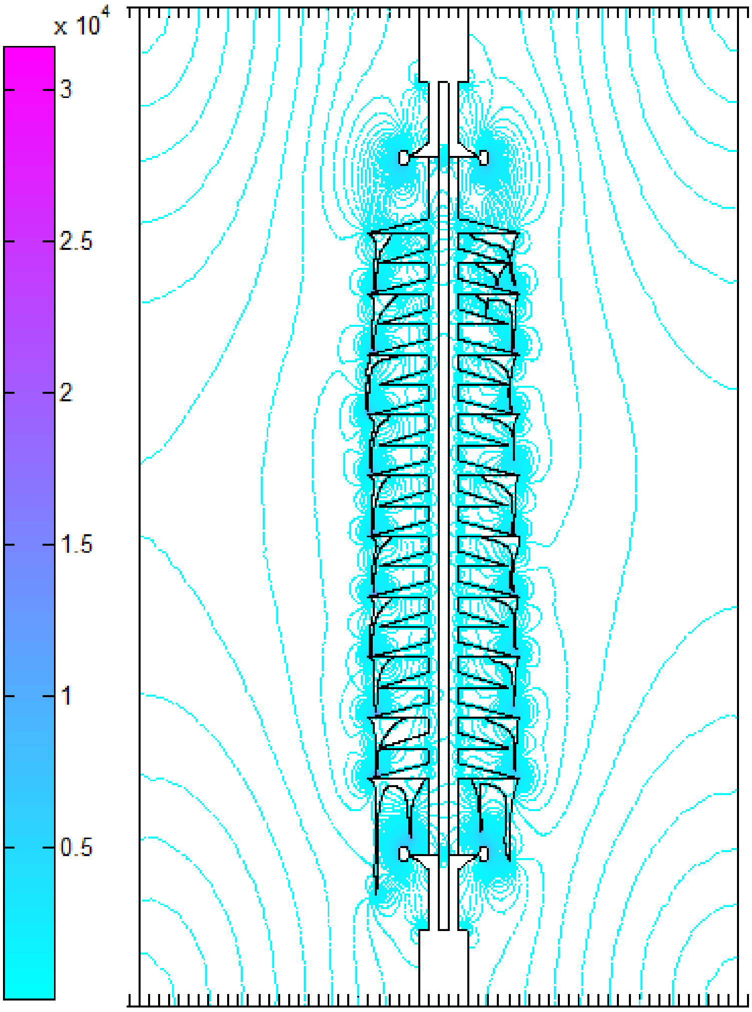


Figure 5. Distribution of electric field lines around the 66 kV insulator in freezing conditions

Pollution Condition

Contamination is the most important cause of external electrical failure on the surface of the insulator, and subsequently the operation of the relays and the exit of the transmission lines from the circuit. Experience has shown that contamination has repeatedly caused the outage of an important high-pressure line from the network. The electric potential and electric field distribution of the 66 kV tensile insulator in pollution conditions are shown in Figures 6 and 7, respectively.

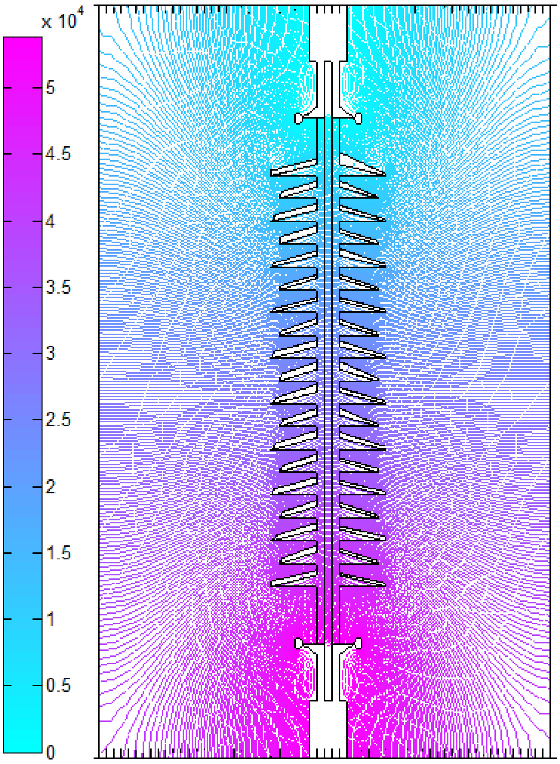


Figure 6. Distribution of equipotential lines around the 66 kV insulator in pollution conditions

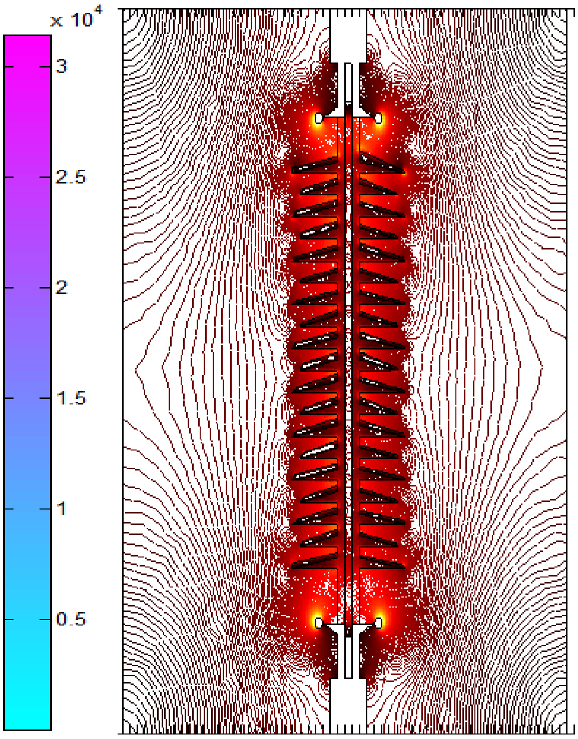


Figure 7. Distribution of electric field lines around the 66 kV insulator in pollution conditions

Similar to normal and freezing conditions, it can be seen that the electric potential is maximum at one end of the insulator and minimum at the other end. Also, the electric field and therefore the leakage current is maximum on one side of the insulator and minimum on the other side. Also, by comparing the amplitude of the electric field, or in other words, the leakage current between the two conditions of normal weather and pollution, it can be seen that the electric field has increased in the freezing condition, but the amplitude of the electric potential has not changed much. It is also observed carefully in the distribution of potential and electric field that in polluted weather conditions, the distribution of lines of electric potential and electric field is denser. This indicates that at the same points of an insulator, the electric potential and electric field of the insulator under the conditions of sometimes heavy pollution is higher than the normal and freezing conditions.

CONCLUSION

This study presents an in-depth electrical and mathematical model to evaluate the performance of high voltage insulators under wet and polluted conditions. The simulation, conducted using MATLAB 2014a, examined the leakage current spectrum across four levels of pollution and varying humidity conditions. The results demonstrate that the intensity of pollution, humidity, and applied voltage significantly influences both the leakage current and breakdown voltage of insulators. Notably, insulators with higher wet contamination levels show increased leakage current peaks. This increase is due to the nonlinear characteristics of contaminated insulators, which also lead to more frequent surface discharges and a lower voltage threshold for flashover. Additionally, as the contamination level rises, the amplitude of leakage current increases, highlighting a direct relationship between pollution severity and current leakage. The study also found that higher humidity levels make changes in leakage current more pronounced under varying pollution intensities, indicating that these environmental factors critically impact insulator performance. Furthermore, the research confirms that the constants associated with electric arcs are dynamic, varying with the insulator profile and pollution intensity. This underscores the necessity for adaptable models in insulator design and maintenance. Overall, these findings provide valuable insights into insulator behavior under challenging environmental conditions, contributing to improved reliability and safety in power transmission systems, especially in regions prone to pollution and humidity.

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