Process and Modeling of AC Arc Development on an Ice Surface

M. Farzaneh, I. Fofana and C. Tavakoli

NSERC / Hydro-Quebec / UQAC Industrial Chair on Atmospheric Icing of Power Network Equipment (CIGELE) and Canada Research Chair on Engineering of Power Network Atmospheric Icing (INGIVRE) at http://www.cigele.ca, Université du Québec à Chicoutimi, Quebec, Canada, G7H 2B1.

Abstract— **Ice accretion along energized insulators is not uniform, as several parts of the insulators are free of ice; these zones are referred to as air gaps. The flashover of ice-covered insulator is initiated by a 'partial arc' phase during which ionized channels appear in the air gaps. The corresponding physical propagation processes of this partial arc are analyzed with the help of the mathematical model taking into account arc re-ignition condition. The use of high speed camera, the measure of leakage current associated with the partial arc allows one to compare simulated parameters to experimental ones. This comparison indicates the feasibility of assessment of flashover prediction, using the proposed model.**

I. Nomenclature

C: arc root – opposite electrode capacitance.
Df : distance far from the discharge axis at which the magnetic field is considered to be zero.
γ_e *: ice surface conductivity, μS/cm.*
I_a *: leakage current.*
k : arc radius parameter.
I_m *: peak AC current.*
L : arc channel inductance, Hm^{-1}.
L_a *: arcing length of an insulator.*
L : leakage path length of an insulator.
P_o*: heat conduction rate.*
q_L *: arc channel average charge per unit length.*
r_{arc} *: arc resistance per unit length,* Ωcm^{-1}.
r : arc root radius.
R_{ice} *: residual ice-layer resistance.*
σ_w*: freezing water conductivity, μS/cm,*
t : time.
τ: arc deionization constant.
v : arc propagation velocity.
V_{ap} *: applied voltage.*
V_m*: peak value of applied voltage.*
V_c *: potential across capacitance C.*
w : ice layer width.
x : arc length.

II. Introduction

In a large number of cold-climate regions, atmospheric ice accumulation on overhead power lines causes problems to the normal operation of the equipment. Particularly, ice accretion on H.V. insulators can sometimes decrease considerably the electrical performance of these devices. In spite of considerable efforts made by several researchers, modelling of arc development on ice-covered insulator surfaces is still a challenging point in the study of outdoor insulation in concerned regions [1-3]. There is therefore a great interest in understanding the physics of ice surface dielectric breakdown under various conditions.

Contrary to mechanical effects, and also due to the complexity of the subject, flashover process on ice-covered insulators has been less studied. The mechanisms of flashover of ice-covered insulators are not yet fully understood. Some tentative explanation has been reported in the scientific literature in this field [1, 3]. Basic studies are essential to the elucidation of the mechanisms involved in the initiation of discharges, and their transition to arc propagation. However, researchers do agree that ice flashover is caused mainly by the combination of several elements, including [1-3]:

- decrease in "effective" leakage distance caused by ice bridging;
- increase in surface conductivity caused by presence of a water film created by various factors, such as process of wet ice accretion, condensation, heating effect of leakage current and partial arcs, rise in air temperature or sunshine;
- formation of air gaps caused by the heating effect of partial arcs, rise in air temperature or ice shedding;
- and, finally, presence of a pollution layer on the surface of the insulator.

Ice accretion along energized insulators is not uniform, as several parts of the insulators are free of ice; these zones are referred to as air gaps. It is generally agreed that the presence of a water film on the surface of the ice is necessary for flashover to occur. The high conductivity of water film (caused by rejection of impurities from the solid part toward the liquid portion of drops or droplets during solidification, and by pollution of the water and ice surface by the products of corona discharge [4]) means that voltage drops occur essentially across the air gaps. The initiation of corona discharges leading to the development of partial arcs in these zones causes a substantial increase in leakage current. Under sufficient electrical stress, arcs propagate along the ice surface, forming a white arc. When the white arc reaches a certain length, the whole insulator suddenly undergoes complete flashover.

Modeling of the partial arc propagation is necessary to predict the physical thresholds for the occurrence of flashover to ice-covered insulators. In the present contribution the fundamental processes of the subsequent phases of AC arc on an ice surface are analyzed. For this purpose, we have based our investigation of basic mechanisms on laboratory studies using a simplified physical model. This type of physical model is particularly suited to study the basic processes of arc propagation over ice surface [5]. For the whole process, a mathematical model is proposed that has been essentially derived and simplified by the authors, in order to develop sequential time-dependent simulation of the laboratory ice surface breakdown. The aim of this mathematical model is to provide numerical tools to simulate the development of an electric arc on ice-covered insulator surface. Such modeling is necessary to predict the physical thresholds for the occurrence of electric arc on ice-covered insulator surface. The proposed mathematical model includes the successive propagation of the arc. The input data of this self-consistent mathematical model are the insulator geometry, the ice layer characteristics and/or properties, the applied voltage and some initial values.

The computed results are compared to the minimum flashover voltage measured experimentally on glass tubing cylindrical insulator. The results indicate the feasibility of assessing the flashover prediction under AC voltage, using the proposed model.

III. Tests Facilities and Procedure

Atmospheric ice was deposited at -12°C on the glass tubing cylinder, suspended vertically in the center of the climate room [3, 6]. The cylindrical object is constituted of three separate parts, two identical electrodes and a glass tube. This makes it possible to do experiments on different lengths of tube using the same electrodes. The type of glass tube used was chosen so as to be sufficiently resistant to overheating from the burning arc. Super-cooled droplets having a mean diameter of 80 µm, were produced by five pneumatic nozzles at a wind velocity of 3.3 m.s^{-1}. Ice deposited under the above conditions was glaze. This kind of ice is the most severe type [1-3, 7]. Once the ice thickness on the monitoring cylinder reached 15 mm, accretion was stopped. Immediately after ice-accumulation, an artificial air gap of 7-8 % of the total length of the insulator was created at the top of the sample, as shown in Fig. 1. This air gap simulates the air gap formed by partial arcs on actual ice-covered insulator strings during the icing period [3, 5].

Fig. 1: Ice sample and flashover test set-up.

A single-phase test voltage transformer of 120 kV (maximum), 240 kVA and 60 Hz was used. The input voltage of this equipment is 600 V. A regulator is used to make it possible to vary the output voltage from 0-120 kV (Fig. 2). The voltage increase may be affected either manually or automatically at an approximately constant rate of 3.9 kV/s.

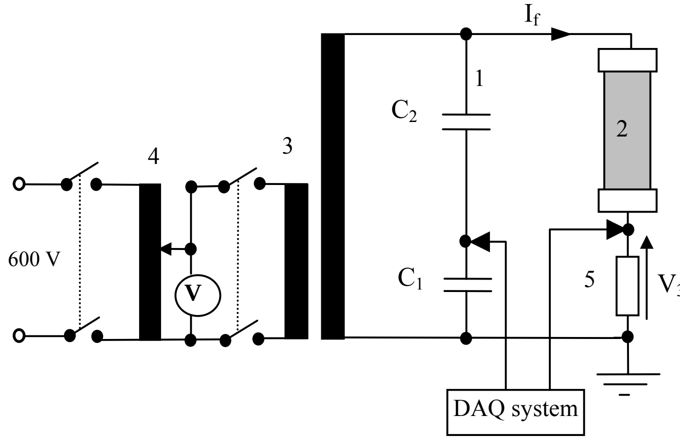

Fig. 2. Measuring circuit for AC breakdown test. 1. Capacitive divider (C_1=0,47 µF and C_2=50 pF), 2. Iced-insulator, 3. high voltage transformer, 4. voltage regulator, 5. Shunt Resistance (R_m=10Ω), $V_2 = V_1.(C_1 + C_2)/C_2$ and $I_f = V_3/R_m$.

The overall short-circuit current of the HV system is about 28 A at the maximum operating voltage of 120 kV rms. A data acquisition system was used for the purpose of gathering current and voltage signal values. Dynamic modeling of the arc leads to the temporal evolution of a number of parameters. In order to be able to compare simulated curves with the ones produced experimentally, the laboratory data should be acquired at a relatively rapid frequency. A LabVIEW graphical software program was used to acquire high quality data. The voltage signal was attenuated by using a capacitive voltage divider. The current signal was transferred to a voltage signal using a low resistance shunt of 10 Ω. The test signals were connected to a measuring set through a conditioning box providing protection and insulation. A NI-DAQ device, model PCI-6035E, was used for this purpose.

During each test, when the arc is strong enough, the current and voltage signals were captured by the DAQ system and arc behavior was filmed by a high-speed camera. The camera takes the photographs uninterruptedly and when flashover occurs the filming process may be brought to a halt, and according to the functional mode, the camera retains the last 3 seconds of data recorded. Meanwhile, the dripping water due to melting ice is collected for subsequent surface conductivity measurements to be used in the final model.

IV. Experimental results

A. Flashover Results

Two different lengths of glass tubing cylinder, 40 and 80 cm, respectively, each with three values of applied water conductivity, σ_w, set at 30, 65 and 100 µS/cm, were the test parameters imposed. The water conductivity was set by adding sodium chloride NaCl, to de-ionized water. This parameter was verified before and after each test. The wet-grown ice used in the experiments was accumulated without applied voltage. The method of maximum withstand, V_{WS}, (and minimum flashover, V_{MF}) voltage calculation is the same as described in the standard IEC507 guidelines (International

Electrotechnical Commission, 1991) [8] and recommended in [6]. The obtained results are summarized in Table 1.

TABLE 1

V_{MF} (KV) FOR ICE-COVERED GLASS TUBING CYLINDER.

σ (µS/cm)	30	65	100
L = 40 cm	48	43	40
L = 80 cm	86	78	74

B. *Effects of Initial Air Gap Length*

A further series of tests was carried out to study the effects of air gap length on flashover voltage. This series was done on a 40 cm long cylinder with the same three conductivities as used previously. The initial air gap length is 6 cm for this series. The air gap was artificially created so as to encompass 15% of the total insulator length. The results are shown in Table 2.

TABLE 2

V_{MF} (KV) FOR A 40 CM CYLINDER AND LONGER INITIAL AIR GAP.

	30 µS/cm	65 µS/cm	100 µS/cm
V_{MF} *(kV)*	47	44	45

A comparison of these results with those of previous tests was made in Fig. 3. It may be seen that, for conductivities of 65 and 100 µS/cm, the flashover voltage is the same as the flashover voltage of a 65 µS/cm ordinary test, where the initial air gap length is 7-8% of the total insulator length.

For higher conductivity (100 µS/cm), when the voltage was less than the flashover value of 65 µS/cm, no discharge was observed and when it was higher or equal to this value, a sudden flashover occurred. This confirms that the flashover voltage obtained is, in fact, the level of threshold voltage for longer artificial air gaps.

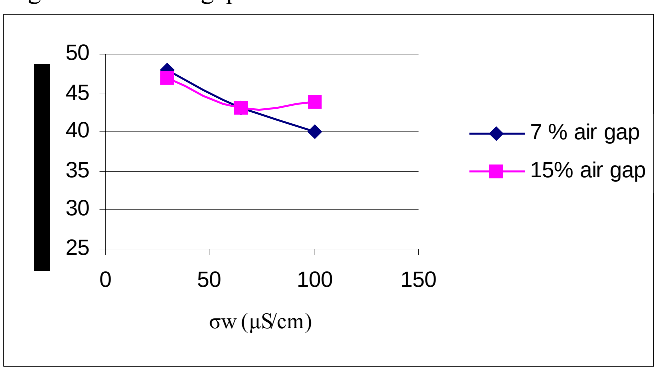

Fig. 3: Comparison of different flashover results for different initial air gap lengths, and different applied water conductivities, σ_w.

This means that the only effect of the initial air gap length is to increase the threshold voltage for breaking down the air gap. Then, after establishing the arc along the air gap and when melting water is present on the insulator surface, this length has no more effect on discharge phenomena.

C. *Current and Voltage Curves*

When flashover takes place, current increases and goes toward short circuit current. The study of current and voltage curves shows that the current curve contains strong harmonics and is not purely sinuous, but also that after the appearance of the white arc, the peak moments of voltage and current occur almost simultaneously. The distortion of the current curve may be due to the nonlinearity of both arc and surface-water resistances (see Fig. 4). In all experiments, flashover occurred when the voltage signal was nearly its maximum value. When a complete flashover occurs, the current increases while the voltage drops to zero (cf. Fig. 4).

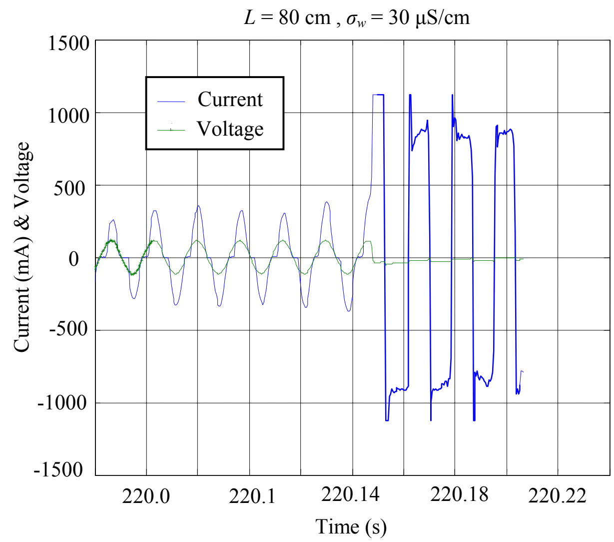

Fig. 4: Typical current and voltage signals for a flashover test.

D. *Arc Length Observations*

The arc behavior during the final propagation stage was observed using a high speed camera. The filming speed was 1000 images per second which makes it possible to take approximately four images every quarter cycle. This filming rate was not sufficient to measure the velocity of arc propagation, particularly during the propagation stage. Therefore the arc velocity was not measured during the experiments.

Photographs reported in ref. [9], show a typical last cycle before flashover for a tested insulator. It was observed that, before flashover, for almost the entire period, arc length remains constant at the same length. Indeed, even if the electrical current circulating through the partial arc is interrupted (AC arcs), the plasma does not disappear instantly because the time constants for plasma decay are, in general, not negligible at the scale of the other durations involved in the phenomenon [10]. The relevant plasma is termed "afterglow". As a rule, exact knowledge of the behavior of afterglow plasma is important in order to determine the possible conditions of either direct or inverse re-ignition. The arc was observed to be stationary for several seconds over a length of 45-60 % of the total insulator length before flashover occurred [9]. The latter variable is independent of initial air gap length.

V. THE MATHEMATICAL MODEL

One of the first quantitative analyses of arcs on contaminated surfaces was carried out by Obenaus [11]. So far, the most practical and useful models proposed by other authors have been based on the commonly-known design in which a polluted insulator is modeled by a simple electrical equivalent circuit consisting of an arc in series with an electrical resistance. To calculate the flashover voltage, the same hypothesis of static modeling [12] is being considered, where the flashover takes place during a short period of time around maximum applied voltage and so the same method [13] is applicable.

The air gaps on ice-covered insulators (or parts of the insulators free of ice) in series with the accumulated ice, and which have a relatively high surface conductivity, present situations similar to the dry bands in series with the wet part of insulators for polluted surfaces. Thus, a comparable model can be used. In this model, we assume the arc channel to a cylindrical one having a radius *r* and length *x*. We also represent it by a RLC electrical network as shown in Fig. 5.

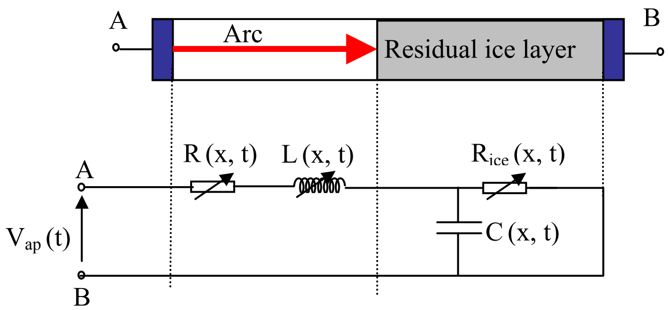

Fig. 5: Modeling principle of the arc propagating on the ice-covered surface.

The model is a self-consistent time-dependant one. The input data are the applied voltage characteristics, the ice-covered insulator geometry and characteristics.

When the arc propagates, the potential wave and current initiated are described by:

$$V_{ap}(t)-V_c(t)=R_a I_a(t)+L\frac{dI_a(t)}{dt} \qquad (1)$$

and

$$I_a(t)=C\frac{dV_c(t)}{dt}-\frac{1}{R_{ice}}V_c(t) \qquad (2)$$

The input data are the insulator geometry, the ice layer characteristics and/or properties, the applied voltage and some initial values. The discharge time base is divided into steps d*t*, starting from $t = 0$. At each time step, the applied voltage $V_{ap}(t)$ is calculated.

The arc channel resistance is obtained from energy balance equations. In order to derive an expression which would connect the electrical conductivity of the channel with the electrical characteristics of the circuit, it may be assumed that the discharge occurs in such a short time that radiation and heat loss by conduction are negligible. Mayr assumed that the heat conduction rate, P_0, is constant and derived a new equation to describe the arc behavior such as [10]:

$$\frac{1}{r_{arc}}\frac{dr_{arc}}{dt}=\frac{1}{\tau}\left(1-\frac{r_{arc}I_{arc}^2}{P_o}\right) \qquad (3)$$

where r_{arc} is the arc resistance per unit and $\tau = W_o/P_o$ is the arc de-ionization factor, which may be considered constant at 100 µs for the arcs in air [14]. The value of P_o may be considered as the arc constant [10, 14] which in this case is 204.7 [9]. This equation is used in order to simulate the arc dynamics during its propagation. The initial value of the arc resistance is achieved using initial values of arc temperature and arc length.

The arc channel root radius *r* (in cm), can be calculated according to Wilkins empirical model [9, 15, 16]:

$$r(t)=\sqrt{\frac{I_{arc}(t)}{k\pi}} \qquad (4)$$

in which, *k* is a constant that has been determined experimentally [15]. For an alternative voltage on ice surface *k* is equal to 0.875.

In order to determine the inductance of the discharge channel, we use a simplification similar to that proposed by Fofana *et al.* [17] for discharge in air gaps, i.e. the end effects are ignored and the inductance per unit length of the channel L_{arc}, is:

$$L_{arc}=\frac{\mu_o}{2\pi}\left[0.25+\ln\left(\frac{Df}{r}\right)\right] \qquad (5)$$

If *Df* is large enough for transient fields, the fractional error, which is of the order of *1/ln(Df/r),* will be low. For these investigations we will set *Df*=100m, a typical value already proposed in reference [16, 17].

The capacitance C(x, t) is calculated using a spherical approximation [16]. This approximation yields:

$$C(x,t)=\Gamma\varepsilon\, r\left(1+\frac{r}{L_f-x}\right) \qquad (6)$$

where Γ represents the solid angle between arc head and the opposite electrode.

Under the estimated flashover voltage, which should be enough to sustain an arc beyond the first arc length, the arc development begins when the propagation criterion is met. The internal conditions (velocity, radius, electrical parameters and so on) as well as the residual ice layer resistance are calculated.

Since ice is almost considered as a non-conductive material [5], the resistance of this part is mainly due to a thin water layer at the ice surface. Such a water film can be obtained either by the increase in the ambient temperature or by thermal exchange between the stabilized arc burning on ice surface. If an axially symmetrical insulator is covered with a thin uniform conductive film of a constant thickness, *h*, and constant specific conductivity, σ_v, then the surface conductivity at any point of the film is defined by:

$$\gamma_e=\sigma_v h \qquad (7)$$

where γ_e is obtained in 1/Ω. In order to take into account the effect of current concentration at the arc root, Wilkins' investigations for narrow strip ($w < L$) lead to following equation [18]:

$$R_{ice}=\frac{1}{2\pi\gamma_e}\sum_{j=-\infty}^{j=+\infty}\frac{1}{2}\log\left[\frac{\left(1+\cosh\frac{\pi(jw+r)}{2L}\right)^2+\tan^2\frac{\pi x}{2L}\sinh^2\frac{\pi(jw+r)}{2L}}{\left(1-\sinh\frac{\pi(jw+r)}{2L}\right)^2+\tan^2\frac{\pi x}{2L}\sinh^2\frac{\pi(jw+r)}{2L}}\right] \qquad (8)$$

where *w*, (*L-x*), and γ_e are the width, arcing distance and conductivity of the conductive layer, respectively, and *r* is the arc root radius.

In some previous investigations [15], the freezing water conductivity has been empirically determined as a function of the conductivity (σ_w) at 20 °C of water used to form the ice, as:

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

where the parameters α and β, function of the applied voltage type, such as: α = 1.08 10^{-6} cm and β = 0.51μS. The value of the surface conductivity may be considered constant from a few cycles before propagation stage to the moment of flashover.

If the initial arc temperature is taken as a relatively high value of 4550 °K maximum [9] (σ = 0.0006 1/Ω.cm [10]), it will ensure attaining a minimum value for critical flashover voltage, since it results in a minimum initial arc per unit resistance [9]. The initial arc length is assumed to be equal to 45% of total insulator length, *L*, since it results in a minimum value for critical flashover voltage [9]. The initial value of the voltage applied may be determined using the Claverie model which was proposed in order to calculate the minimum peak voltage, V_0, able to re-ignite an arc which carries the peak current, I_0, along the initial arc length, x_0 [9]. Using the constants proposed for ice-covered insulators, the relationship reads as follows [15]:

$$V_o = \frac{1118 x_o}{I_0^{0.5277}} \qquad (10)$$

Although many mechanisms have been suggested over the years to account for arc motion mostly over contaminated surfaces, very little information is available on arc velocity. A review of some proposed models can be found in [19, 20]. Various simulations have, however, shown that formulation proposed by Les Renardières group [21] gives good agreement with experimental data. These authors postulate that the propagation velocity is proportional to the discharge current:

$$v(t) = \frac{I_{arc}(t)}{q_L} \qquad (11)$$

where q_L can practically be considered constant.

$$q_L = \frac{1}{x}\int_0^t I_{arc}(t) \qquad (12)$$

At each time step *dt*, the critical conditions for continued propagation of the discharge are tested and, if they are satisfied, the discharge continues to progress up to the final jump stage. To achieve the minimum critical flashover voltage, we use the condition proposed by Hesketh [22]:

$$dP_{arc}/dx > 0 \qquad (13)$$

where P_{arc} is the power supplied to the arc by the power source. At the time when *x*, arc length, will be equal to the insulator length L_f, then flashover will take place. Under AC voltage this moment happens at the peak value of last quarter negative cycle [9] and so the velocity is adjusted to achieve a total flashover at this time. Before this moment, when the surface conductivity is less than its critical value, the length of arc is being considered constant and the change in the current is due to the change of the surface water conductivity, as well as arc resistance. Then under calculated value of flashover voltage, the simulation will be repeated to calculate the parameters in the last stage. At each time step *dt*, arc resistance and length should be initialized. In the case the criterion is not met, the arc extinguishes and flashover cannot take place. At this time a new step is considered by increasing the applied voltage. The simulation is restarted again with initialization of the input data.

VI. Results and Discussions

Fig. 6 represents an illustration of the model performance in predicting a typical current cycle as it occurs a few cycles before flashover on a glass tubing cylinder insulator covered with ice.

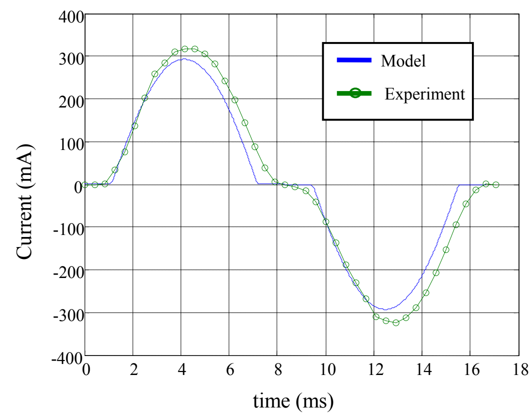

Fig. 6: Comparison of the simulation and experimental leakage current (L = 40 cm , σ_w = 30 μS/cm , V_{eff} = 48 kV).

The simulated current is also compared to the one obtained from experiments. The non-linearity of arc resistance and inductance causes a deformation in the arc current wave when the current passes through zero. The phase difference between simulated and experimental results involves the necessity for correcting the inductance relationship. In fact, using Eq. (5) produces very small values for arc inductance so that this factor becomes negligible compared to the resistance of the arc. This phase difference confirms that the real inductance of the arc should be higher than the one obtained using Eq. (5), at least with regard to insulator lengths of less than 1 m. The disparity between the results of the simulated and experimental current, when the arc current approaches zero, may be due to the use of the arc root radius equation. This equation was derived from peak values of the current [15] and may possibly not be applicable to all instants of a cycle.

Figs 7 and 8 compare the critical flashover voltage values, V_c, obtained by the model, with those emerging from the experiments. The error bars indicate the percentage of error between the experimental points and the corresponding model results. These figures show that these results are in satisfactory concordance, although the percentage of error tends to increase for smaller lengths and lower conductivities or greater length and higher conductivities. The error in the calculation obviously is the result of assuming a constant value for P_0 (eq. 3), since this parameter showed a considerable variation as a reason of variation in insulator lengths, and in applied water conductivities [9]: this appears to be related to the non-linear plasma processes that drive the channel conductivity [10].

A part of the variation in calculation of P_0 may be due to the use of Eq. (9) for calculating surface conductivity, since the equation was based on the experimental results from a relatively short test object [15]. This relation (Eq. 9) was obtained by assuming equality between the surface resistance measured and its analytical relation, displaying a relatively high degree of error, up to 50% [15]. This deviation confirms that the surface conductivity at the moment of flashover is not only a function of applied water conductivity but also of further parameters.

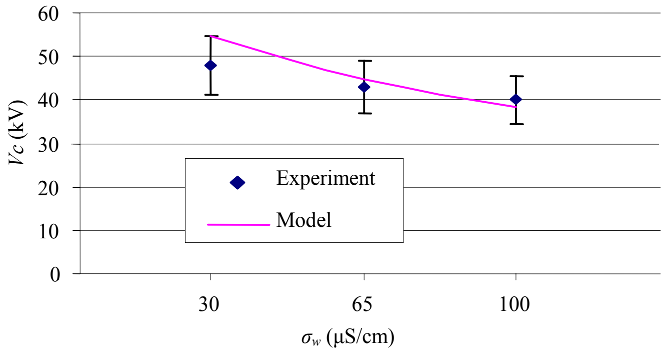

Fig. 7: Flashover results for a 40 cm iced cylinder and different applied water conductivities with 13.6% accuracy.

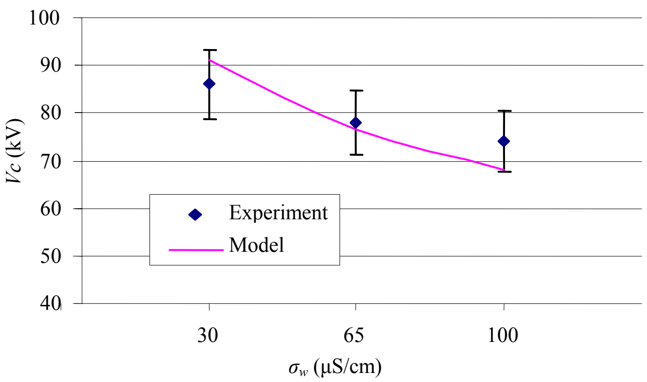

Fig. 8: Flashover results for an 80 cm iced cylinder and different applied water conductivities with 8.9% accuracy.

During the experiments carried out in the context of this study, it was observed that, at the moment of flashover, the conductivity of dripping water changes as a result of changes in insulator length. On the other hand, this relationship is based on a concept that water film thickness is constant. If the length of the insulator is increased, this concept may no longer be applicable. Thus, for more accurate calculation this relationship (Eq. 9) needs to be investigated in much greater detail.

VII. Conclusion

In this paper, we investigated the feasibility of using dynamic arc modeling of iced insulators to predict AC flashover. The mathematical presented model is based on a simplified simulation of the successive phases of flashover development process on iced insulators. The flashover voltages calculated from the model have been compared to those obtained on a glass tubing cylinder insulators. A number of experiments were carried out in order to obtain minimum flashover voltage as well as current and voltage variation on different ice-covered glass tubing insulators. Two lengths and three applied water conductivities were tested resulting in 12 series of tests. There is a good agreement between the minimum withstand flashover voltage and leakage current of ice-covered glass tubing insulators obtained in the laboratory and values predicted by the mathematical model. Works are still in progress to improve the model, and the authors expect to publish their results in a future work.

VIII. Acknowledgements

This research was carried out within the framework of the NSERC/Hydro-Quebec Industrial Chair on Atmospheric Icing of Power Network Equipment (CIGELE) and the Canada Research Chair on Atmospheric Icing Engineering of Power Network (INGIVRE) at the Université du Québec à Chicoutimi. The authors would like to thank all the sponsors of the project for their financial support.

IX. References

[1] M. Farzaneh, "Ice accretion on high voltage conductors and insulators and related phenomena", *Phil. Trans. of the Royal Soc*. vol. 358, No. 1776, pp. 2971-3005, 2000.

[2] CIGRE Task Force 33.04.09, "Influence of ice and snow on the flashover performance of outdoor insulators, part I: Effects of Ice", *Electra*, No. 187, pp. 91-111, Dec. 1999.

[3] M. Farzaneh and J. Kiernicki "Flashover performance of IEEE standard Insulators under ice conditions", *IEEE Electrical Insulation Magazine*, vol. 11, No 2, pp. 5-17, March/April 1995.

[4] M. Farzaneh and O.T. Melo, "Properties and Effect of Freezing and Winter Fog on Outline Insulators", Journal of Cold Regions Science and Technology, No. 19, February 1990, pp. 33-46.

[5] X. Chen, "Modeling of Electrical Arc on Polluted Ice Surfaces", PhD Dissertation, University of Montreal, February 2000.

[6] M. Farzaneh et al. "Insulator Icing Test Methods and Procedures" A position paper prepared by the IEEE Task Force on Insulator Icing Test Methods, *IEEE Trans. on Power Del.*, 18 (4): 1503-1515 OCT 2003.

[7] C. L. Phan and H. Matsuo, "Minimum flashover voltage of iced-insulators", *IEEE Trans. on Elec. Insul.*, vol. 18, No 6, pp. 605-618, 1983.

[8] International Electrotechnical Commission (IEC), "Artificial Pollution Tests on High-voltage Insulators to be Used on AC Systems," International Standard 507, 1991.

[9] C. Tavakoli, "Dynamic modelling of AC arc development on an ice surface", Ph.D. Thesis, University of Quebec in Chicoutimi, Canada, 2000.

[10] M. F. Hoyaux "Arc Physics" Srpinger-Verlag New York inc, 1968.

[11] F. Obenaus, "Fremdschichtüberschlag und Kriechweglänge", *Deutsche Elektrotechnik*, vol. 4, pp. 135-136, 1958.

[12] Dhahbi-Megriche N., "Modélisation Dynamique des Décharges sur les Surfaces d'Isolateurs Pollués sous Différentes Formes de Tension: Elaboration d'un Critère Analytique de Propagation," *Ph.D. Dissertation, Ecole Central de Lyon*, France, 1998.

[13] Chaurasia D. C., "Scintillation Modelling for Insulator Strings Under Polluted Conditions," *High Voltage Eng. Sym., IEE Conf. Pub*., No. 467, August 1999.

[14] Rizk A. M. & Nguyen D. H., "Digital Simulation of Source-Insulator Interaction in HVDC Pollution Tests," *IEEE Trans. on Pow. Del.*, Vol. 3, No. 1, 1988.

[15] J. Zhang, M. Farzaneh: "Propagation of AC and DC Arcs on Ice Surfaces", IEEE Trans. on Dielectrics and Electrical Insulation, Vol. 7, No. 2, pp. 269-276, 2000.

[16] M. Farzaneh, I. Fofana, C. Tavakoli and X. Chen, "Dynamic Modeling of DC Arc Discharge on Ice Surfaces", IEEE Trans. on Diel. and Elec. Insul., Vol. 10, No. 3, pp. 463-474, 2003.

[17] I. Fofana, A. Beroual, "A predictive model of the positive discharge in long air gaps under pure and oscillating impulse shapes". *J. Phys. D: Appl. Phys*., Vol. 30, pp 1653-67, 1997.

[18] R. Wilkins, "Flashover voltage of HV insulators with uniform surface pollution films, Proc. IEE, Vol. 116, No. 3, pp. 457-65, 1969.

[19] I. Fofana, M. Farzaneh and C. Tavakoli, "*Modeling Arc Propagation Velocity on Ice-covered Surfaces*", The 10th International Workshop on Atmospheric Icing of Structures, Brno, Czech Republic, June 17-20th 2002.

[20] F. A. M. Rizk, "Mathematical models for pollution flashover". *Electra*, Vol. 78, pp. 71-103, 1981.

[21] Les Renardières Group, "Positive discharges in long air gaps at les Renardières". *Electra*, No 53, pp. 31-153, 1977.
[22] S. Hesketh "General criterion for the prediction of pollution flashover", *Proc. IEE*, Vol. 114, No. 4, pp. 1886-92, 1967.