Experimental Study and Mathematical Modeling of Flashover on EHV Insulators Covered with Ice

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ABSTRACT

Using a test method developed at CIGELE, the relationship between the minimum flashover voltage (V_{MF}) and the insulator dry arcing distance for standard porcelain station post insulators, as typically used in Hydro-Quebec substations, was investigated under icing conditions. The experimental results show that, under wet-grown ice, known as the most dangerous type of ice for power transmission systems, the V_{MF} increases nonlinearly with an increase in insulator length. Based on these results, an improved mathematical model for predicting the minimum flashover voltage vs. length of ice-covered standard design insulators is presented. This model is helpful for understanding the flashover phenomena on ice-covered insulators and presents a powerful tool for choosing proper length of outdoor insulators in cold climate regions.

Key words: atmospheric icing, arc, flashover, insulator, modeling

INTRODUCTION

In cold climate regions, one of the major problems for power systems is atmospheric icing due to freezing rain or drizzle, in-cloud icing, icing fog, wet snow, or frost. In addition to mechanical damages due to excessive ice accumulation and dynamic loads caused by wind, the presence of ice and snow on insulators may lead to flashover faults, and consequent power outages. For example, on April 18, 1988, at the Hydro-Quebec Arnaud substation, a series of six flashovers occurred on insulators covered with wet snow and resulted in a major power interruption for a large part of the province of Quebec (Hydro-Quebec, 1988). Also, power outages caused by ice and snow accretion have been reported by many authors in Canada (Chisholm et al., 1996 and Cherney, 1980), the United States (Cherney, 1980), Japan (Matsuda et al., 1991), Norway (Fikke et al., 1992), China (Su & Hu, 1998), and England (Forrest, 1969).

This problem has received a great deal of attention from many researchers and a large number of investigations and theoretical studies have been carried out in several laboratories (Farzaneh, 2000). Reviews of most of these investigations were reported in previous work (Farzaneh & Kiernicki, 1997, and Farzaneh & Kiernicki, 1995) and recent papers by IEEE (M. Farzaneh et al., 2003a) and CIGRE (CIGRE TF 33 04 09, 1999 & 2000) task forces. The flashover phenomenon on ice-covered insulators has been studied for over 25 years in the HV laboratories of Université du Québec à Chicoutimi (UQAC) (Phan, 1974) and, subsequently, of the NSERC/Hydro-Quebec/UQAC Industrial Chair on Atmospheric Icing of Power Network Equipment (CIGELE). A mathematical model has been established for predicting the

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critical flashover voltage of ice-covered insulators, and has been successfully applied to a short insulator string covered with a wet-grown ice layer (Farzaneh et al., 1997). However, mainly due to limited laboratory conditions, very few experimental results for the flashover voltage of full-scale EHV insulators under icing conditions are available. This situation makes it difficult to apply this model to long, ice-covered insulators for engineering purposes.

The main objectives of the present study are to evaluate the critical flashover performance of a standard post insulator, as typically used in 735 kV Hydro-Quebec substations, under icing conditions and, based on the experimental results, to improve the mathematical model for application to long, ice-covered insulators.

FLASHOVER MECHANISM OF ICE-COVERED INSULATORS

Flashover on ice-covered insulators is a very complex phenomenon, as arc is not only an electrical process, but also thermal and electro-chemical. Figure 1 shows an example of a flashover on standard line insulators covered with ice. The flashover of ice-covered insulators includes the following steps:

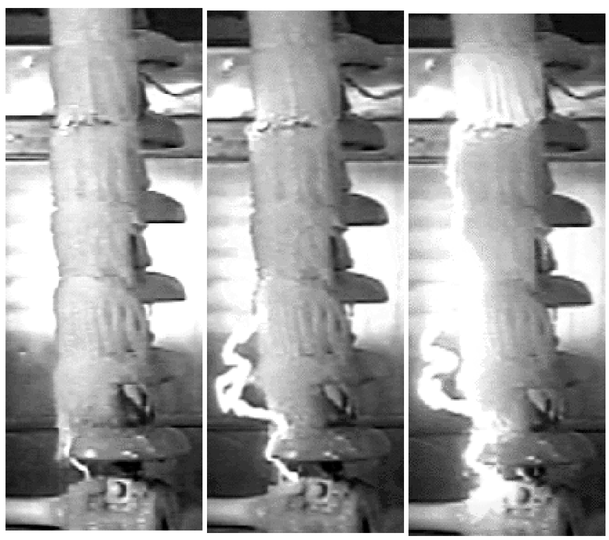

Figure 1. Flashover on ice-covered insulators

i) Atmospheric ice accretion on insulator surface due to the hoar frost, in-cloud icing, or precipitation icing. Precipitation icing can occur in several ways, including freezing rain and drizzle, as well as wet and dry snow. Glaze with icicles is the most dangerous type of atmospheric icing.
ii) The distribution of ice on insulators is seldom uniform. The windward side is usually free of ice. Also, for long insulators, no accretion usually occurs in areas of high electric stress, i.e., air gaps. These air gaps are caused by the melting or shedding of ice from some parts of the insulator.
iii) Dry ice has high resistivity and does not reduce significantly the electrical properties of insulators. However, due to the effects of sunshine, a rise in air temperature, condensation, and/or the heating effect of leakage current, a water film will form on the ice surface. This water film has very high conductivity and may cause predictably large voltage drops across the air gaps. Therefore, the initial corona discharges and the consequent local arcs will develop at these sections of the insulator.
iv) If the applied voltage is high enough, the local arc will change to a white arc and extend along the ice surface. When the local arc reaches the critical length, it will result in complete flashover.

Therefore, it can be noted that the flashover process is a local arc propagation process on an ice surface. It may be considered as local arcs in series with the residual ice layer.

TEST FACILITIES AND PROCEDURE

In order to determine the minimum flashover voltage of the EHV insulators under icing conditions, a series of tests was carried out in one of the CIGELE climatic rooms. This room, 6 m (w) × 6 m (l) × 9 m (h), is equipped with a HV SF_6 composite bushing, as well as a sophisticated water droplet generator for physical simulations of cold precipitations. The ammonia cooling system and computer-controlled regulators allow for rapid cooling to temperatures as low as –30 ± 0.2°C. The water droplet generator is comprised of a system of 6 oscillating pneumatic nozzles located in front of a diffusing honeycomb panel. Behind the panel, a set of fans in a tapering box produce adjustable wind velocities. The specific design of the water droplet generator can produce a very uniform ice deposit on the test object. Figure 2 shows the inside of the climatic room, featuring the water droplet generator (1), the insulators under test (2) and the HV bushing (3).

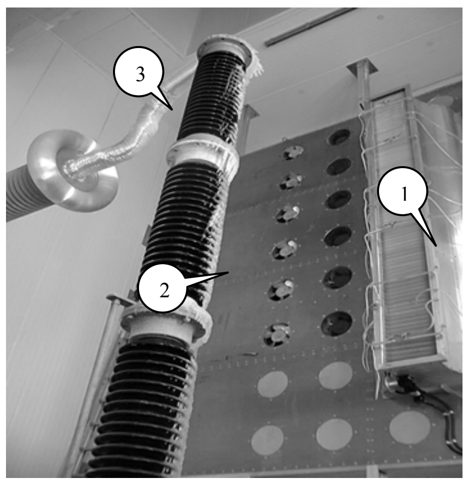

Figure 2. Interior of the UQAC climate room used in this study

The high-voltage system is composed of a 350-kV, 700-kVA transformer and its associated voltage regulator (Fig. 3), specially designed for flashover tests on insulators under icing conditions. This system, with its 2 tap switches, has a minimum short-circuit current of 10 A at 130 kV, and maximums of 42 A at 240 kV, and 32 A at 350 kV.

Figure 3. UQAC 350 kV alternating high-voltage system

Standard porcelain insulators, which are typically used in Hydro-Québec 735-kV substations, were tested in this study. Figure 4 shows one unit of the tested insulators and some of its characteristics.

Height	1540 mm
Arc distance	1390 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
Skirts	
Number	26
Spacing	50 mm

Figure 4. 735 kV porcelain station post insulator with normal glaze and standard shed profile

At CIGELE, two test procedures for evaluating the electrical performance of ice-covered insulators, i.e. an icing regime and a melting regime, were developed according to a systematic investigation program undertaken jointly by Hydro-Québec and UQAC since 1989. Under a careful control of test conditions, these two methods present similar results (Farzaneh et al., 2003b). Compared to the melting regime, the icing regime method is more time efficient and, therefore, is used in this study. This method is summarized as follows:

This procedure includes two sequences, i.e., ice accretion and evaluation of the maximum flashover voltage (Fig. 5). During the ice accretion sequence, water with a conductivity of 80 μS/cm was used to build up a uniform wet-grown ice layer on entire length of the vertically installed insulators, energized at 80 kV_{rms}/m. This type of ice is considered to be the most dangerous since it is associated with the highest probability of flashover (Farzaneh & Kiernicki, 1995 and Farzaneh& Kiernicki, 1992). Once the desired 15 mm ice thickness was reached, measured on the rotating monitoring cylinder, the water spraying system and the voltage applied to the insulator were turned off. The details of test conditions for the ice accretion period are summarized and listed in Table 1. Then, the icing process is stopped and the insulator is photographed. This period, Δt_0, takes less than two minutes to ensure the existence of a water film on the ice surface. Then, the voltage is immediately applied to the insulators and raised from 0 to an estimated test value (V_E), corresponding to the start-up of the evaluation sequence, in a rate of 3.9 kV/s.

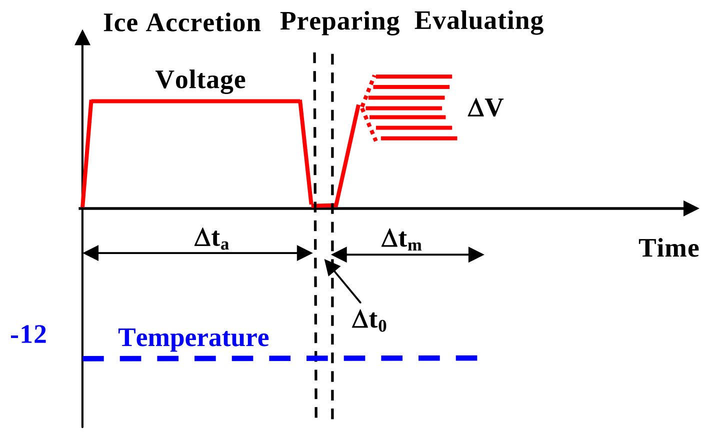

Figure 5. Sequences of the icing regime test procedure

The maximum withstand voltage, V_{WS}, was considered the maximum level of applied voltage at which flashover did not occur for a minimum of 3 tests out of 4, under similar experimental conditions. For each withstand test, the insulators were kept at the test voltage for a period of at least 15 min. to ensure that no flashover occurred during this period. The minimum flashover voltage, V_{MF}, corresponds to a voltage level ~5% higher than V_{WS} at which 2 flashovers out of a maximum of 4 tests was produced.

Table 1: Test parameters for the ice accretion sequence

Test parameters	Parameters values
Air temperature	–12°C (± 0.2°C)
Average water droplet size	80 µm
Freezing water conductivity	80 µS/cm at 20°C
Precipitation intensity	34 mm/h (± 7 mm/h)
Incidence angle	53° (± 5°)
Wind velocity	3.3 m/s
Ice thickness on monitoring cylinder	15 mm
Voltage gradient	80 kV_{rms}/m

EXPERIMENTAL RESULTS AND DISCUSSION

Using these facilities and procedure, a series of tests was carried out. The minimum flashover voltage, V_{MF}, were determined for different insulator lengths. In this study, 5 insulator lengths, corresponding dry arcing distances of 139, 2002, 307, 351, and 417 cm, were chosen. The last length corresponds to the full-scale insulators used in 735 kV power substations. The results are shown in Table 2 and Fig. 6.

Table 2: Flashover performance of standard porcelain post insulator

Dry arcing distance (m)	V_{MF} (kV_{rms})	V_{MF}/m (kV_{rms}/m)
1.39	120	86.3
2.02	150	74.3
3.07	216	70.4
3.51	266	75.8
4.17	304	72.9

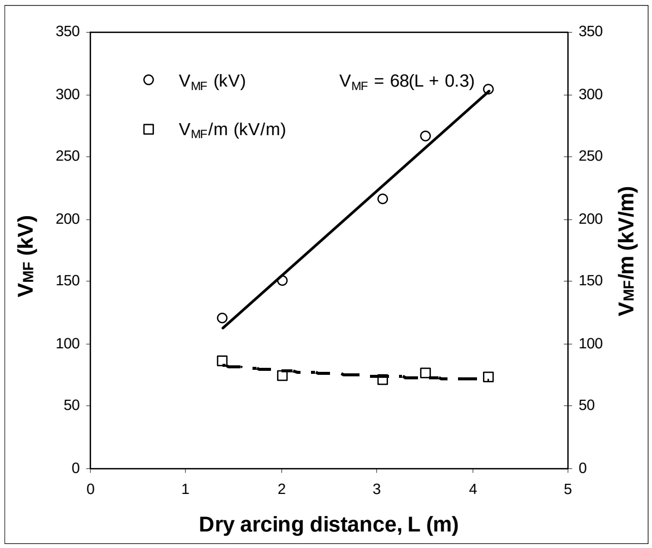

Figure 6. Minimum flashover voltage and stress as a function of dry arcing distance

It can be observed that V_{MF} increases with the increase in insulator dry arcing distance. However, the flashover stress decreases as the insulator dry arcing distance increases, which suggests that the minimum flashover voltage shows a slightly non-linear increase with the increase in insulator dry arcing distance. Under the test conditions, i.e. freezing water conductivity of 80 µS/cm and ice layer thickness of 15 mm, the flashover stress of tested insulators is only about 70% of the service voltage stress (105 kV_{rms}/m) of 735 kV substations.

PREDICTION OF MINIMUM FLASHOVER VOLTAGE OF ICE-COVERED INSULATORS

The in-field or laboratory investigation for determining the minimum flashover voltage of ice-covered insulators is generally costly and time consuming. Therefore, using a mathematical model is probably one of the most interesting ways of estimating the critical flashover voltage of ice-covered insulators. As mentioned above, one such model has been developed at CIGELE, but needs to be improved for predicting the flashover voltage of large-scale, ice-covered insulators, i.e. longer than 1m.

In the flashover tests carried out in this study, it was observed that, in the case of long insulators, the electric arcs were usually established at both ends of insulator i.e. the H.V and ground ends (Fig. 7). This phenomenon will change current distribution along the ice surface and, consequently, bring some modification into the exiting mathematical model (Chaarani, 2003).

Figure 7. Two arcs are established at both ends of the ice-covered insulator

In this case, the flashover is the result of two local arcs, at both electrodes, in series with a residual ice layer in the middle section of the insulator (Fig. 8). The equation for this circuit model can be expressed as follows (Farzaneh et al., 1997):

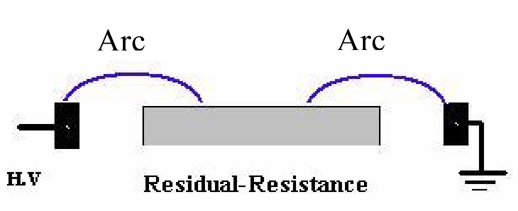

Figure 8. Model of flashover on an ice surface with two arcs

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

where x (in cm) is the total length of the two arcs; V_m (in V) and I_m (in A) are the peak values of applied voltage and leakage current; A and n are the arc constants; R(x) (in Ω), is the residual resistance of the part of the ice not bridged by the arc. For the insulator string covered with a semi-cylindrical ice layer and two local arcs at both ends, R(x) can be calculated as follows (Chaarani, 2003):

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

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

Under AC conditions, in order to maintain an arc propagating on a dielectric surface, not only Equation (1'), but also the arc re-ignition conditions, which can be expressed by Equation (3), must be satisfied (Farzaneh et al., 1997).

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

where k and b are re-ignition constants. This arc reignition condition represents the maximum length *x* the arc can reach under the applied voltage, V_m, and the corresponding leakage current, I_m.

In the existing mathematical model (Zhang & Farzaneh, 2000 and Farzaneh et al., 1997), using a triangular ice sample, all the necessary parameters in Equations (1), (2), and (3) have been determined as follows:

$$A=204.7 \qquad (4)$$

$$n=0.5607 \qquad (5)$$

$$r = \sqrt{\frac{I_m}{0.875\pi}} \qquad (6)$$

$$\gamma_e = 0.0675\ \sigma + 2.45 \quad (\mu S) \qquad (7)$$

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

$$k=1118 \qquad (9)$$

where σ (in µS/cm) is the freezing water conductivity at 20 °C.

The arc constants A and n, the arc root radius r, as well as the arc reignition constant b, are independent from insulator dimensions, while the arc reignition k is affected by the insulator parameters such as diameter (Chaarani, 2003). Therefore, keeping the value of k as a constant will bring some error into the calculation results when applying this model to the insulators with different parameters. The relation between the value of k and the insulator diameter was experimentally determined in a previous study (Chaarani, 2003). Based on the experimental results of the present study, it was found that the value of k should be modified to 1,300 for the tested insulators. Thus, the mathematical model, i.e., Equations (1) and (3) can be used for predicting the flashover voltage of full-scale EHV insulators covered with ice. As an application, this improved model was validated by the experimental results obtained with the standard porcelain post insulators used in this study (Fig. 4), with five different lengths. The results are shown in Table 3 and Fig. 9. From these results, it may be observed that there is good concordance, in view of engineering application, between the experimental results and those calculated from the improved model. The maximum error is 6.7%. This model is helpful for understanding the flashover phenomena on ice-covered insulators, and a powerful tool for design of outdoor insulators in cold climate regions.

Table 3. Comparison of experimental results and those from the model for the STD porcelain post insulator (Fig. 4)

Dry arcing distance (m)	V_{MF} from the model (kV_{rms})	V_{MF} from experiments (kV_{rms})	Difference (%)	Critical arc length, x_c (m)	$R(x_c)$ (kΩ)
1.39	118	120	–1.7	1.13	180
2.02	160.8	150	6.7	1.54	241
3.07	230	216	6.1	2.21	345
3.51	260	266	–2.6	2.49	389
4.17	303.5	304	–0.2	2.92	454

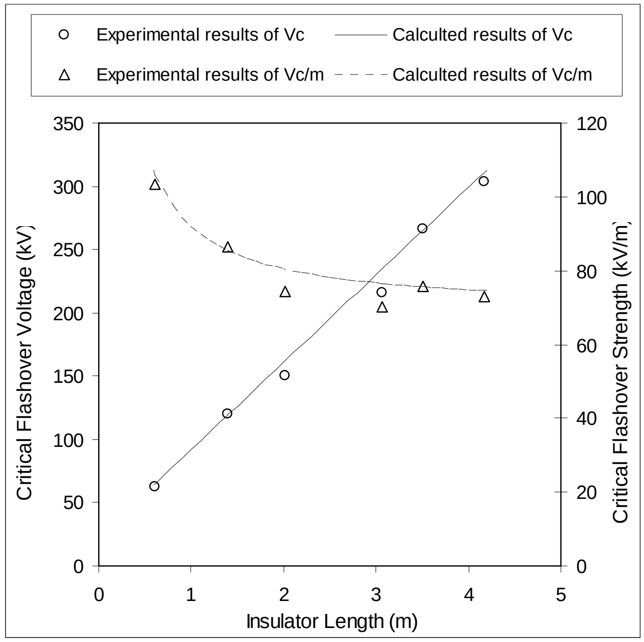

Figure 9. Experimental results and those calculated from the model

CONCLUSIONS

An improved and validated mathematical model for predicting the flashover voltage of ice-covered insulators was presented. From the results obtained, the following conclusions may be drawn:

1). The electrical performance of standard 735-kV station post insulator with arcing distances, up to 4.17 m for full scale, was evaluated under severe icing conditions. The V_{MF} increases with an increase in insulator dry arcing distance. The flashover stress decreases as the insulator dry arcing distance increases. This suggests that the V_{MF} presents a slight non-linear increase with the increase in insulator dry arcing distance.

2). For a freezing water conductivity of 80 μS/cm and ice layer thickness of 15 mm, the minimum flashover stress of the 735-kV station insulators tested is about 30% lower than that of the service voltage stress of 105 kV_{rms}/m.

3). There is good concordance between the flashover voltage calculated from the improved mathematical model and the experimental results.

4). This model is useful for understanding the flashover phenomena on ice-covered insulators, and a powerful tool for design of outdoor insulators in cold climate regions.

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