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Electric Field Computation of Stranded Over-Head Transmission Line Conductors Under the Application of Lightning Over Voltages

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***Abstract:** Efficient design of insulation systems always relies upon accuracy in the assessment of the electric field of the electrode geometry. In overhead transmission lines, stranded conductors are often used to reduce the inductance and increase the mechanical strength. Transmission lines are subjected to power frequency and lightning flashovers, which necessitate a careful analysis of electric and critical fields before erection. The dependence of maximum electric field intensity on power frequency and lightning impulse for stranded conductors of different strands using Aluminium Conductor Steel Reinforced (ACSR) has been analysed in this work. It involves the field computation of stranded conductors which have different numbers of strands. Conductors of 1,7,19 and 37 strands have been analyzed. Field computation is achieved by the Finite element method in COMSOL Multiphysics.*

***Keywords**: Overhead Transmission Line, Stranded Conductors, Field Computations, Finite Element Method*

Abbreviations:
ACSR: Aluminium Conductor Steel Reinforced

I. INTRODUCTION

Power transmission over long distances depends on the efficient design of the transmission line. Transmission line conductors may be configured in strands like 1, 7,19, or 37 stranded conductors. The advantages of stranded conductors include increased strength, flexibility, and ease of current flow, which reduces the skin effect. Hence, stranded conductors are widely used in transmission lines for power transmission. The design of the overhead transmission line mainly depends on the electric field distribution between the conductors. Accurate calculation of the field distribution near stranded conductors plays a crucial role in the design of transmission lines. Different types of faults in power systems are due to insulation failures [1]. Air is the most common insulation in overhead transmission lines [2]. explains pre-breakdown occurrences in short rod-plane gaps under positive and negative polarity lightning voltages. In [3]The authors developed a simplified model for simulating the development of positive sparks in long air gaps. The negative discharge characteristics of air under lightning impulses were well studied.

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explained [4], which mainly considered the discharge as an RLC network. The theoretical aspects of streamer development in short air gaps have been discussed in [5]. Modelling and computation of discharge parameters of discharges propagating in the air at atmospheric pressure on various materials under positive lightning impulse voltage was done in [6]. The streamer development under impulse voltages for nonuniform air gaps was studied and classified in [7] models.

In [8] the authors developed a hybrid prediction method for power frequency breakdown voltage of short air gaps with atypical electrodes [9]. In [10]The prediction method was extended to include different electrode configurations, and the errors were compared. Considering the energy storage features, the switching impulse breakdown characteristics were obtained for long air gaps. A model based on a Support Vector Classifier developed for switching impulse voltage was used to predict the breakdown voltage for transmission line air gaps. [11]. One of the early models developed in the field of air breakdown, known as the Disruptive Effect Model, is popularly referred to as the Generalised Integration Method. It predicts the time to break down, rather than the breakdown voltage. This method for modelling and predicting impulse volt-time characteristics has been discussed in [12]. Modelling of partial discharge inception and extinction voltages for sheet samples of solid insulating materials using an artificial neural network is performed. [13].

Breakdown voltage prediction of sphere gap by a data mining model established by a back propagation network has been discussed in [14]. An ensemble learning algorithm was used to model the breakdown in transmission towers, which has been proposed in [15]. Feature extraction and pattern recognition based on neural networks to assess the partial discharge formed in solid dielectric material have been done in [16]. A multilayer perceptron neural network-based model has been developed to predict the short breakdown in air gaps [17]. In [18], the prediction of leakage current of polymeric insulators using an artificial neural network has been proposed.

From the above survey, we understand that the applications of theoretical computations for critical field values under lightning impulses are limited and different formulations need to be carried out for different configurations [19]. Moreover, today's power system uses multi-stranded conductors, including 1, 7, 19, and 37 strands for power transmission. In a power transmission scheme that utilises stranded conductor geometries, the efficient computation of the field is required before erecting the transmission line to prevent frequent flashovers. Satisfactory theoretical computations are not available for this case, which highlights the need for simulations. Field computations can be done by the Finite element method, the finite difference method, and the charge simulation method. In this work, the electric field intensity at which air breakdown occurs at the surface of transmission lines with 1, 7, 19, and 37 stranded conductors has been investigated using FEM computations with the help of COMSOL Multiphysics.

II. MATERIALS AND METHODS

The equation for the computation of breakdown voltages of homogeneous field gaps, obtained from Schumann's equation, is given by (1).

$$V_b = \left(\frac{E}{p}\right)_c pd + \sqrt{\frac{K}{c}}\sqrt{pd} \quad \dots \quad (1)$$

On substitution of values of constants, (1) becomes

$$V_b = 6.72\sqrt{pd} + 24.36(pd)kV \quad \dots \quad (2)$$

Often, gas density δ is used instead of gas pressure p, and the calculation of breakdown voltages proves valid for a wide range of pressures and gap distances.

$$\frac{E_b}{p} = \frac{6.72}{\sqrt{pd}} + 24.36\,\frac{\text{kV}}{\text{cmbar}} \quad \dots \quad (3)$$

The above equation was found to be more accurate in the range of gap lengths extending from 1 mm to 100 mm.

A power system experiences different gap geometries, including non-uniform configurations and distances, and the application of the above-stated equations is limited in these cases. For significant gaps, such as transmission lines, the phenomenon of corona is observed. In coaxial cylindrical geometry, the critical field strength is given by Peek's law, as shown in (4), for smooth conductors.

$$\frac{E_c}{\delta} = 31.53 + \frac{9.63}{\delta r} \quad \dots \quad (4)$$

This equation proved more accurate for (δr) values less than 1cm; hence, a more precise formula is given by (5)

$$\left(\frac{E_c}{\delta}\right) - 2\left(\frac{E_c}{\delta}\right)E_0 \ln\left[\frac{1}{E_0}\left(\frac{E_c}{\delta}\right)^2\right] - E_0^2 = \frac{\frac{K}{C}}{\delta r} \quad \dots \quad (5)$$

When used to transmission line conductors with varying topologies, the aforementioned formulas for computing the field, as published in the literature, present challenges and reduce accuracy. Hence, a simulation-based approach is proposed in this work, which is described in Section III. The critical contributions of the work are,

1. Development of the finite element model for transmission lines with conductors having 1, 7, 19, and 37 strands.
2. Computation of the values of the electric field in the region between the two electrodes.
3. Computation of the applied voltage sufficient to cause breakdown for different configurations from the obtained field values.

III. COMPUTATION OF FIELD BY SIMULATION

The breakdown strength of air at standard atmospheric conditions is found to be 30kV/cm for smooth conductors under standard atmospheric conditions. This value has been chosen as the critical value of the field at the electrode surface, which causes the breakdown of the electrode gap. The input voltage to the model is increased until the electric field value across the gap exceeds the critical field.

The following steps have been implemented to compute the applied voltage value at which the gaps break down. The geometry of the transmission line conductors for 1, 7, 19, and 37 strands is created in COMSOL Multiphysics in the first step. After making the geometry, the material has been assigned to it. Aluminium conductor steel-reinforced conductors and steel plates are modelled, and the surrounding medium is air-filled. A lightning impulse of positive polarity has been applied to the stranded conductor. This is done by writing the equation in the COMSOL multiphysics. An electrostatic physics module is used to do the computations. The following boundary conditions have been applied to the model.

Charge conservation: To all nodes

Zero charge: The initial charge on all nodes is assumed to be zero

Initial values: The initial value of potential is assumed to be zero.

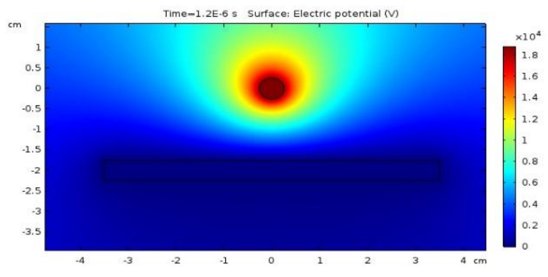
Electric potential: The lightning impulse of positive polarity is applied to the top electrode.

Ground: Ground boundary condition is applied to the bottom electrode.

It is essential to compute the value of the electric field for the design of the insulation system. Hence, a method using simulation in COMSOL Multiphysics software is proposed in this work. The technique is described as follows. The model of the required geometry is created in COMSOL software in the first step. After applying the necessary boundary conditions, lightning impulses of the required polarity are applied to the top electrode, with the bottom electrode grounded. The obtained electric field values after simulation have been observed. If the value of the field at the top electrode is greater than or equal to 30 kV, the corresponding applied voltage is considered the breakdown voltage. If the value of the field is observed to be less than 30 kV, the magnitude of the applied voltage is increased gradually until it reaches 30 kV.

IV. RESULTS AND DISCUSSIONS

Fig. 1 shows the potential distribution plot of a transmission line conductor with one strand. The red colour indicates high voltage values. The transition from red to blue colour indicates a change in the value of potential from high to low.



[Fig.1: Potential Distribution Plot with Single Conductor Strand with a Plane Electrode]

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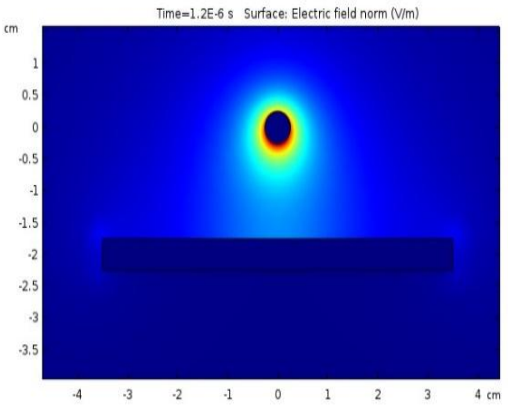
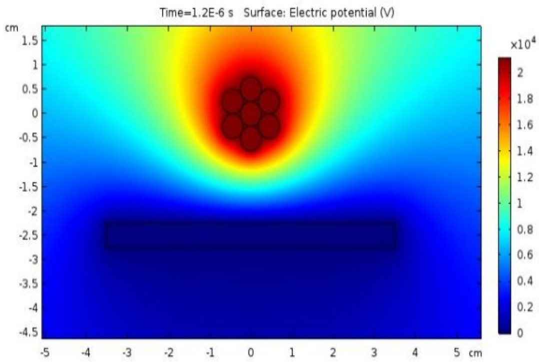
Fig. 2 shows the electrical field intensity plot of the single-stranded conductor above. Electric field intensity refers to the variation in electric potential with distance. By measuring this quantity, we can determine the breakdown strength of a dielectric medium. The total distance between the electrodes is kept at 1.5 cm in all the configurations. Here, the change in field variation from a high value to a low value indicates the colour change from red to blue.

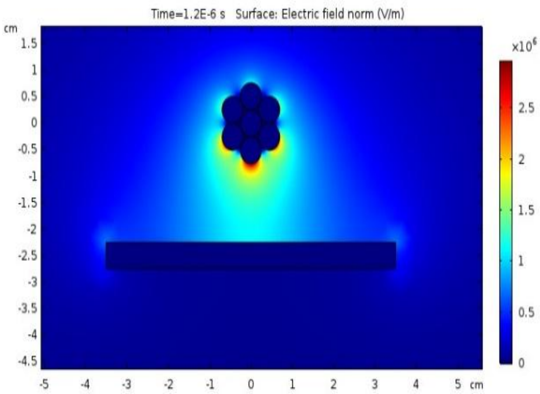


[Fig.2: Electrical Field Intensity Plot with Single Conductor Strand with a Plane Electrode]

Fig. 3 and Fig. 4 show the potential distribution plot and electric field intensity plot, respectively, for a seven-stranded conductor.

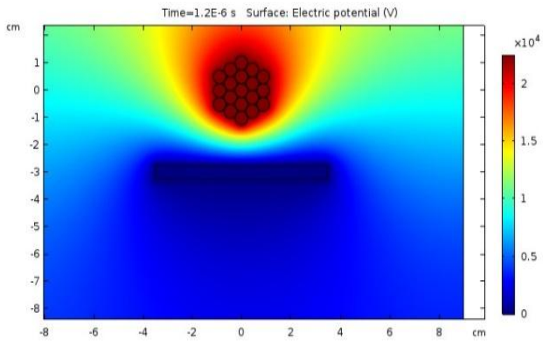


[Fig.3: Potential Distribution Plot with 7 Stranded Conductor Strand with a Plane Electrode]

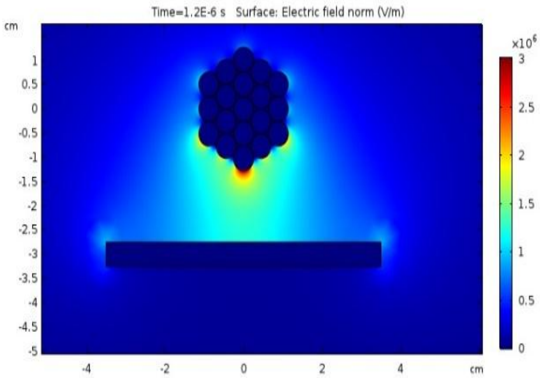


[Fig.4: Electrical Field Intensity Plot with 7 Stranded Conductors with a Plane Electrode]

Fig. 5 and Fig. 6 show the potential distribution plot and electric field intensity plot, respectively, of a 19-stranded conductor.

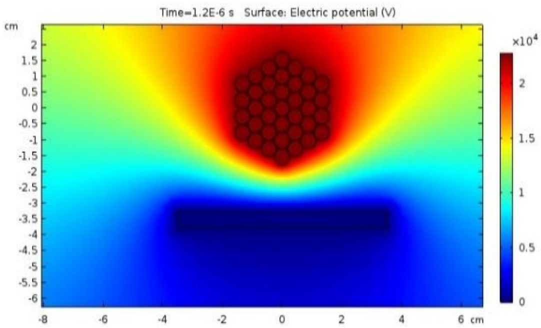


[Fig.5: Potential Distribution Plot with 19 Stranded Conductor Strands with a Plane Electrode]

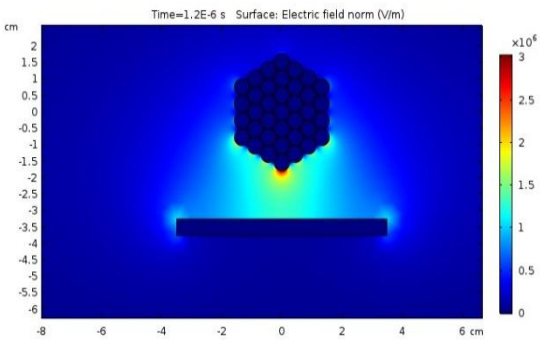


[Fig.6: Electrical Field Intensity Plot with 19 Stranded Conductors with a Plane Electrode]

Fig. 7 and Fig. 8 show the potential distribution plot and electric field intensity plot for a 37-stranded conductor.



[Fig.7: Potential Distribution Plot with 36 Stranded Conductors with a Plane Electrode]



[Fig.8: Electrical Field Intensity Plot with 36 Stranded Conductors with a Plane Electrode]

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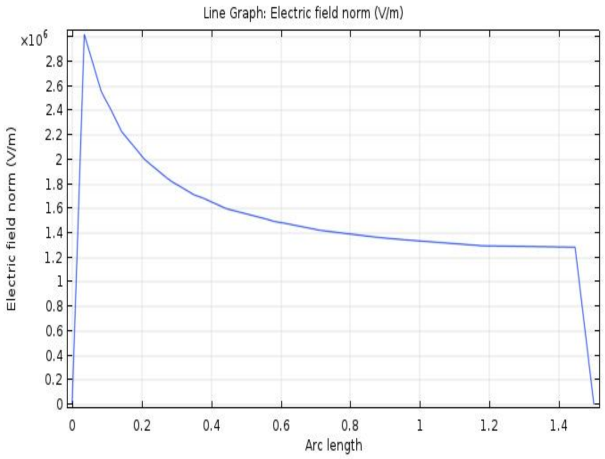
The method of finding the applied voltage for breakdown involves determining the voltage at which the electric field intensity at the surface of the upper electrode exceeds 30 kV/cm, which is the breakdown strength of air. This is done by analyzing the electric field intensity values between the two electrodes. Fig. 9 shows the sample electric field intensity graph of a 7-stranded conductor configuration. These graphs are obtained by taking the electric field intensity values along a cutline drawn from the surface of the top electrode to the bottom electrode of different configurations. By defining a cutline or cut point in COMSOL software, the values of electric field intensity at any point in the geometry can be found. Similar plots have been obtained for other configurations. From these plots, the applied voltage sufficient to achieve the desired electric field intensity at the electrode's surface has been determined and is shown in Table I.



[Fig.9: Sample Graph of the Electric Field Intensity of a 7-Stranded Conductor]

Table I: Applied Voltage Values that Cause the Electric Field Intensity at the Surface of the Top Electrode to 30kV/cm

No. of Strands	Applied Voltage (kV)
1	19.2 kV
7	21.6 kV
19	22.9 kV
37	23.25kV

It is observed that the value of the applied voltage to start the ionisation in the gap is found to increase from a single-stranded conductor to a 37-stranded conductor.

V. CONCLUSION

The computation of the field for 1, 7, 19, and 37 stranded transmission lines under the application of lightning impulses has been carried out using the finite element method. The model of the transmission line has been built in COMSOL multiphysics software. The field values obtained between two electrodes have been used to determine the applied voltage that causes the critical voltage at the electrode surface to exceed the air breakdown voltage. It is observed that the value of the applied voltage increases for 1, 7, 19, and 37 stranded conductors. The study will help in the design of transmission lines for multi-stranded conductors.

DECLARATION STATEMENT

I must verify the accuracy of the following information as the article's author.

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- **Funding Support:** This article has not been sponsored or funded by any organization or agency. The independence of this research is a crucial factor in affirming its impartiality, as it was conducted without any external influence.
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- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Author's Contributions:** The authorship of this article is contributed solely.

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