Prediction of the Flashover Performance of Ice-Covered Insulators

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***Abstract* — In this paper, the mathematical model for predicting the critical flashover voltage of ice-covered insulators is presented. It is applied to different insulators covered with ice and then the results are validated with experimental results obtained for various insulators in laboratories. Based on these results, the effects of insulator parameters, including the insulator type, length, and diameter, on the flashover performance of ice-covered insulators are determined and analyzed. The results will be helpful for properly selecting the parameters of insulators used in cold climate regions.**

I. Introduction

The performance of outdoor insulators is one of the major factors for the safe operation of power systems, influenced by environmental and meteorological conditions. In cold climate regions, one of the major factors affecting the outdoor insulator performance is atmospheric icing. The presence of ice on insulators will reduce drastically their insulating strength, sometimes leading to flashover faults and consequent power outages. This problem has been reported from several countries and received a great deal of attention from many researchers [1-5]. A large number of investigations and theoretical studies have been carried out in several laboratories [6-10].

At the Research Group on Atmospheric Environment Engineering (GRIEA) and the later created NSERC/Hydro-Québec/UQAC Chair on Atmospheric Icing of Power Network Equipment (CIGELE) in the University of Quebec in Chicoutimi (UQAC), this topic has been the subject of investigations for over 25 years [11], mostly focusing on the study of the ice accretion process and classification of ice types [12-13], determination of flashover performance of ice-covered insulators [14-15], as well as many fundamental studies and modeling on flashover phenomena on ice surfaces [16-21].

Compared to the field and laboratory investigations, the mathematical modeling of the flashover phenomenon on ice-covered insulators is a more time efficient and low cost method. Therefore, within the framework of CIGELE, a mathematical model has been elaborated for predicting the critical flashover voltage of ice-covered insulators, and has been successfully applied to a short insulator string covered with a wet-grown ice layer [20-21]. Recently, this mathematical model has been improved for application to EHV post insulators [22-23].

This paper describes this mathematical model for different types of insulators. Then the model is applied to different insulators covered with ice and validated with experimental results obtained in laboratories. Based on these results, the effects of insulator parameters, including insulator type, length, and diameter, on the flashover performance of ice-covered insulators are determined and analyzed. The results will be helpful for properly selecting the parameters of insulators for use in cold climate regions.

II. Mathematical Model for Predicting the Flashover Voltage of Ice-Covered Insulators

Flashover on ice-covered insulators is a complex phenomenon, and consists of several steps. For a suspension insulator string, generally, when the ice accretes on energized insulator surfaces, it results in a situation of an air gap between the icicles and H.V electrode in series with the accumulated ice (Fig. 1). When a water film is formed on the ice surface by melting ice, as a result of a rise in air temperature, sunshine, the heating effects of corona discharge and leakage current, the ice layer shows a high surface conductivity, and almost all the applied voltage drops along the air gap. If the applied voltage is high enough, a local arc will be triggered along the air gap (Fig. 1). This creates a situation similar to that of polluted insulators, i.e., an arc in series with a residual resistance. Therefore, the Obenaus model can also be used to describe the flashover of ice-covered insulators [20].

The circuit equation for this model is follows [20]:

$$V_m = AxI_m^{-n} + I_m R(x) \qquad (1)$$

where V_m (V) is the peak value of applied voltage; x (cm) is the local arc length; I_m (A) is the peak value of leakage current; $R(x)$ (Ω) is the residual resistance of ice layer; and A and n are the arc constants.

Under AC voltage, the current passes through zero twice in each cycle and, consequently, the local arc extinguishes and re-ignites twice. Therefore, not only Equation (1) but also the

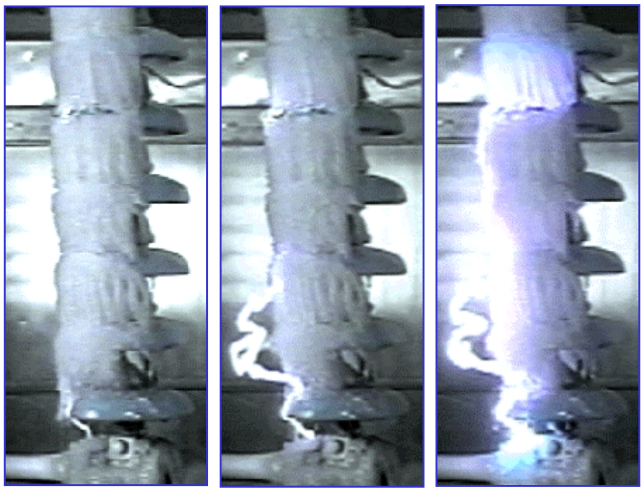


Fig. 1: Flashover on ice-covered insulators

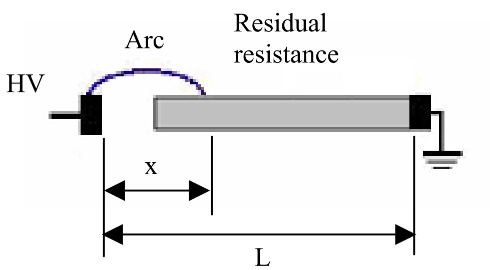


Fig. 2: Obenaus Model for flashover on ice-covered insulators

arc re-ignition conditions must be satisfied, which can be expressed as follows:

$$V_m \geq \frac{kx}{I_m^b} \qquad (2)$$

and the critical condition is:

$$V_m = \frac{kx}{I_m^b} \qquad (3)$$

where k and b are the arc re-ignition constants.

Studies have shown that when the insulator is completely covered with ice, the flashover voltage is lowest [6]. In this case, the ice layer can be simplified as a half cylinder [20], and the residual resistance can be calculated using the following formula [20]:

$$R(x) = \frac{1}{2\pi\gamma_e}\left[\frac{4(L-x)}{D+2d} + \ln\left(\frac{D+2d}{4r}\right)\right] \qquad (4)$$

where γ_e (in µS) is the surface conductivity of the ice layer; *L* and *D* are the length and diameter of the insulator string, respectively; *d* is the thickness of the ice layer; and *r* is the arc root radius.

In our previous studies, all the parameters have been experimentally determined as follows:

$$A = 204.7 \qquad (5)$$

$$n = 0.5607 \qquad (6)$$

$$k=1118 \qquad (7)$$

$$b= 0.5277 \qquad (8)$$

$$\gamma_e=0.0675\sigma+2.45 \qquad (9)$$

$$r = \sqrt{\frac{I_m}{0.875\pi}} \qquad (10)$$

where σ (in µS/cm) is the conductivity of applied water forming the ice layer.

In the study, it was found that for insulators longer than 1 m, particularly for the post type insulators, there usually were two air gaps along ice layer, one near the HV electrode and another at the lower part of the insulator (Fig. 3). Consequently, if the applied voltage is high enough, there will be two arcs in series with the residual ice layer.

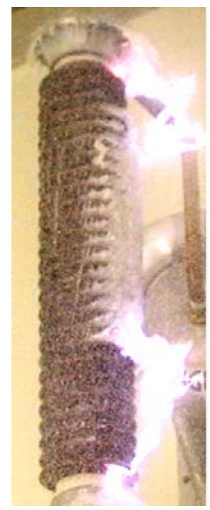
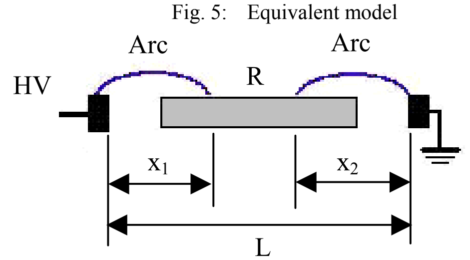


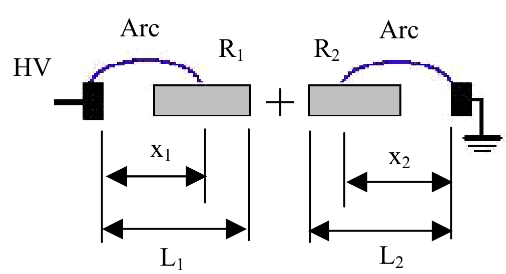
Fig. 3: Flashover on post type insulators

In this case, the flashover on ice-covered, post-type insulator should be described by the double-arc model [23].

Fig. 4: Double arcs model

Fig. 5: Equivalent model





The calculation of residual resistance should consider the current concentration at two arc roots. In fact, the model can be equivalently split into two parts, as shown in Fig. 5: where

$L_1 + L_2 = L$; $x = x_1 + x_2$ is the total length of the local arc. Thus, from Equation (4), the residual resistance of the ice layer can be expressed as follows:

$$R(x) = R_1(x_1) + R_2(x_2) \qquad (11)$$

where
$$R_1(x_1) = \frac{1}{2\pi\gamma_e}\left[\frac{4(L_1 - x_1)}{D+2d} + \ln\left(\frac{D+2d}{4r}\right)\right] \qquad (12)$$

$$R_2(x_2) = \frac{1}{2\pi\gamma_e}\left[\frac{4(L_2 - x_2)}{D+2d} + \ln\left(\frac{D+2d}{4r}\right)\right] \qquad (13)$$

Thus
$$R(x) = \frac{1}{2\pi\gamma_e}\left[\frac{4(L - x)}{D+2d} + 2\ln\left(\frac{D+2d}{4r}\right)\right] \qquad (14)$$

Also, it was found that, for post-type insulators, all values of the parameters in Equations (5) to (10) can be used, but only the value of arc ignition constant k should be modified as [23]:

$$k = 1300 \qquad (15)$$

This is because of the air gap close to the high voltage (HV) electrode. For suspension insulator strings, the HV electrode is at the bottom of the string. It is easier to maintain an arc and make it propagate along the suspension insulator surface due to the thermal buoyant force created by the arc itself, compared to post-type insulators, on which the HV electrode is at the top. Therefore, the value of k is a little higher for post insulators than that for suspension insulators.

All the necessary parameters in Equations (1), (3) and (4) were determined. Then, this model can be used to predict critical voltage of various insulators covered with ice. These equations are complex and have no analytic solution. Numerical methods were used to solve them, and FORTRAN and a MATLAB programs were developed for this purpose.

III. APPLICATIONS OF THE MODEL

Due to the limit of laboratory conditions, the experimental results of the flashover performance of ice-covered insulators, particularly long insulators, are very few. Therefore, this model was validated mainly by the results obtained in the laboratories of CIGELE. During these flashover tests, the ambient air temperature was kept constant at -12 °C.

A. Suspension insulators

The model is first applied to suspension insulators. An IEEE standard insulator was used for this purpose (Fig. 6). The critical flashover voltage, V_c, was experimentally determined in laboratory and calculated from the mathematical model, as functions of dry arcing distance, applied water conductivity, and shed diameter.

V_c as a function of dry arcing distance

The dry arcing distance is one of the main factors affecting the flashover voltage of ice-covered insulators. There are no available results published for suspension insulator strings long than 1 m. The model was validated with the results of short insulator strings. For an IEEE standard insulator number

Dimensions (mm)	
Shed diameter	254
Unit spacing	146
Leakage distance	305

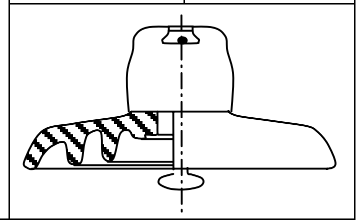


Fig. 6: IEEE standard insulator

varying from 1 to 6, the dry arcing distances are 22.5, 37.1, 51.7, 66.3, 80.9, and 95.5, respectively. Fig. 7 shows the results calculated from the model, as a function of dry arc distance, considering the thickness of ice on the insulator surface to be 2 cm, and the applied water conductivity, 80 μS/cm. The experimental results were taken from [13] and also plotted in Fig. 7. It may be observed that there is good agreement between the calculated and experimental results. The maximum error is 8% for 1 unit only. Also, the critical flashover voltage, V_c, increases almost linearly with the increase in dry arcing distance of ice-covered insulators.

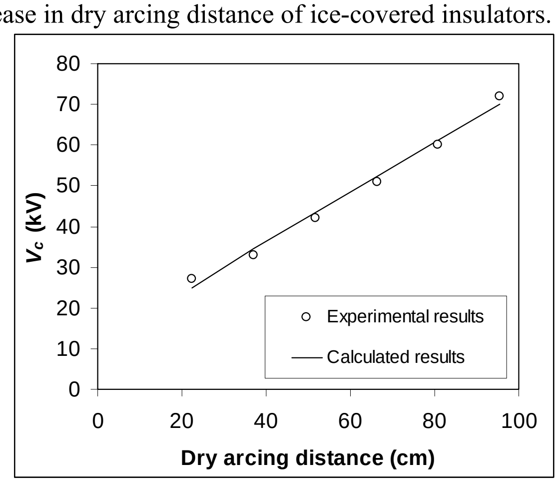


Fig. 7: V_c as a function of dry arcing distance for IEEE standard insulator string, σ = 80 μS/cm and d = 2 cm

V_c as a function of applied water conductivity

Due to the different atmospheric pollution levels in various regions, the conductivity of water melted from atmospheric ice may change. In order to simulate this case, the model was applied to ice-covered insulators with different applied water conductivities and the results were compared with the experimental ones [20]. Fig. 8 shows the results. In the calculation, the dry arcing distance was set to 80.9 cm (5

IEEE standard units) and the thickness of the ice layer was 2 cm. Again, the results show a good agreement and the maximum error is about 6%. The critical flashover voltage deceases with the increase in applied water conductivity.

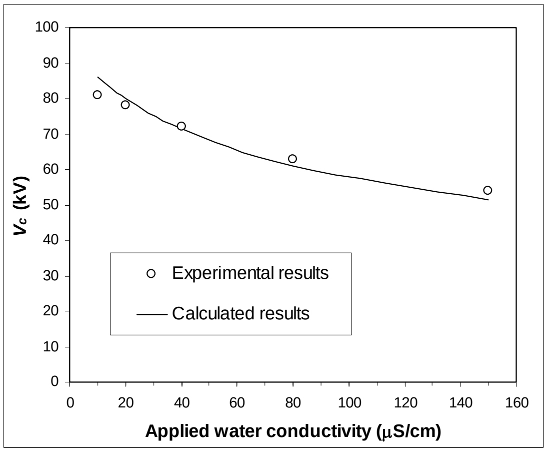
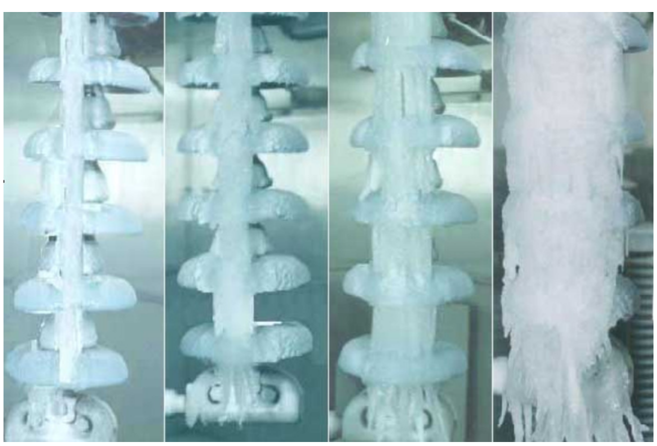


Fig. 8: V_c as a function of applied water conductivity for IEEE standard insulator string, L = 80.9 cm and d = 2 cm

V_c as a function of ice layer width

The insulator diameter is another parameter affecting the flashover performance of ice-covered insulators [9]. The width of the ice layer accreted on insulators is directly related to insulator diameter. From the point of view of the mathematical model, the small insulator diameter will collect a narrow ice layer. This will increase the residual resistance of the ice layer, thus increasing the flashover voltage. In order to study the effects of insulator diameter on flashover performance, a series of tests were carried out [24]. To eliminate the effects of the insulator shed space, 5 IEEE standard insulator units were used and the ice layer width was changed for simulating different insulator diameters (Fig. 9). The applied water conductivity was 80 μS/cm. Fig. 10 shows the experimental results and those calculated from the model. The maximum error is about 6.9%.



5 cm 10 cm 15 cm 46 cm

Fig. 9: IEEE standard insulator string with different ice layer width to simulate effects of insulator diameter

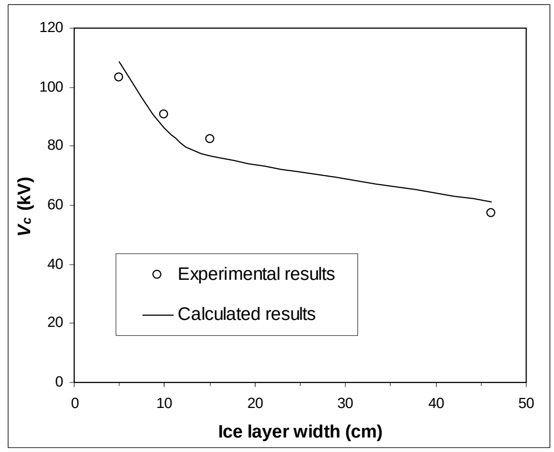


Fig. 10: V_c as a function of ice layer width (insulator diameter), L = 80.9 cm, σ = 80 μS/cm and d = 2 cm

B. *Post type insulators*

In order to study the flashover performance of ice-covered, post-type insulators longer than 1 m, using 3 standard post insulator units (Fig. 11), a series of tests was carried out in the 9-m-high climate room [23]. The minimum flashover voltage, V_{MF}, was determined for 5 different insulator lengths, corresponding to dry arcing distances of 139, 202, 307, 351, and 417 cm. The last length corresponds to the full-scale insulators used in 735 kV power substations in Quebec. As an application, the mathematical model was applied to the post-type insulators and validated by the experimental results, shown in Fig. 12. It may be observed that there is good agreement, in view of engineering application, between the experimental results and those calculated from the improved model. The maximum error is 6.7%. It may also be noted that V_c increases with an increase in insulator dry-arcing distance in a slightly non-linear manner, that is, the flashover strength, V_c/m, decreases with the increase in dry arcing distance.

Height 1540 mm
Arc distance 1360 mm
Leakage path 3500 mm

Higher part
Interior diam. 154 mm
Exterior diam. 246 mm
Middle part
Interior diam. 168 mm
Exterior diam. 262 mm

Number of Skirts 26

Fig. 11: Post type porcelain station insulator

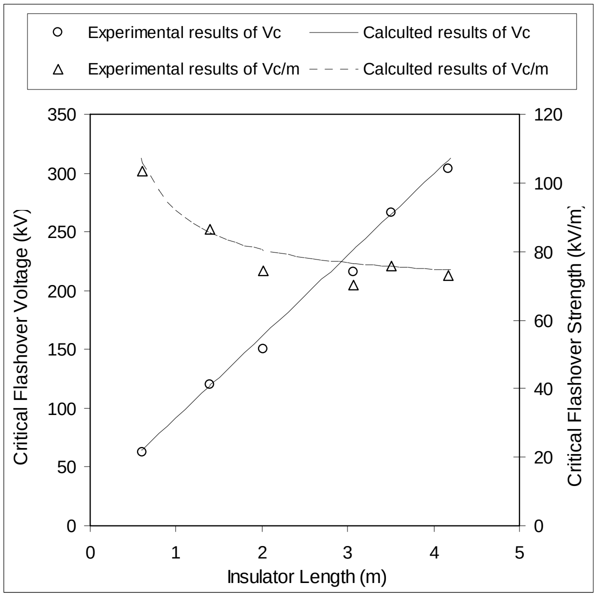


Fig. 12: V_c as a function of dry arcing distance of post type insulator, σ = 80 μS/cm and d = 2 cm

C. Cylindrical ice sample

In order to validate the mathematical model, it was also applied to a cylindrical ice sample and the results were compared with the experimental ones. The cylindrical ice sample was made by accumulating supercooled water droplets on a glass tube (Fig. 13) [25]. After the ice was accreted, an air gap was artificially created at the top of ice sample (Fig. 13). This represents a situation similar to a post-type insulator. Therefore, the mathematical model for post-type insulators was applied to the cylindrical ice sample, i.e., the arc reignition constant, *k*, was set to 1300. However, in this case, due to only one air gap, the one-arc model was used for calculating the critical flashover voltages.

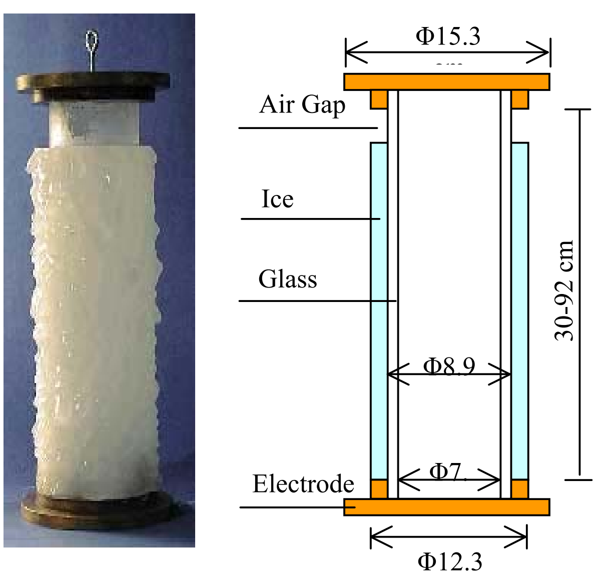


Fig. 13: Cylindrical ice sample

Figs 14 and 15 show the experimental and calculated results obtained for different dry arcing distances and for different applied water conductivities, respectively.

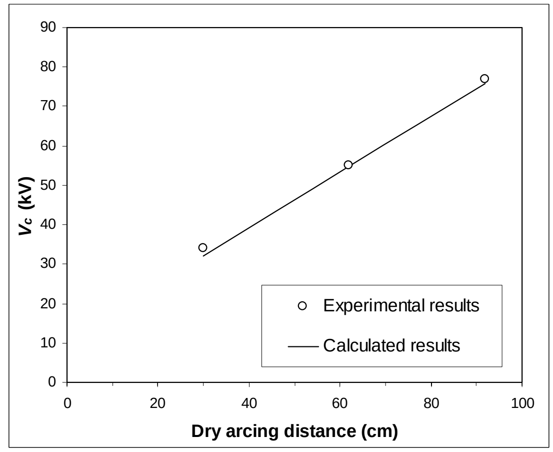


Fig. 14: V_c as a function of dry arcing distance for cylindrical ice sample, σ = 80 μS/cm and d = 1.5 cm

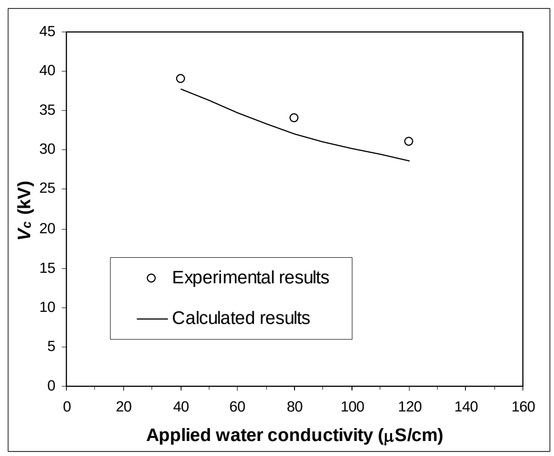


Fig. 15: V_c as a function of applied water conductivity for cylindrical ice sample, L = 30 cm and d = 1.5 cm

It may be noted that there is also a good agreement between the experimental and calculated results for this kind of ice samples.

This demonstrated that, if the number and position of arcs (air gaps) are known, the mathematical model can be used to predict the critical flashover voltage of various insulators under heavy icing conditions. The results will be helpful for properly selecting the parameters of insulators for use in cold climate regions.

IV. Conclusions

A mathematical model for predicting the critical flashover voltage of ice-covered insulators was developed. From the results obtained from its application to insulators, the following conclusions may be drawn:

1) The number and position of air gaps vary for different types of insulators. When the air gap is at the bottom of

insulator string, it is easier to maintain an arc and make it propagate along insulator surface, due to the thermal buoyant force created by the arc itself. In this case, the value of k is higher than that when the air gap is at the top.

2) When the model is applied to the suspension insulator string, there is good agreement between the calculated results and those obtained experimentally in laboratory. The critical flashover voltage increases almost linearly with the increase in arcing distance of the insulator string, up to 1 m, while it decreases non-linearly with the increase in applied water conductivity and insulator diameter.

3) There is also good agreement, in view of engineering applications, between the experimental results and those calculated from the model, when the model is applied to post-type insulators; the maximum error is 6.7%. The calculated and experimental results show that V_c increases with an increase in insulator dry-arcing distance in a slightly non-linear manner, that is, the flashover strength, V_c/m, decreases with the increase in dry arcing distance.

4) There is also good agreement between the experimental and calculated results obtained for a cylindrical ice sample. This demonstrated that, if the number and position of arcs (air gaps) are known, the mathematical model can be used to predict the critical flashover voltage of various insulators under heavy icing conditions. The results will be helpful for properly selecting the parameters of insulators for use in cold climate regions.

V. ACKNOWLEDGMENTS

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