# Modeling of DC Flashover on Ice-Covered HV Insulators Based on Electric Field Analysis

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**ABSTRACT:** In this paper, a model based on dynamic electric field analysis has been developed to predict the flashover voltage of the ice-covered HV insulators, under dc voltage. The potential and electric field calculation models before and after air gap breakdown are built respectively based on finite element method (FEM). The arc initiation process is determined based on the model before air gap breakdown. The critical applied voltage and leakage current to maintain an arc with certain length are obtained based on the electric field calculation model after air gap breakdown and the U-I characteristic of the arc. Moreover, the improved Hampton criterion has been employed to determine the critical flashover of the ice-covered insulator. The results obtained from the dynamic electric field analysis model have been compared with experimental results and got a great agreement.

**Key words:** Ice-covered insulator, electric field analysis, finite element method, arc, and flashover.

## 1 INTRODUCTION

**ICING** is a worldwide natural phenomenon which has great influence on outdoor insulators. There are many reports on power system tripped-out incidents which are caused by insulator icing [1-4]. The scholars have proceeded some experiments and analysis on the flashover of ice-covered insulator. The static and dynamic mathematical flashover models of ice-covered insulator are put forward, which can predict the flashover voltage of ice-covered insulators under dc or ac voltage [5-7].

In addition, there is a close relation between the electric discharge process and the simultaneous electric field distribution, especially the initial condition and propagation process of the arc. The initial condition of the arc in the mathematical model is not easy to be defined. The calculation of the mathematical model always begins with an initial short arc [5-6]. Moreover, it cannot show the influence of the arc and the distribution of electric field on the final flashover voltage during the whole process. Meanwhile, due to the difference in flashover property between ice-covered and contaminative insulators, for example, the electric field distribution along the air gap of the ice-covered insulator has a great influence on the arc initiation and propagation [8-12]. It is insufficient to use the mathematical model without referring to the electric field interference. The influence of the electric field distribution on the discharge process of the ice-covered insulators should also be analyzed.

In this paper, an electric field calculation model is built on the basis of the former research work on the ice-covered insulators put forward by Chongqing University [13-14]. According to the electric field theory, combining the whole propagation process of the arc with the electric field distribution on the surface of ice-covered insulators, a new dynamic model is deduced which can predict the flashover voltage and process of the ice-covered insulators under dc voltage.

## 2 DEVELOPED DYNAMIC ICE-COVERED INSULATOR FLASHOVER MODEL

### 2.1 THE INITIATION OF THE ARC

Because of the melting effect of the partial arc, the ice cannot cover the insulator completely. The air gaps appear near the high voltage end or ground end of the insulator [8-10].

Figure 1 shows the three-dimensional electric field calculation model of a cylindrical ice-covered model the air gap breakdown. Based on the commercial finite element software, Comsol Multiphysics®, the finite element method is adopted to calculate the potential distribution of this model, that is, to minimize the energy function of the whole domain.

The water film in the model is simulated as a thin dielectric on the surface of the ice with certain conductivity of 80 μS/cm and uniform thickness of 0.15 mm.

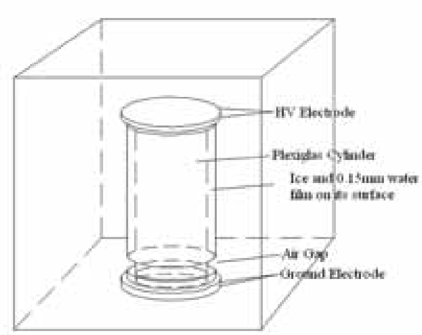


**Figure 1.** Three-dimensional electric field calculation model before air gap breakdown.

From the potential distribution around the ice-covered insulator shown in Figure 2, it can be found that before the arc initiation, the air gap near the ground end sustains most of the applied voltage of the insulator. Thus the air gap near the high voltage end and the ground end of the insulator is the usual initiation place of the arc.

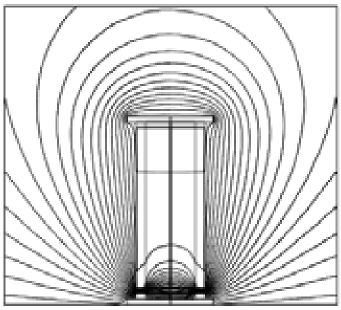

**Figure 2.** The potential distribution around the insulator before air gap breakdown.

Equation (1) represents the relationship between the breakdown electric field and the length of the ice air gaps ranging from 2 to 20 cm [12].

$$E_c\,(\mathrm{kV/cm}) = 3.96 + \frac{7.49}{x(\mathrm{cm})} \tag{1}$$

When the average electric field strength of the air gap exceeds the critical breakdown electric field strength, the arc appears and bridges the air gap. The applied voltage on the insulator before the arc initiation changes with the time. From the electric field distribution of the whole domain and the relation between electric field strength and the current density, equation (2) can be deduced to calculate the leakage current before the arc initiation.

$$J = \gamma E\,,\quad I = \int_S J dS \tag{2}$$

where $J$ is the current density in A/m$^2$ and $\gamma$ is the conductivity in S/m. Therefore, the integration of the current density of any cross section $S$ on the water film can deduce the leakage current $I$ when voltage $U$ is applied to the insulator.

### 2.2 ARC PROPAGATION AFTER THE AIR GAP BREAKDOWN

Figure 3 presents the relationship between the applied voltage and the leakage current with a given length arc on ice-covered insulator. When the arc initiates to bridge the air gap, it can be deduced from the mathematical flashover model that the arc remains in a stable state (like $U_0$ and $I_0$ in Figure 3) if the power supply capability is large enough. When the applied voltage increases, the arc will propagate and get into another stable state. Therefore, $U_0$ and $I_0$ are the critical voltage and the current to maintain an arc burning with a length of $l_0$.

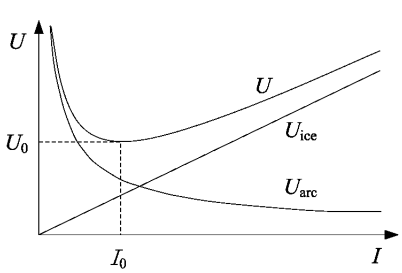


**Figure 3.** The $U$-$I$ curve of arc propagation on ice-covered insulators [34].

From Figure 3, it can be seen that the applied voltage, $U$, of an arc with a given length, decreases at the beginning and then increases with the increase of the leakage current $I$. When the applied voltage reaches the minimum value, it is the critical voltage that maintains this arc. The corresponding leakage current is the critical current to maintain this arc. Therefore, if the current of an arc with a given length, instead of the applied voltage, is taken as the external excitation source in the electric field calculation model, the $U_{\mathrm{arc}}$, $U_{\mathrm{ice}}$ and $U$ at a given arc length and a given leakage current can be obtained by the electric field calculation. Then, the minimum $U$ can be obtained by the electric field calculation with the gradual increase of the leakage current.

Due to the negative current-voltage characteristic of the arc, the voltage drop and gradient of the arc cannot be deduced by the traditional Maxwell equations and the traditional electric field solution method. Therefore, the electric field calculation model after air gap breakdown can be built as Figure 4, which only includes the arc root instead of the arc, the residual ice instead of the ice and the residual insulator instead of the insulator in this model. The electric field distribution from the arc root to the high voltage end is calculated in this model with the leakage current through the arc root as the external excitation source.

In contrast with the model before air gap breakdown, the high voltage end here is supposed to be grounded in the model after air gap breakdown. It is because the arc initiates from the ground end in this cylindrical ice-covered model. However, if the arc initiates from the high voltage end, the condition of the ground end in the electric field calculation model does not need to be changed.

The boundary condition at the arc root is supposed to be,

$$J = I / S \tag{3}$$

where, $J$ is the current density in A/m$^2$, $I$ is the leakage current in A and $S$ is the cross section area at the arc root in m$^2$.

The other boundary conditions and the solution method of the whole field are in accordance with the electric model before air gap breakdown. The radius of the arc root is defined as equation (4) [6],

$$r = \sqrt{\frac{I}{k\pi}} \tag{4}$$

where, $r$ is expressed in cm and $I$ is in A, the value of constant $k$ is 1.67 under dc negative arc condition and 1.75 under dc positive arc condition. This arc root, with a uniform thickness of 0.15 mm, is connected to the water film on the ice surface as shown in Figure 4, which can make almost all of the leakage current flow into the water film.

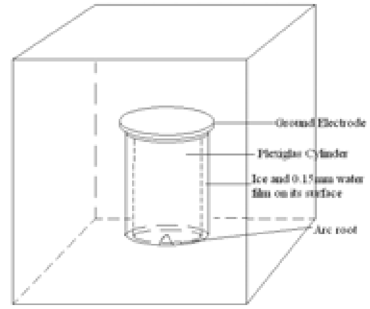


**Figure 4.** The electric field calculation model of ice-covered insulators after arc initiation.

After the electric field distribution of the residual ice-covered insulator with the given arc length and the given leakage current are calculated, from the equation $U=Ed$, the voltage on the residual ice, $U_{ice}$, can be obtained by integrating the electric field strength of any curve from the arc root to the grounded side. Meanwhile, the voltage on the arc under the given arc length and the given leakage current can be calculated as [6],

$$U_{arc} = E_{arc} l_{arc} = 84.6 I^{-0.772} l_{arc} \quad \text{for dc- arc} \tag{5}$$

$$U_{arc} = E_{arc} = 208.9 I^{-0.449} l_{arc} \quad \text{for dc+ arc} \tag{6}$$

Thus, the applied voltage, $U$, can be calculated under this given arc length and this given leakage current. Therefore, when the external excitation source in the electric field calculation model, the leakage current through the arc root, increases gradually, the applied voltage corresponding to each given leakage current can be obtained. As it is mentioned above, the applied voltage, $U$, of an arc with a given length, decreases at the beginning and then increases with the increase of the leakage current $I$. Therefore, when the applied voltage decreases to the critical minimum one, the critical applied voltage and the critical leakage current corresponding to the given arc length can be deduced.

By increasing the arc length gradually, the critical voltage and current to maintain each arc with the corresponding length can be obtained based on the above method. Therefore, the arc propagation process along the insulator can also be found. The relationship between the critical voltage as well as the critical leakage current and the corresponding arc length can be deduced as,

$$U = f(l_{arc}) \quad i = g(l_{arc}) \tag{7}$$

### 2.3 CRITICAL FLASHOVER CRITERION

In this model, the improved Hampton criterion is adopted as the critical flashover criterion. When the improved Hampton criterion is satisfied, the leakage current will increase continuously, which leads to the acceleration of the air ionization on the arc head, then promotes the arc propagation till flashover without the applied voltage increases.

In the model of this paper, after the critical applied voltage and the leakage current of any given arc length are calculated, the arc voltage gradient $E_{arc}$ can be calculated under the given critical voltage and current. The main point of improved Hampton criterion is that the voltage gradient of the residual ice layer, $E_p$ is replaced by the electric field strength near the arc root instead of the average voltage gradient of the residual ice layer, which can accurately present whether the electric field strength of the air near the arc root can accelerates the air ionization of the arc head and improve the precision of Hampton criterion. When $E_p$ is higher than $E_{arc}$ for the first time, the simultaneous arc length is the critical one, that is to say, the arc will propagate automatically until the flashover occurs. The critical applied voltage and leakage current at this time are the flashover voltage and the flashover leakage current.

### 2.4 THE RELATIONSHIP OF *I-t* AND *U-I*

The second and third part of this section present the methods to obtain the relationship between the applied voltage $U$ and the leakage current $I$ before and after the air gap breakdown. In the actual flashover experiment, the applied voltage increases with the time, as shown in equation (8).

$$U = k(t) \tag{8}$$

From equations (7) and (8), the mapping relationships between the applied voltage and the leakage current, and between the leakage current and time can be deduced.

$$U = f(g^{-1}(i)) \tag{9}$$

$$i = (fg^{-1})^{-1}\left[k(t)\right] \tag{10}$$

The *I-t* and *U-I* relationship of the whole process can be obtained by banding together the *I-t* and *U-I* relationships before and after the air gap breakdown

## 3 APPLICATION TO THE ICE-COVERED LINE INSULATORS

Based on the test results carried out in the artificial climate chamber and the results from the electric field model in this paper, the dc flashover voltage of an ice-covered 10 kV composite insulator and two units of XZP-160 porcelain insulators have been studied and compared. The physical parameters of the two type insulators are shown in Table 1. The flashover experiment of ice-covered insulator is carried out in the multi-functional artificial climate chamber in Chongqing University [14].

The test is carried out according to the method recommended by IEEE Task Force. The average thickness of ice on the insulators is checked by measuring the thickness of the ice accumulated on a monitoring cylinder with a diameter of 28 mm and rotating at one r.p.m. The air temperature during the ice deposit is -12 °C. When ice thickness reaches the target value and the temperature recovers to -1.0--0.5 °C at a speed of 2 °C -3 °C /h. Then, the flashover tests are carried out according to the method recommended by IEEE Task Force.

**Table 1.** The physical parameters of the two type insulators.

| | XZP-160 | Composite insulator |
|---|---|---|
| Shed diameter | 320 mm | 195 mm |
| Structure height | 170 mm | 545 mm |
| Leakage distance | 545 mm | 600 mm |

The icing condition of 10 kV composite insulator and two units of XZP-160 porcelain insulators are shown in Figures 5a and 5b, respectively. The sheds of the composite insulator and the XZP-160 insulator strings are completely bridged by the ice. The ice accumulation obtained for 10kV composite insulator and two units of XZP-160 insulator for a 23 mm of ice thickness are presented in Figures 5a and 5b, respectively. The air gap appears near the high voltage end of the insulator, which is the arc initiation area.

The flashover voltages of these two insulator strings are calculated based on the method presented in this paper. When the arc initiates on the surface of the ice, the leakage current is simulated as a constriction external excitation source on the arc root. Then, although the current density distribution along the ice surface is non-uniform, the voltage on the residual ice, $U_{ice}$, can be calculated by integrating the electric field strength density of any curve from the arc root to the grounded, without calculating the residual ice resistance, $R_{ice}$.

(a) 10 kV composite insulator (b) two unites XZP-160 insulators

**Figure 14.** The ice-covered insulators in artificial climate chamber (radial ice thickness measured on the monitoring cylinder is 23 mm).

The calculation and experiment results are shown in Table 3. Comparing the flashover test results with the calculation results of the presented model in this paper, it can be found from Table 2 that the experiment result is almost identical with the calculation results with the error less than 10%. The results show that the electric field model presented in this paper can be used to calculate the flashover voltage of a short line insulator with single arc during the flashover process. The error is mainly caused by the difference between the simulation model and the actual insulator. It is still difficult to simulate the configuration of the ice accurately owing to the asymmetry of the ice and the water-film on the ice surface.

**Table 2.** The comparison between calculation result and the experiment result.

| | Composite insulator | | 2-unit XZP-160 | |
|---|---|---|---|---|
| | dc+ | dc- | dc+ | dc- |
| Experiment | 32 kV | 29 kV | 49 kV | 43 kV |
| Calculation | 29.2 kV | 27.8 kV | 44.5 kV | 40.7 kV |
| Error | 8.8% | 4.1% | 9.2% | 5.3% |

## 4 CONCLUSION

The flashover model of the ice-covered insulator is built in this paper to predict the flashover voltage which is based on the dynamic electric field analysis. By analyzing the electric field around the ice-covered insulator before and after the arc initiation and combining with the *U-I* characteristic of arc, the arc initiation and propagation process along the ice-covered insulator can be obtained. The characteristics of *U-I* and *I-t* in the flashover experiment of ice-covered insulator can also be simulated with this model. For the line insulator model, it can be found that there is good agreement between the calculation results and the test results. Therefore, the dynamic electric field analysis model in this paper can predict the flashover voltage of an ice-covered insulator accurately and can be applied to the solution of the flashover voltage of an ice-covered insulator.

However, when the length of the insulator string is long enough, several arcs initiate simultaneously, the model in this paper is not feasible. Therefore, this model needs further improvement, especially for the calculation of the critical voltage and current to maintain the arc when several arcs initiate at the same time.

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