Dynamic Modelling of Flashover Process
on Ice-covered Insulator Surface

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ABSTRACT

The aim of this contribution is to present a self-consistent dynamic model allowing the prediction of the process of the DC arc development on ice-covered insulators. The arc channel is assumed to be cylindrical and represented by a time-dependent impedance.

Model inputs are insulator geometry, ice layer and applied voltage characteristics. Particularly, several factors influencing flashover on ice surfaces, such as freezing water conductivity, voltage type and arcing distance are taken into account. This model makes it possible to determine the temporal evolution of leakage current, arc channel radius, potential gradient in arc channel and propagation velocity. The results, and in particular the current and the instantaneous propagation velocity of arc, are found to be in good agreement with the experimental results obtained using a simplify ied physical model.

Key words: atmospheric icing, flashover, outdoor insulation.

INTRODUCTION

Atmospheric icing of power transmission systems is a serious problem in many cold regions of the world. Ice and/or snow accretion and shedding can lead, under windy conditions, to mechanical stresses whose resulting consequences are well known by transmission lines designers. Ice and snow accretion on an insulator, also decreases the electrical performances (Farzaneh & Kiernicki 1997, CIGRE 1999). The rate of this decrease depends on several major parameters related not only to ice and snow but also to the environmental conditions and insulator characteristics. As a consequence of ice and snow accretion, the local arc sometimes leads to a complete flashover of insulator and power outages occurs. Insulator flashover incidents caused by cold precipitation on the network have been reported by Ontario Hydro in Canada (CIGRE 1999). The most remarkable events occurred on March 9-10, 1986. Major incidents also took place on April 1988, March 1991, January 1995 on the Hydro Quebec networks in Canada (Farzaneh 2000). A series of flashovers resulted in major interruption of electricity to a large part of Quebec. The incidents caused by flashover on ice-covered insulators have also been reported by different authors from various countries; for example in the west coast areas of Canada and the United States (CIGRE 1999), in Norway (CIGRE 1999, Fikke *et al.* 1993), and in Japan (CIGRE 1999, Matsuda *et al.* 1991).

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Until now most of the published research has been concentrated on determining the withstand voltage of insulators under icing conditions (CIGRE 1999, Farzaneh & Zhang 2000, Zhang & Farzaneh 2000). The need for a mathematical dynamic model able to predict and describe thewhole flashover process, from inception to flashover, even in atmospheric pollution cases, has been long known and still remains a challenge to the study of outdoor insulation. Such a model will be helpful for understanding the whole flashover phenomenon and aid in the design of suitable equipment.

The present research aims primarily at understanding the physics of the discharge development and at presenting a dynamic mathematical model able to describe the entire discharge activities on ice-covered insulator surface. This model, which takes into account the instantaneous changes of the arc parameters, allows prediction of the critical flashover voltage and the time-dependent characteristics of the arc channel such as current and velocity. Good agreement is found between simulated results and those obtained experimentally using a simplified physical model.

MODEL OF THE DISCHARGE

The presence of ice on the insulators can be a special type of pollution and pollution based methods were usually used to study flashover on ice-covered insulating surfaces (Farzaneh & Zhang 2000, Zhang & Farzaneh 2000). Despite the complexity of the mechanisms involved in the discharge (arc) phenomenon, numerous models describing the flashover processes of a polluted insulator have been proposed (Rizk 1981, Obenaus 1958). Most models are limited to the static state and cannot be considered complete models capable of predicting the temporal evolution of the flashover process.

The complexity of arcing phenomena necessitates that many simplifying assumptions have to be made in order to make mathematical modelling feasible. A common feature of these models is a simplified representation of a propagating arc consisting of a partial arc in series with the resistance of the non-bridged section of the polluted layer.
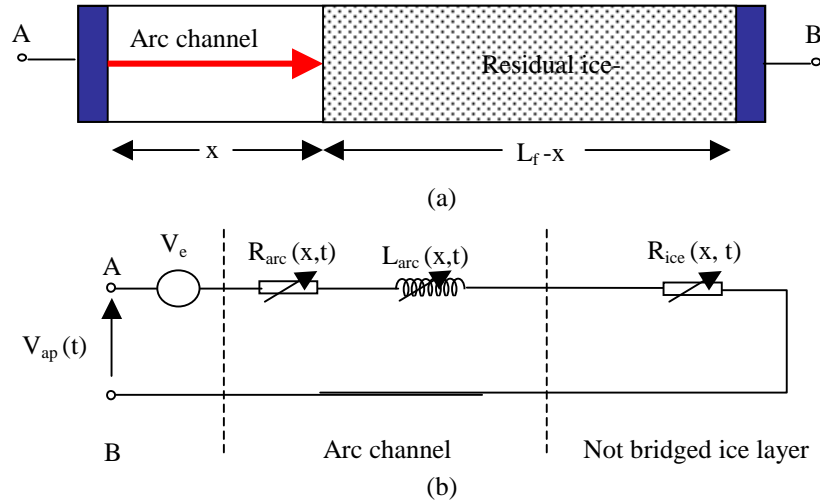
V_e: the voltage drop at the electrodes.
R_{arc} (x, t) : arc channel resistance
L_{arc}(x, t) : arc channel inductance.
R_{ice} (x, t): the (residual) not bridged ice-layer resistance.
V_{ap}(t) : applied voltage.

Figure 1.   Principle of the mathematical model used to described the arc propagation on the ice-covered surface.
(a) : Simplified representation of an arc propagating on a ice-covered surface.
(b) : Equivalent electrical network used to represent the whole phenomena.

One of the first quantitative analyses of arcs on contaminated surfaces was made by Obenaus 1958. This approach models the flashover process as a discharge in series with a resistance representing the non-bridged portion of the insulator. Several other improvements of Obenaus' approach have been reported (Rizk 1981, Sundararajan & Gorur 1993).

Altogether, the most useful proposed models, describing the growth of the discharge are those that base their calculations on a simple electrical equivalent circuit (Rizk 1981, Sundararajan & Gorur 1993, Fofana & Béroual 1997).

The development of the ice covered insulator flashover model which can take into account the real experimental conditions is somewhat difficult due to the complexity of the involved phenomena. Such complexity is the result of non-uniformity of the ice deposits, the surrounding air temperature, freezing water conductivity, type of ice formed, the icing process, and then of multiple arcs (Farzaneh & Kiernicki 1997, CIGRE 1999, Farzaneh & Zhang 2000, Zhang & Farzaneh 2000). In order to develop such a model, some assumptions have to be made such as single dominant arc propagating along the insulator surface and a uniform ice distribution along the insulator. Subsequently, the arc is assumed to move only on a uniform surface. Moreover, the arc is assumed to be a cylindrical channel of radius r, and length x, represented by a RL circuit in series. Furthermore, we assumed that the arc propagation on the ice covered insulator surface can be modeled by an equivalent electrical network as shown in Figure 1, where V_{ap} is the applied voltage, R_{arc} and L_{arc} are respectively the resistance and inductance of the arc channel while R_{ice} is the equivalent resistance of the non-shortened portion of the ice surface. The resistive aspect of the ice layer has been verified by many investigators (Farzaneh & Zhang 2000, Zhang & Farzaneh 2000, Chen 2000).
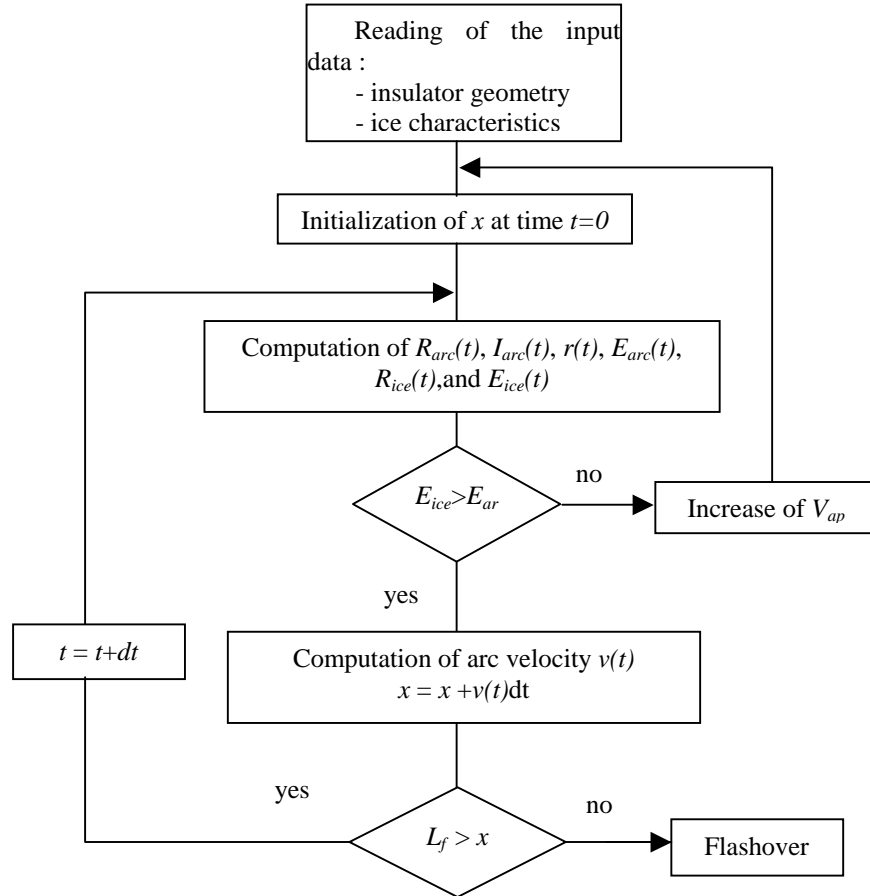

Figure 2. General flowchart of the modelling.

On the other hand, the discharge has been assumed to have an initial length of x_o. Such a length represents the air gap formed near one of the electrodes on the actual ice-covered insulators during the icing period (Farzaneh & Kiernicki 1997). This initial discharge is assumed to have a resistance R_o in series with an inductance L_o; while R_{iceo} is the resistance of the non-shortened ice band.

In this contribution, we were not interested in determining the flashover voltage but in the discharge characteristics evolution. Under the estimated flashover voltage, the arc development begins when the propagation criterion is met. The internal conditions and velocity of the arc channel as well as the residual ice layer resistance are calculated. The voltage and the current will be governed by the following equation:

$$V_{ap} - V_e = (R_{ice} + R_{arc})I_{arc} + L_{arc}\frac{dI_{arc}}{dt} \tag{1}$$

where I_{arc} represents the arc current.

At each time step, 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. Otherwise 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. At the time when x will be equal to the insulator length L_f, then flashover will take place. The above described process is simply shown in the flowchart represented in Figure 2.

PARAMETERS OF EQUIVALENT ELECTRICAL CIRCUIT

The arc channel, the so-called positive column, is a volume of ionized gas. Its resistance can be calculated using the Local Thermodynamic Equilibrium (*LTE*) assumption. Considering the channel cylindrical in shape and all crossed sections identical, its resistance per unit length can be calculated as:

$$R = \frac{1}{\sigma \pi r^2} \qquad (\Omega cm^{-1}) \tag{2}$$

where σ is the arc channel conductivity; such a conductivity being due to charge carriers within the channel. Because of their low mobility, the term relevant to heavy particles will be neglected, arc conductivity can therefore be obtained in the same way as for metallic conductors :

$$\sigma = n_e\, e\, \mu_e \tag{3}$$

where $\mu_e \approx const.n_a^{-1}T^{1/2}$ ($cm^2V^{-1}s^{-1}$) is the electron mobility.

The neutral particles density n_a is given by : $n_a = p/KT$, where p is the pressure inside the channel, considered to be equal to the ambient pressure (Les Renardières 1977, Hoyaux 1968) and K, the Boltzmann's constant.
The electronic density n_e can be calculated using Saha's equation (Les Renardières 1977):

$$n_e = 4.93*10^7 n_a^{1/2}T^{3/4}exp(-90500/T) \qquad (cm^{-3}) \tag{4}$$

Under *LTE* considerations, the temperature within the channel can be considered equal to the electronic temperature (Les Renardières 1977, Hoyaux 1968). In fact, an interdependent relationship exists between arc temperature and current, but in a simplified approach, we will consider this temperature constant, a typical value of it being equal to $15000^{o}K$ (Hoyaux 1968).
The arc channel root radius r (in cm), is also calculated at each step time according to Wilkins empirical model (Hampton 1964):

$$r(t)=\sqrt{\frac{I_{arc}(t)}{k\pi}} \qquad (5)$$

in which, k, is a constant which has been experimentally determined by Farzaneh & Zhang (2000). For a positive arc propagating on ice surface, k is equal to 0.648, and k is 0.624 for a negative arc.

In order to determine the inductance of the discharge channel, we use a simplification similar to that proposed by Fofana & Béroual (1997) for discharge in air gaps, i.e. the end effects are ignored and the inductance per unit length of the channel l_{arc}, is the sum of two inductances. The first part of it deduced from the electromagnetic energy stored in the channel (the internal inductance) is given by:

$$l_1=\frac{1}{4}\frac{\mu_0}{2\pi} \qquad (Hm^{-1}) \qquad (6)$$

while the second part of it deduced from the electromagnetic field radiated by the current flowing through the channel is such as:

$$l_2=\frac{\mu_0[ln(D_f/r)]}{2\pi} \qquad (Hm^{-1}) \qquad (7)$$

The channel inductance per unit length is thus:

$$\qquad (Hm^{-1}) \qquad (8)$$

$$L_{arc}=\frac{\mu_0}{2\pi}[0.25+ln(D_f/r)]$$

where Df represents the distance far from the discharge axis at which the magnetic field is considered to be zero.
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 by Fofana & Béroual (1997).

The resistance of the ice layer R_{ice}, is calculated taking into account the insulator geometry and the constriction of current at the arc root. For a narrow ice band, this resistance is given by (Farzaneh & Zhang 2000, Chen 2000):

$$R_{ice}=\frac{1}{2\pi\gamma_e}\left[\frac{\pi(L_f-x)}{a}+ln\frac{a}{2\pi r}\right] \qquad (9)$$

and in the case of large ice band, it can be obtained by the following equation (Chen 2000):

$$R_{ice}=\frac{1}{2\pi\gamma_e}\left[ln\frac{2L_f}{\pi r}-ln\left(tan\frac{\pi x}{2L_f}\right)\right] \qquad (10)$$

where γ_e is the freezing water conductivity and a the ice layer width, which in a cylindrical configuration is given by:

$$a=\pi\left(\frac{1}{2}D+e_{ice}\right) \qquad (11)$$

D being the insulator diameter and e_{ice} the ice thickness. In some previous investigations (Farzaneh & Zhang 2000, Chen 2000), the freezing water conductivity has been empirically determined as a function of the conductivity at 20 °C of water (σ_w) used to form the ice, as:

$$\gamma_e(\mu s) = \alpha \sigma_w(\mu s/cm) + \beta \tag{12}$$

where the parameters α and β, function of the voltage type, such as : $\alpha = 0.082$ cm and $\beta = 1.79$ μS for DC+ and $\alpha = 0.0599$ cm and $\beta = 2.59$ μS for DC- (Farzaneh & Zhang 2000).

PROPAGATION CRITERION AND VELOCITY

According to Hampton's investigations (1964), in the case of a cylindrical configuration having a constant resistivity, an arc will propagate if the voltage gradient along the cylinder (water column in Hampton tests) E_{ice}, is higher than the voltage gradient in the arc column E_{arc} :

$$E_{arc} \ < \ E_{ice} \tag{13}$$

For calculating the arc gradient we use the Obenaus concept (1958):

$$E_{arc} = AI^n \qquad (V/cm) \tag{14}$$

where arc constants are $A = 208.9$, $n = 0.449$ for DC+ and $A = 84.6$, $n = 0.772$ for DC- (Farzaneh & Zhang 2000). E_{ice}, as a constant resistance field, can be deduced simply by:

$$E_{ice} = \frac{R_{ice} I_{arc}}{L_f - x} \qquad (V/cm) \tag{15}$$

A review of some arc propagation velocity models proposed for pollution flashover can be found in (Rizk 1981). A simulation of these various models proposed, based either on mobility or field gradient, *etc* (Rizk 1981, Sundararajan & Gorur 1993), shows that the model proposed by Les Renardières group (1977), gives results in a good agreement with experimental data. These authors considered that the propagation velocity is proportional to the discharge current :

$$v(t) = \frac{I_{arc}}{q_{arc}} \tag{16}$$

where q_{arc} is constant and represents the arc charge per unit length. The value of it, which affects the velocity of arc, will be chosen to have the same flashover time as the experimental data.

VALIDATION AND DISCUSSION

Considering the lack of valuable temporal evaluation of discharge characteristics over an iced surface, the model is validated by comparing the results with the experimental data, obtained by Chen (2000) on a simplified physical model depicted in Figure 3.

In a climate room, wet-grown ice was formed from super-cooled droplets sprayed onto the surface of a plexiglass cylinder. In order to accumulate a uniform ice thickness, the cylindrical glass tube was installed vertically and rotated at one rpm. The expected conductivity of freezing water was obtained by adding sodium chloride to de-ionised water. Once the ice thickness reached 17 mm, accretion was stopped, the icicle cylinder was removed and 1 cm air gap was made by cutting and removing a small part of the ice at the top of the sample. This air gap simulates air gap formed by partial discharge on actual ice-covered insulator strings during the icing period and will represent the initial arc length. The DC voltage used in that work (Chen 2000) was provided by a constant voltage/current supply with a maximum operating voltage of 50 kV and a maximum operating current of 10 mA.

Figures 4 to 7 depict the comparison of computed values of the instantaneous arc propagation velocity and current to those measured experimentally for both voltage types DC+ and DC-. It can be observed that the present model gives values that agree satisfactorily with the experimental ones.
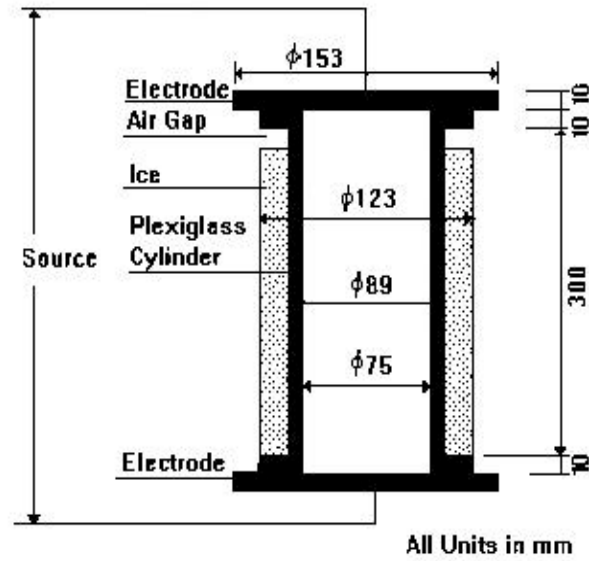
Figure 3.   Ice sample and flashover test set-up.

This concerns not only the shape but also the amplitude of each parameter. The slight parameters difference between measurements and simulations, particularly for currents, could be due to some probabilistic parameters, such as arc propagation trajectory, the complexity of flashover mechanism, icing process, as well as to the simplifications used to calculate the arc channel parameters. Moreover, flashover generally occurs due to a number of separate series arcs spanning the ice-covered insulator surface. It is clear that further work is needed to investigate how the multiple discharges can be taken into account in our model.
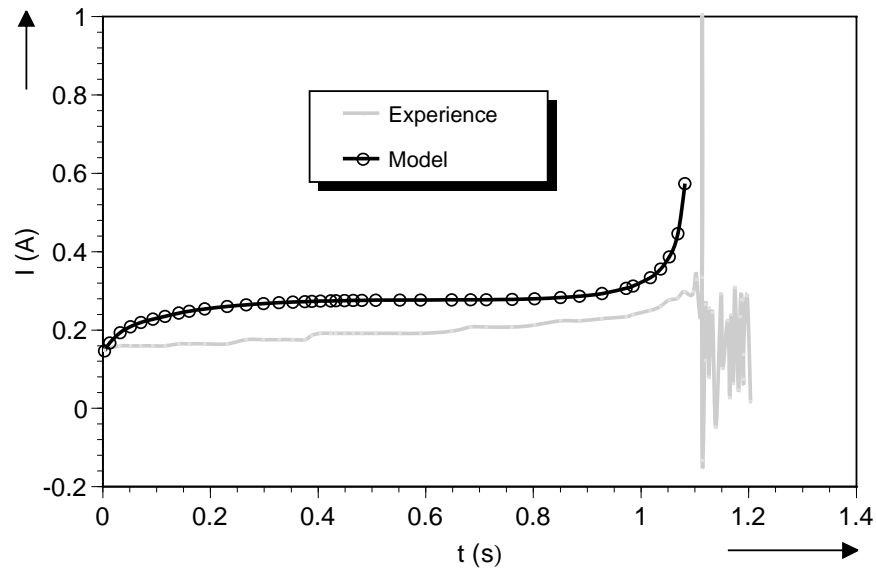

Figure 4.   Comparison of the measured and computed leakage current for positive arc, σ = 80 μS/cm and V=36 kV.
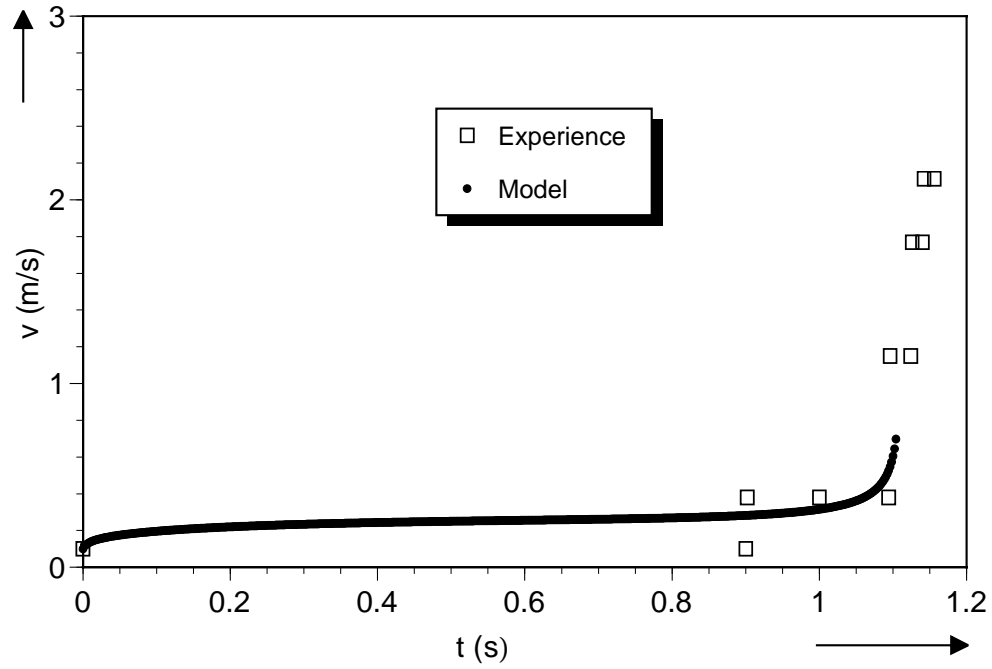
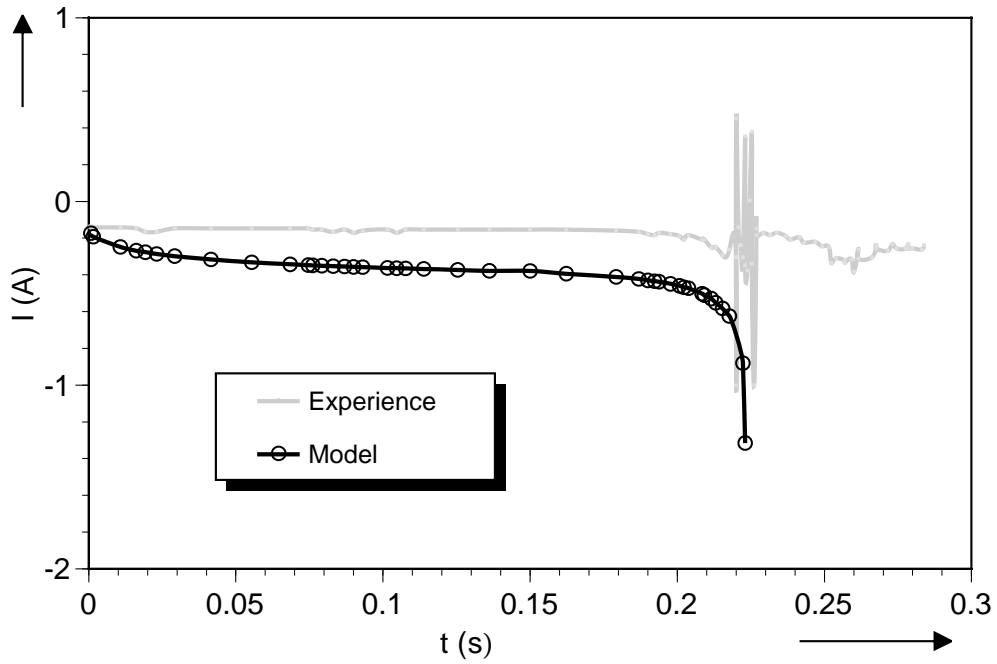Figure 5.   Comparison of the measured and computed positive arc velocity for σ = 80 μS/cm and V=36 kV.

Figure 6.   Comparison of the measured and computed leakage current for negative arc, σ = 80 μS/cm and V=-36 kV.

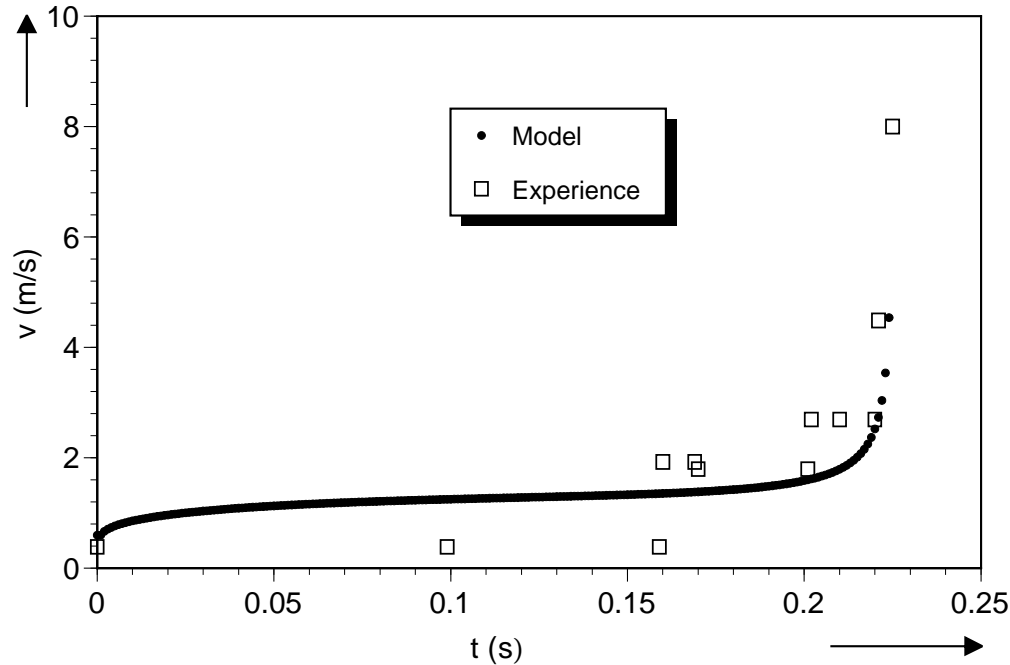Figure 7.   Comparison of the measured and computed negative arc velocity for $\sigma = 80$ μS/cm and V= -36 kV.

CONCLUSION

The efficiency of applying one classical equation for the determination of critical flashover voltage of ice-covered insulators by the selection of appropriate arc constants *A* and *n,* has been used to determine the evolution of arc characteristics under DC voltage. The proposed dynamic model thus takes into account the effect of change in the insulator geometry, ice type, water freezing conductivity and voltage polarity, to predict as accurately as possible arc characteristics such as current, root diameter, velocity and voltage gradient versus time to flashover. The model is verified against experimental data and is found to be good in predicting the above-mentioned values. Moreover, research is still in progress with the aim of applying the developed model to actual outdoor insulators under ice and snow conditions with/without pollution, such a step constituting yet another challenge.

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