IWAIS XI, Yokohama (Japan); October 2007

Processes of Ice Surface Discharge under Lightning Impulse Voltage

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***Abstract*— This paper summarizes some results of research recently undertaken at CIGELE on the development of an ice surface discharge. Several major parameters that may strongly influence the streamer characteristics have been considered, including gap configuration, freezing water conductivity and surrounding temperature. Investigations were carried out using a high-speed framing camera and a photomultiplier to detect the light emitted by the streamer. The experiments were performed using a rod-plane gap configuration and the applied voltage was a standardized lightning impulse. Various parameters such as the corona inception field, discharge mean velocity and the charge deposited into the gap, as a function of form factor, applied field, freezing water conductivity and temperature were studied. The results were discussed and compared to those obtained from an ice-free rod-plane configuration.**

I. Introduction

On the power networks a discharge may end up as a failure in the insulation system. The insulators are the most vulnerable elements of such an event since they are very sensitive to the environmental factors. Even if they are designed to operate under the most stringent climatic conditions, their performance may be drastically reduced by ice accumulation on their surface [1]. Indeed, under these conditions, corona discharge and partial arcs are initiated at a voltage lower than in absence of ice and can develop to complete flashover in a shorter period. The relative vulnerability of insulators under icing conditions underscores the need of furthering our basic knowledge of ice surface discharge, leading to a better understanding of the physical mechanisms by which ice-covered insulator flashover is initiated. Up to now, many investigations have been carried out with the aim of establishing a reliable and complete analytical model of the phenomenon [2-5]. They have shown so far, the complexity and the stochastic characteristics of mechanisms involved in ice surface discharge inception and propagation. This complexity arises from the existence of a quasi-liquid layer on the surface of the ice and from the impurities that may be present in the freezing water which is solidified to form the ice bulk. These factors have been already identified as the main ones that strongly influence the discharge inception and propagation characteristics [1-5].

This paper summarizes some results of investigations on the first nanoseconds of corona streamers development along an ice surface. Investigations were carried out using a highly sensitive, high-resolution, high-speed framing camera and a photomultiplier to detect the light emitted by the streamer in order to determine the discharge parameters. The voltage and leakage current associated with the streamer discharge were simultaneously measured by a voltage divider and a Rogowski coil respectively. The experiments were performed using a rod-plane gap configuration and a standard 1.2/50 µs positive lightning impulse voltage was applied. Various parameters, such as discharge inception field, streamer mean propagation velocity and charge deposited by the first corona, as a function of electrode gap geometry, freezing water conductivity and surrounding temperature were obtained. The results are discussed and compared to those obtained from an ice-free rod-plane referred as to air gap.

II. Experimental Investigations

Since the shape of outdoor insulators is very complex, a simplified physical model of rod-plane configuration as illustrated in Fig. 1 has been used in this investigation.

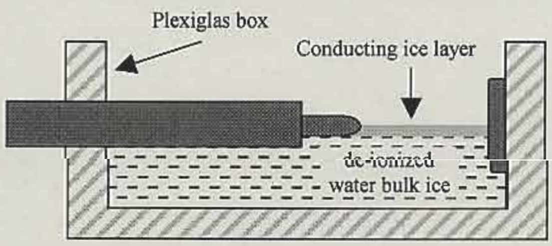


Fig. 1: Vertical section of the physical ice model.

Corona discharges were investigated with different electrode gap distances of 35, 50 and 70 mm and rod radii of 1.5, 3 and 6 mm. Varying radius and gap distance allowed us to investigate the effect of the form factor of the electrode system and the dependence of the streamer propagation velocity upon the applied geometric field. The ice mass was built in several steps in order to half submerge the electrodes and obtain the flattest possible surface, as shown in Fig. 1. Detailed information about the formation of the ice surface can be found in our previous works [2-5].

All experiments were performed by placing the physical model inside a climate chamber kept at the investigated temperatures which are -12, -6 and -2°C. Three different values of freezing water conductivity were considered in this investigation, each one associated with a distinct ice surface. Several theoretical investigations as well as experimental ones already showed the dependency of the dielectric properties of ice upon the temperature and the frequency of applied voltage [6,7]. Since in our investigations the applied voltage is a lightning impulse wave, its frequency can be considered in the high frequency range. It is widely accepted that the real part of the complex permittivity of ice has a constant value of about 3.2 at high frequency [6,7]. This so-called high-frequency permittivity is generally assumed to be independent of temperature and of impurities in the freezing aqueous solution [6-8]. Recent studies have also shown that bulk ice doped with a small amount of chemical impurities, such as salts, has a high frequency and a dielectric loss factor comparable to that of pure ice, which is approximately 0.1 [8]. Moreover, investigations have revealed that for higher concentrations of impurities (though still only a few p.p.m.) the DC and the high frequency conductivities are similar in magnitude [6] and are almost independent of temperature for values around and above -10°C [7,8]. The static conductivity of the ice surface, which can reach values as high as ten times those of freezing water conductivity [9], was also evaluated. For numerical simulation purposes, a surface conductivity 8 times higher than that of the freezing conductivity was considered.

A Hamamatsu R928 photomultiplier, used to detect the light emitted by the streamers was directed at grazing incidence to the HV electrode. Since the PMT detects instantaneously the emissions of light associated with corona streamers, various parameters of the streamer inception including time to first corona (half-widths of the PMT signal), inception voltage and the corresponding electric field at the rod electrode were obtained from its output signal. The time to first corona (t_{inc}) is the time at which a first visible discharge signals is detected by the PMT. It is therefore possible to deduce the inception voltage, U_{inc}, from the voltage wave. The inception electric field, E_{inc}, is obtained by using numerical field calculations computed by Coulomb 3D, an integrated engineering software. In assessing the dielectric performance of different electrode configurations, parameters such as form factor and maximum field strength are generally used. The form factor, F, of a non-uniform field electrode configuration is defined as:

$$F = \frac{E_{mean}}{E_{\max}} \qquad (1)$$

where E_{mean} is the average field strength of the arrangement, that is the applied voltage over the electrode spacing, usually referred to as gap length, and where E_{max} is the highest field strength between the electrodes. The calculated results of the maximum electric field E_{max}, using Coulomb 3D, and the form factors of the different gap geometries are listed in Table 1 to 3. Obtained values for air are given in brackets.

Table 1. Maximum field and form factors for 70-mm gap distance.

Radius, r (mm)	*1.5*	*3*	*6*
E_{max} (V/cm) p.u.	2.12 (1.73)	1.49 (1.14)	0.997 (0.786)
F	0.067 (0.082)	0.096 (0.125)	0.143 (0.182)

Table 2. Maximum field and form factors for 50-mm gap distance.

Radius, r (mm)	*1.5*	*3*	*6*
E_{max} (V/cm) p.u.	2.59 (2.02)	1.78 (1.34)	1.23 (0.937)
F	0.077 (0.099)	0.112 (0.149)	0.162 (0.213)

Table 3. Maximum field and form factors for 35-mm gap distance.

Radius, r (mm)	*1.5*	*3*	*6*
E_{max} (V/cm) p.u.	3.13 (2.43)	2.06 (1.64)	1.47 (1.16)
F	0.091 (0.117)	0.138 (0.174)	0.194 (0.246)

An ultra sensitive high-speed framing camera was used to record the streamer propagation in two dimensions. The camera was an Imacon 200, coupled to a CCD camera allowing digital data analysis and image storage on a desktop computer. The camera exposure duration can be set as low as 5 ns. Based on its recordings, streamer propagation characteristics were computed. Those characteristics are described in terms of inception region, lengths, spatial development and propagation velocity. Typical framing camera recordings are given in Fig. 2.

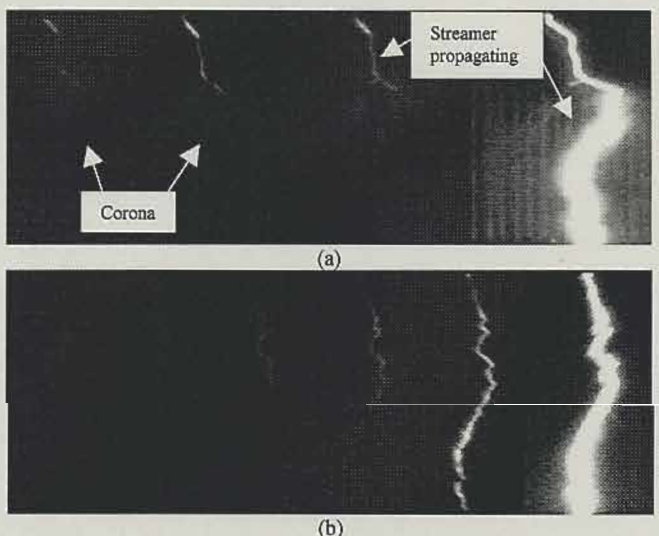


Fig. 2. Typical recordings of corona development. (a): in air with 10-ns inter-framing time. (b): in presence of ice with 5-ns inter-framing time.

III. RESULTS AND DISCUSSIONS

Fig. 3 and Fig. 4 compare the streamer inception fields (E_{inc}) as a function of the form factor while Fig. 5 and Fig. 6 show the results of streamer velocity measurements as a function of the applied electric field for the three ice surfaces. The obtained values for the air reference case are also included. Fig. 3 shows the electric field for inception at temperature -12°C while Fig. 4 summarizes values measured at -2°C. The graphs indicate an important reduction in the inception field in presence of ice, compared to that in air. For a given form factor, F, it can be observed that E_{inc} decreases with an increase in freezing water conductivity.

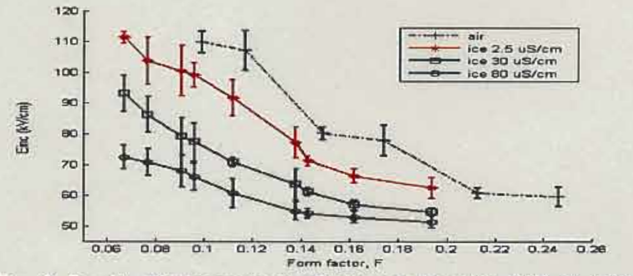


Fig. 3: Results of measurements of streamer inception field at -12°C, in presence or without the presence of ice layer, for various form factor (F).

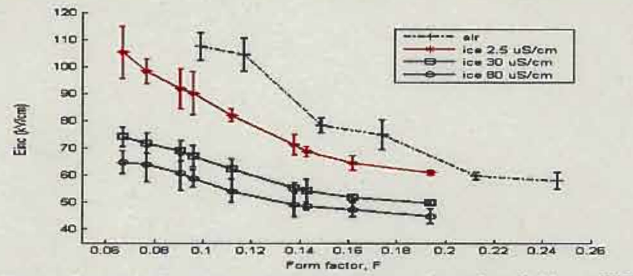


Fig. 4: Results of measurements of streamer inception field at -2°C, in presence or without the presence of ice layer, for various form factor (F).

It can also be observed that the E_{inc} values at -2°C are significantly lower than those at -12°C for a given surface. These results indicate that both the impurities present in the ice and the temperature have specific effects on streamer inception. This point will be emphasized in the discussions.

An important feature essential to the understanding of the interaction between a discharge and a dielectric surface is the velocity of the streamer when it propagates along the surface. This property was investigated by using the framing camera.

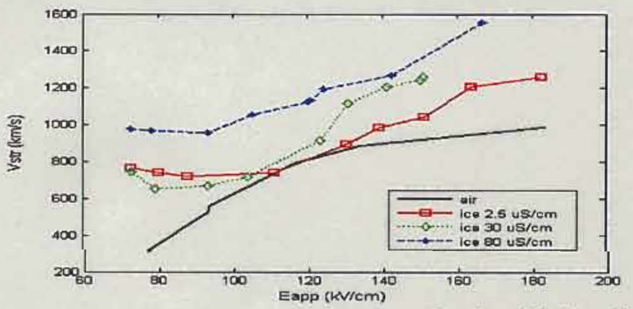


Fig. 5: Mean streamer propagation velocity as a function of field applied at the rod electrode at -12°C.

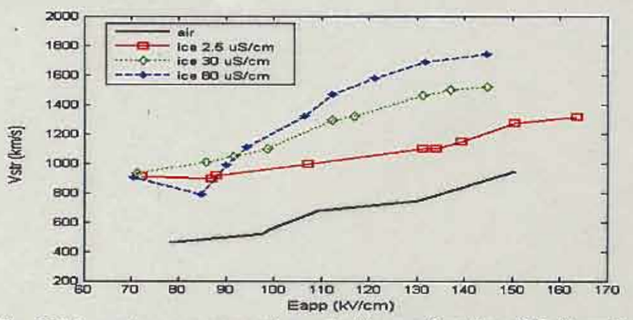


Fig. 6: Mean streamer propagation velocity as a function of field applied at the rod electrode at -2°C.

It can be observed that the streamer velocity augments with an increase in the applied field. Obtained values are more intense in the presence of an ice surface than in air alone. It was also observed that the higher the freezing water conductivity, the greater the streamer velocity is. This indicates that the velocity of streamer is considerably influenced by the freezing water conductivity i.e. the amount of impurities present at the surface of the ice. This observation seems to be quite in agreement with the analysis performed in [10]. Indeed, it was suggested that the velocity of a streamer propagating over an insulator surface is higher than that in air alone.

The results show that the development of a discharge in the presence of an ice surface is largely influenced by the presence of a water film and so far by the impurities incorporated into the freezing water. This would mean that the ice surface temperature and the freezing water conductivity have major effects upon the dynamics of the ice surface discharge. Several other important factors including the applied electric field magnitude, the voltage shape, the gap non-uniformity and the deposited surface charge can also combine their effects to strengthen the influence of the ice surface upon the discharge processes. The specific or combined influences of these factors are analyzed here to investigate more deeply the physical processes involved in the ice surface discharge development.

A. Effects of impurities and temperature

An important observation based on the obtained results is that an increase in the freezing water conductivity i.e. an increase in impurities density leads to a reduction of the streamer field inception and to an enhancement of the streamer propagation velocity. It was also noticed that the deviation between the three surfaces is less pronounced when the temperature increases from -12°C to -2°C. However the difference between streamer propagation velocities in the presence of an ice surface and in the case of air gaps is more pronounced when the temperature increases.

The specific influences of the temperature and the impurities can be combined and analyzed using a single parameter which is the surface conductivity. Indeed, some recent works have shown that the surrounding temperature and the impurities present in the freezing water act directly to increase the ice surface conductivity and to modify its physical structure [11]. Fig. 7 below presents the structure of an ice surface and the influence of temperature upon its atomic disorder.

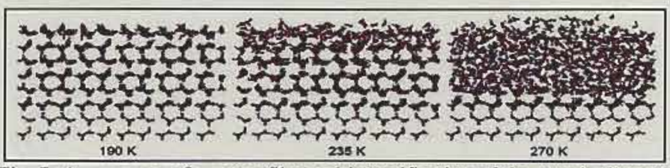
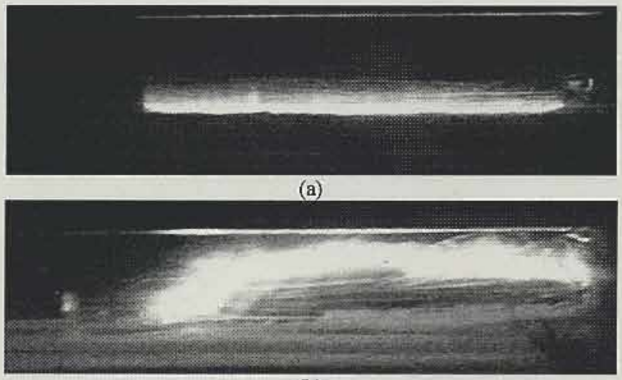


Fig. 7: Appearance of a water film and intensification of the atomic disorder on the ice surface with an increase in temperature [11].

In addition to temperature, water film thickness was also found to be extremely sensitive to the presence of impurities on the ice surface [6,7]. These impurities are generally rejected from the solid part of the ice into the liquid portion of drops or droplets during the solidification/freezing process, or they are deposited by pollution. Therefore, the higher the freezing water conductivity, the higher the density of impurities on the surface is. Since the impurities are non-volatile, an increase in their density will lead to an intensification of the surface atomic structure disorder and a decrease in surface activation energy. This will support a higher ionization rate at the air/ice surface interface, an enhancement of the probability of streamer generation and an increase in the discharge propagation velocity. It was also established that for the lower polluted surfaces (σ_w=2.5 µS/cm) the characteristics of corona streamer inception and propagation are comparable with that in air alone, especially when the temperature is lower (T=-12°C). The high-speed camera recordings showed moreover that for these surfaces the discharge can initiate or propagate partly or entirely in the air while for higher polluted ice surfaces the discharge propagates entirely at the air/ice interface close to the surface.



(a)

(b)

Fig. 8: Typical recordings, in horizontal view, of discharge propagating on ice surface. (a): discharge propagating on ice surface with σ_w=30 µS/cm. (b): discharge propagating in air above ice surface with σ_w=2.5 µS/cm.

It is well known that avalanche growth and streamer propagation is controlled by the ionization rate which is function of the local electric field. Because molecules present on the ice surface are more mobile and electrically more active, increased ice surface conductivity will lead to a much faster streamer development. In air, the photo-ionization mechanisms result only from photons of energy higher than the ionization energy of oxygen (O_2) molecules or nitrogen (N_2) molecules. However, in the presence of ice surface the ionization energy of atoms involved in the discharge processes such as NaCl and derivate atoms is lower than that in air [3]. This suggests that in the presence of an ice surface an increase in freezing water conductivity will lead to an increase in water film thickness and conductivity which, in turn, will support an enhancement of electron extraction from the surface, as well as an intensification of collisional ionizations and of the local electric field by the effect of an apparent permittivity. Another phenomenon which also emphasizes the influence of the water film is its loss factor which is higher than that of bulk ice [12]. Previous works that studied the behavior of ice and water film in rapidly varying high intensity electromagnetic fields showed that the energy absorption of water film can exceed that of ice by two orders of magnitude. In light of these results, it can be established that when ice is exposed to a high frequency field, energy would be absorbed chiefly on the surface and edges of impurities. As a result the water film would grow and the mechanical strength of ice would fall, leading to shattering of the atomic bonds in the ice surface. This will support an increase in the ionization rate and in the streamer propagation velocity when the freezing water conductivity or temperature increases. In addition it was suggested in recent studies that in the presence of ice, the discharge could propagate with a surface and an air component [13]. In air alone, it was already shown that specific temperature effects lead to the variation of air density and critical field (E_c) at the head of the streamer [14,15]. As concerns the surface component, the temperature affect the thickness of the water film on the ice surface [6,7]. In analyzing the streamer propagation when temperature varies from -12°C to -2°C, the ratio of velocities shows that temperature has a more pronounced influence in the presence of ice than in air alone. The table below presents the results for a gap configuration of 1.5 mm HV rod electrode radius and clearance of 35 mm.

Table 4: Velocity ratios as function of the temperature for a gap configuration of 1.5 mm radius and a clearance of 35 mm. Applied field of 140 kV/cm.

	Vstr (km/s); T = -12°C	Vstr (km/s); T=-2°C	$\frac{V_{str}(T=-2°C)}{V_{str}(T=-12°C)}$
Air	750	900	***1.2***
Ice surface **2.5 µS/cm**	1025	1250	***1.22***
Ice surface **80 µS/cm**	1200	1700	***1.42***

It can be observed that in the presence of an ice surface the influence of temperature is intensified. However, for low polluted ice surfaces the intensification is comparable to that in air. These results well show that an increased air temperature generates several phenomena which contribute to the enhancement of streamer velocity along the ice surface.

B. Effects of the form factor (F) and the applied field (E_{app})

When analyzing the streamer inception characteristics for a given form factor, it can be observed that corona streamer is always initiated at fields of lower intensity in the presence of an ice surface compared to that in air alone. Studying the streamer inception characteristics according to the form factor made it possible to better assess the contribution of the ice surface. The results showed that an increase in the form factor leads to reducing the discrepancy between the different ice surfaces and may cause the values of inception field to become comparable with that in air alone. The higher permittivity of ice (ε_{ice}=3.2) compared to that of air (ε_{air}=1) and the distortion of field lines which it generates are the main explanations. Indeed, when an insulator surface is placed along an electrode axis (ice in the present case) the electric field lines are distorted towards the surface and the geometric field is enhanced in the vicinity of the rod electrode. Due to that field enhancement, the inception voltage is strongly reduced and the streamer propagation velocity largely increased compared to that in air. Such mechanisms are moreover supported by the electron emission induced by the enhanced field close to the surface. Therefore the higher the distortion, which means a lower form factor, the higher the tangential field is and then, the higher the contribution of the surface is. A higher form factor suggests a field lines distortion less severe and in this situation the probability of streamer to be initiated in the free air increases and even would become comparable with that on the ice surface. As results, for a higher form factor the deviation between the streamer inception fields, when ice is present in the gap and those in air tends to be reduced.

However, a small difference is still observed and that could be associated to some other physical parameters such as the primary electron density, which is expected to be higher in the presence of an ice surface, and the so-called critical field strength, E_c, i.e. the field at which the ionization quantities equal that of attachment. Numerical calculations have been made in order to estimate the ionization rate at air/ice surface interface and the critical electric field. More detailed information about the computer model can be found in [16]. The input parameters have been upgraded to fit the new experimental results, and the estimation of ionization and attachment quantities has been made using the configuration with the smallest form factor since it is that with the highest probability of the discharge to propagate at air/ice surface interface. Obtained values of critical field for different insulation mediums are listed in Table 5 below.

Table 5: Critical electric field, E_c, in air alone and in the presence of ice as a function of the temperature.

Insulating medium		E_c (kV/cm); T=-12°C	Ec (kV/cm); T=-2°C
Air	Numerical model	39.57	35.5
	Peek's law	39.11	37.74
Ice surface (2.5 µS/cm)		37.74	29.62
Ice surface (30 µS/cm)		35.37	23.29
Ice surface (80 µS/cm)		31.68	19.93

The results show that an increase in temperature has a more severe influence upon the critical field than an increase in freezing water conductivity. The generation of a larger quantity of water film at -2°C compared to that at -12°C may explain this observation. The results would confirm whereas for the smaller form factor, the probability of the discharge to propagate along the ice surface will be higher than that to propagate in air alone.

C. Effects of surface charge

An important phenomenon that could strongly affect the dynamics of an insulator discharge is the charge deposited on the insulator surface prior to the discharge propagation. The surface charge plays a significant role since it can change the pre-breakdown conditions and can cause field distortion midway at the surface to initiate a discharge at a lower applied field. It can also influence the discharge dynamics by its pre-energy on the surface and may enhance the ionization rate in the streamer head to prematurely provoke a breakdown.

Numerous works highlighted that under DC voltage, surface charge may be accumulated by several means [17,18]. Many of them suggested however, that field emission at the electrodes or charge distribution within the bulk insulator due the inhomogeneity of the material are the most significant sources which affect most strongly the charge density. Under impulse voltage however, as is within the scope of the present investigation, these latter mechanisms could not be sufficiently relevant to sustain a surface charge accumulation process. The reason is primarily that for such mechanisms, the time constant can be in the order of hours [18]. This magnitude is obviously largely higher than the time of the wave application under impulse voltage. In addition, some investigations showed that under an impulse voltage the surface charge is essentially produced by corona [19]. Moreover in our investigations, the measured currents were only associated to the streamers and no current activity was detected in absence of corona.

The charges injected from the anode and induced at the cathode are quantified by time-integration of the respective measured currents. The streamer charge remaining in the gap is expected to be deposited on the surface in the case of ice surface discharge. Its value can be evaluated by determining the difference between the time-integrated currents at the anode and the cathode. The results of the net charge deposited (i.e. integration up to the time currents drop to zero) in the gap spacing are summarized in Table 6.

Table 6. Streamer charge injected and remaining into the gap in the presence of ice and in the air reference case.

	Air	Ice surface; σ_w=2.5 µS/cm	Ice surface; σ_w=80 µS/cm
Charge injected at the rod electrode (nC)	4.6	6.1	28.7
Charge induced at the cathode (nC)	1.2	2.5	12.4
Charge deposited in the gap spacing (nC)	*-3.4*	*-3.6*	*-16.3*

From these results, it may be concluded that, the higher the freezing water conductivity, the higher the net charge deposited on the ice surface will be.

As concerns ice, recent works have revealed that its contact with metallic electrodes permits the occurrence of electrolytic processes at the metal/ice interface [20]. This leads to non-ohmic contact which does not allow free conversion between electronic charge carriers in the metal and the positive ions in the ice. Subsequently, space charge accumulation can be observed at the surface of ice building up an excess or deficit of electrons in the metal and H_3O^+ ions close to the cathode or OH^- ions close to the anode. The positive and negative ions involved in this process would arise from the defects and impurities present at the ice surface particularly when the water film thickness is important.

As already mentioned above, when an aqueous solution is frozen, the chemical impurities are not incorporated in the proportion originally present in the solute [6,7]. In the case of sodium chloride solution (NaCl), which was used to build up the ice in these investigations, Cl^- enters the ice leaving Na^+ and OH^- in the liquid phase [21]. This process increases impurities on the ice surface (excess release of H_3O^+ and OH^-) which will enhance space charge relaxation at the surface near the electrodes. It can therefore be expected that higher freezing water conductivities will induce considerable space charge build-up near the electrodes.

Streamer propagation is known to be the result of ionization rate in its front which is in turn, function of the local electric field. Any enhancement of the field at the streamer head will increase the rate of ionization coefficient and so to speak, the streamer velocity. There are specifically two possible sources that might enhance the electric field around its head. The first one is the permittivity of the insulator material and the second one is the presence of accumulated surface charge. The effect of the permittivity and that of the deposited charge can be analyzed by comparing the maximum electric field strengths in the presence of ice and in the ice-free case. The ice surface is assumed to be defined by its permittivity while the streamer velocity is assumed to be controlled by the maximum electric field (E_{max}) around the head of the streamer. For example, considering the configuration with 1.5 mm HV rod radius and 35 mm gap distance, the ratio of those maximums for ice and air in the absence of any charge density in the gap, is:

$$\frac{E_{max}\ (Ice\ ;\varepsilon_r = 3.2)}{E_{max}\ (Air\ ;\varepsilon_r = 1)} = 1.29 \qquad (2)$$

Numerical simulations have been performed with a preset charge on ice surface. Values obtained from experiments in the case of σ_w=80 μS/cm (Table 6) was considered. Considering a surface charge of Q=-16 nC, the following ratio between the maximum electric fields is obtained:

$$\frac{E_{max}(\text{Ice}, q = -16\text{nC})}{E_{max}(\text{Air}, q = 0)} = 2.35 \qquad (3)$$

From this comparison, it can be seen that the magnitude of maximum field in front of the streamer head is more largely enhanced by the presence of surface charge than by the permittivity alone. This indicates that the ionization coefficient and streamer velocity will be obviously increased due to the accumulated negative charge on the surface. However, the development of more advanced approaches allowing the evaluation of experimental results along with their scatter would warrant further investigations.

IV. Conclusions

The obtained results expectedly showed that corona streamer characteristics are considerably affected by the presence of an ice surface. Investigations have revealed that an increase in freezing water conductivity for a given temperature or an increase in temperature for a given conductivity reduces the corona inception field and enhances the streamer propagation velocity. The existence of a water film on the ice surface especially at higher temperatures has a major influence on the development of the streamers. However, for slightly polluted ice, it was observed that the characteristics of the streamers were comparable with those in air. In that case, it was found that the discharge could partially or entirely propagate through free air far from the ice surface. In addition, high-speed camera recordings showed that the corona streamers in the presence of an ice surface had smaller extensions and were less branched compared to those in air alone. By evaluating the charge deposited on the ice surface prior to streamer propagation, it was established that it contributes more to enhancing the streamer propagation velocity than ice permittivity. The analysis of the physical mechanisms involved in ice surface discharge development made it possible to show that the electron emission due to surface bombardment and intensity of tangential field in the head of the streamer is more effective than photo-ionization in air. This conclusion largely explains the streamer velocities obtained and the physical aspects of corona in the presence of an ice surface.

V. Acknowledgements

This work was carried out within the framework of the NSERC/Hydro-Quebec/UQAC Industrial Chair on Atmospheric Icing of Power Network Equipment (CIGELE) and the Canada Research Chair on Engineering of Power Network Atmospheric Icing (INGIVRE) at Université du Québec à Chicoutimi. The authors would like to thank the CIGELE partners (Hydro-Québec, Hydro One, Électricité de France, Alcan Cable, K-Line Insulators, CQRDA and FUQAC) whose financial support made this research possible. The authors would also like to thank Dr S. Brettschneider and Dr C. Volat for useful discussions.

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