Study of Ice Surface Breakdown using Ultra-High Speed Photography

(Student Paper Contest Winner Presentation)

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ABSTRACT

During the recent past, disruptive discharges on ice-covered insulators have led to a number of power failures in electric energy distribution networks. Ice accretion on high voltage insulators decreases their insulation capacity. Under certain meteorological conditions, electrical discharges may be initiated on the surface of the ice leading to electrical breakdown, which means the creation of a conductive path in form of an electrical arc. To further the understanding of ice surface breakdown, a high-speed streak camera was used to record the discharge development in this laboratory study. A physical model with two metallic hemispherical capped electrodes, half submerged in ice, was used for the experiments. The effects of air temperature, freezing water conductivity, and voltage polarity on the 50 % lightning impulse breakdown voltage were investigated. The research showed that the decrease of the critical breakdown voltage due to atmospheric influences is interconnected to a faster discharge development.

Key words: Ice surface breakdown, 50 % lightning impulse breakdown voltage, ultra-high speed photography, streak camera

INTRODUCTION

Interruption of electric energy distribution caused by ice accretion on power network equipment has been reported in several countries (Chisholm et al. 1993; Farzaneh, Drapeau 1995; Fikke et al 1993; Kannus et al. 1998; Matsuda et al. 1991). One of the impacts of ice accretion on power lines is the reduction of electric insulation capacity of high voltage insulators. Short circuits in the form of electric arcs may occur on theses devices even under service voltage for certain meteorological conditions, leading to power failures (Farzaneh, Kiernicki 1997). Despite a relatively large number of worthy research projects by different researchers over the past years, which have been reviewed recently (Farzaneh 1999; Farzaneh, Kiernicki 1995), there still exists a lack of comprehensive studies on this subject. Particularly, the early stages of electric discharge activities on the ice surface, ice surface breakdown characteristics, and charge deposition on the surface of the ice remain unexplained. In the recent past, such fundamental studies on electrical insulation performance under atmospheric icing conditions received considerable attention. Some of the topics of the Industrial Chair on Atmospheric Icing of Power Networks (CIGELE) at the University of Quebec in Chicoutimi focus on the identification of ice surface breakdown processes (Farzaneh et al. 1999a, Farzaneh et al. 1998) and flashover characteristics

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(Farzaneh et al. 1999b; Farzaneh, Kiernicki 1997), as well as on the development of models for predicting the breakdown voltage on industrial insulators covered with atmospheric ice (Farzaneh et al. 1997a).

Ultra-high speed photography is an experimental technique developed to study the fast surface breakdown processes. Numerous applications have been reported, for example flashover in compressed gases and liquids, as well as surface breakdown on synthetic spacer surfaces (Asokan, Sudarshan 1993; Li et al. 1995; The Liquids Dielectrics Committee International Study Group 1998). The analysis of fundamental ice surface flashover process and characteristics, using an adaptation of ultra-high speed photography, are the subject of the present paper. The knowledge of the physics of the breakdown on the ice surface is for example necessary to develop numerical tools for the determination of critical voltage of ice-covered insulators and electric field calculations around this equipment.

EXPERIMENTAL SET-UP AND PROCEDURE

Physical Model

The physical model used for the experiments consists of two hemispherical stainless-steel capped rods 12 mm in diameter, half submerged in the ice bulk. A vertical cut through the axis of the electrodes and a photography of the physical model are shown in Figure 1.

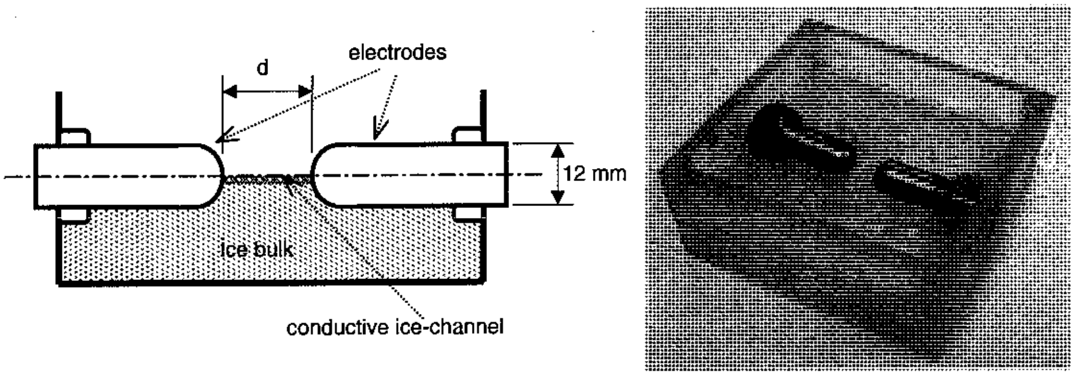

Figure 1. Vertical cut and photography of the ice model

The surface electrical field distribution along the axis of the electrodes is quasi-uniform (Li et al. 1995). The maximum field at the tip of the electrodes was calculated to be 0.66 V/cm for 1 V applied between the electrodes. To form the ice and also to keep the two electrodes in the right position, the electrodes were screwed into a rectangular plastic box. The same model has been used in the previous studies relating to ice surface breakdown (Farzaneh et al. 1999a; Farzaneh et al. 1998).

The ice bulk was built up in several layers to achieve a flat surface using de-ionised water. Once the ice was formed, a layer of salt water with a thickness of 6 mm and with a given conductivity was added to the ice surface.

To observe the development of the arc with the type of ultra-high speed camera used in this investigation, the arc has to follow a straight line between the two electrodes. In order to force the arc to propagate along the axis of the electrodes, a very shallow (2 mm) and narrow (1 mm) groove was created in the ice surface along the axis of the electrodes. For the test series with the ultra-high speed camera, the uppermost ice layer was also formed with de-ionised water and only the groove was filled with saltwater of a given conductivity. For the case of an ice surface formed from de-ionised water, the groove was kept empty. This technique was derived from experiments on synthetic spacer surfaces where the arc was kept straight through the use of such a groove between the electrodes (Li ct al. 1995).

Electronical and Optical Measuring System

Figure 2 shows the experimental set up, which consists of a high voltage generator and an ultra-high speed imaging system placed in front of the window of the cold chamber that contained the ice model. For all experiments, the high voltage generator was adjusted to provide a 1.2/50 μs positive lightning impulse voltage. The ultra-high speed camera used to record the optical phenomena was a Hamamatsu model C2830 streak camera, coupled to a CCD camera model C3640, which allowed digital data analysis and image storage in a desktop computer. The sweep duration of the streak unit can be varied from 0.5 ns to 1 ms. To record the optical phenomena emitted by the visible discharges on the ice surface, the ice sample was placed in a vertical position inside the cold chamber. The axis of the electrodes was placed in a horizontal position parallel to the slit of the streak camera. Details about image recording and analysis using this type of camera may be found in Li et al. (1995).

The voltage was measured using a capacitive divider. The signal was displayed and stored with a digital oscilloscope.

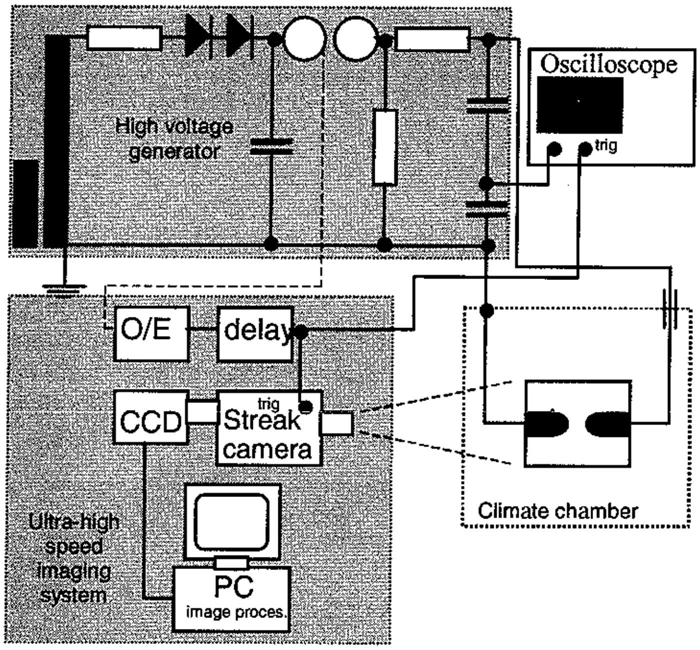

Figure 2. Schematic diagram of the electrical and optical systems

Experimental Procedure

Two series of experiments were carried out. The first series of experiments aimed to study the influence of different parameters on the 50 % lightning impulse breakdown voltage. The experiments were performed with a distance *d* of 18 mm between the electrodes. The influence of three parameters are presented in this paper:

- Freezing water conductivity (2.5, 30, 80 and 160 μS/cm)
- Ambient air temperature (-12 and 0 °C)
- Polarity of applied impulse voltage (positive and negative voltage)

The 50 % lightning impulse breakdown voltage was determined according to the international high voltage test standards IEC-507 and IEC-60-1. The up and down method with steps of about 10 % of the initial voltage was used to perform the experiments. For each test series, at least 10 useful tests were carried out. After each test (regardless of the result, breakdown or withstand), the ice specimen was replaced to ensure that only one impulse was applied to each ice sample.

In the second series of experiments, the development of visible discharge activities on the ice surface was studied. In this case, a distance *d* of 7 mm between the electrodes was chosen. As in the first series, the ambient air temperature (-20 and 0 °C) and freezing water conductivity (1 and 100μS/cm) were changed to study their influence on the discharge development on the ice surface.

All the streak images presented in this paper were recorded with a sweep duration of 200 ns and for positive voltage applied to the ice model.

RESULTS

Table 1 shows the results of the 50 % lightning impulse breakdown voltage V_{50} and the standard deviation σ_{50} for different freezing water conductivities and two ambient air temperatures.

Table 1: 50 % lightning impulse breakdown voltage and standard deviation for different freezing water conductivities and ambient air temperatures

T		*2.5* µS/cm	*30* µS/cm	*80* µS/cm	*160* µS/cm
-12 °C	$+V_{50}$(kV)	43.7	41.9	32.6	25.8
	σ_{50}(kV)	2.2	2.8	1.5	2.4
-12 °C	$-V_{50}$(kV)	46.7	39.6	28.3	22.8
	σ_{50}(kV)	2.2	4.7	1.7	2.5
0 °C	$+V_{50}$(kV)	41.9	24.3	22.3	17.1
	σ_{50}(kV)	2.8	2.4	1.8	2.1
0 °C	$-V_{50}$(kV)	43.1	27.3	21.8	19.2
	σ_{50}(kV)	2.8	1.8	2.4	2.5

To study the development of visible discharge activities for different conditions of ice surface, streak images were recorded during the second series of experiments and are presented in Figures 3 to 5. These streak images represent the temporal development of the visible discharges in one geometric dimension. The vertical axis of the image presents the space *x* along the axis of the electrodes. On the horizontal axis, the time dimension t_{sweep} is disposed.

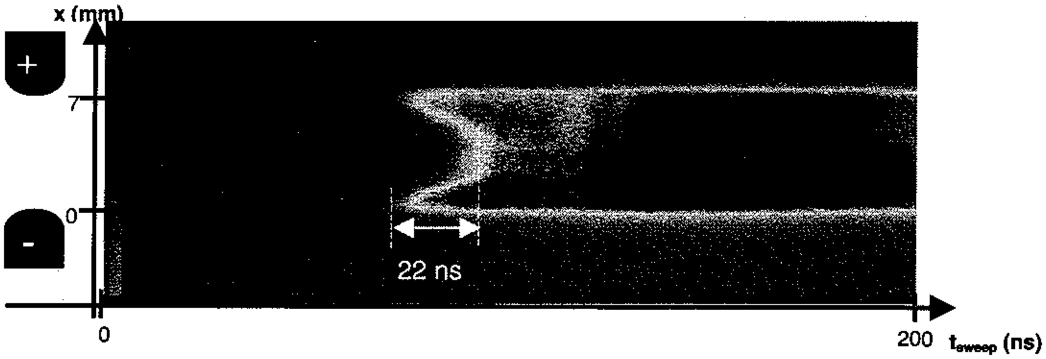

Figure 3. Streak recordings of the discharge development for T=-20 °C, σ=1 µS/cm

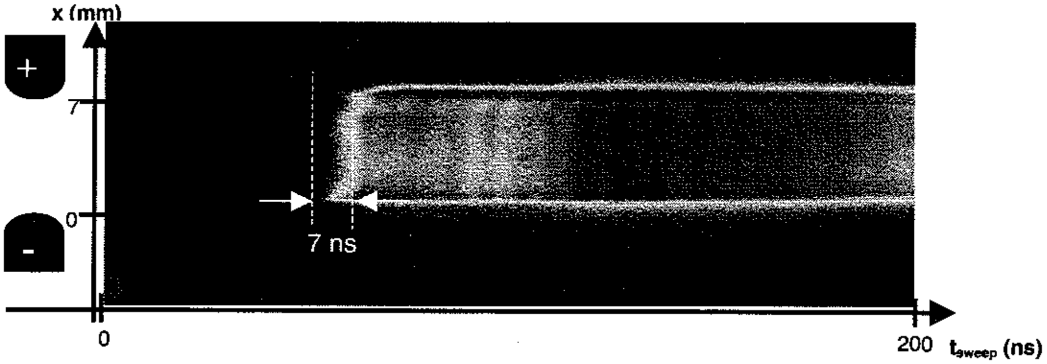

Figure 4. Streak recordings of the discharge development for T=-20 °C, σ=100 µS/cm

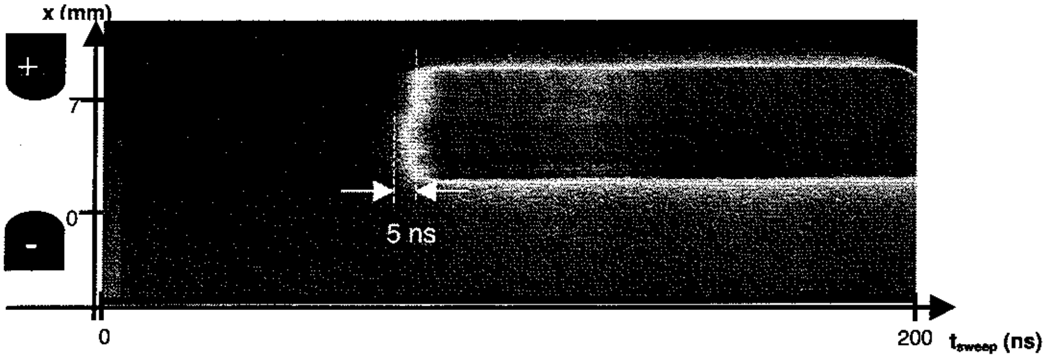

Figure 5. Streak recordings of the discharge development for T=0 °C, σ=1 µS/cm

DISCUSSION

Figure 6 shows the positive 50 % lightning impulse breakdown voltage on the surface of the ice as a function of freezing water conductivity for two different ambient air temperatures. The range of conductivities was chosen in accordance to values observed on natural icing sites (Chisholm, Tam 1990; Fikke et al 1993). These studies revealed that different compounds contribute to the conductivity of the precipitations. As the present investigation deals with the influence of the total electric conductivity of the ice samples, salt was the only pollutant used to adjust the conductivity of the freezing water. It may be observed that for both ambient air temperatures the breakdown voltage decreased as freezing water conductivity increased. Furthermore, the breakdown voltage was significantly lower at 0 °C than it was at −12 °C for all samples tested. In fact, increasing freezing water conductivity will lead to a higher leakage current, which provokes the electric breakdown on the ice surface at lower voltages. Furthermore, the presence of a water film on the ice surface at 0 °C also increases considerably the surface conductivity of the ice.

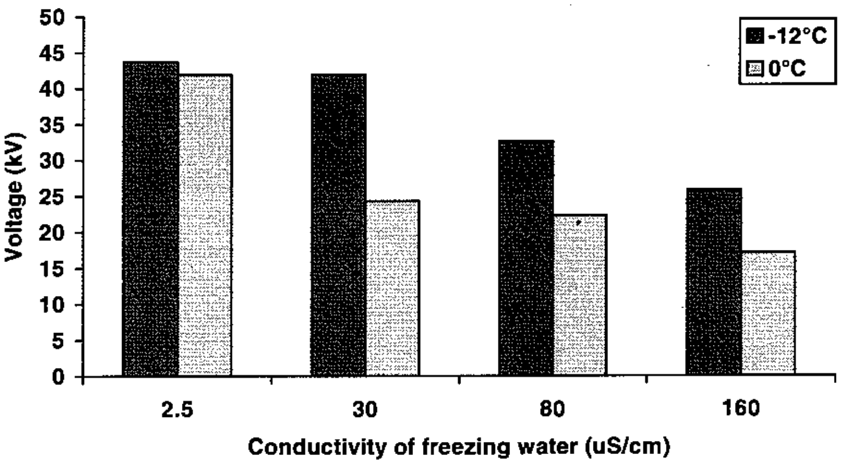

Figure 6. 50 % breakdown voltage for two ambient air temperatures as a function of freezing water conductivity (for positive voltage)

Concerning the effects of voltage polarity on the 50 % impulse breakdown voltage, it may be seen in Table 2 that, depending on the air temperature, a lower value of breakdown voltage was obtained for both negative and positive polarities. For an air temperature of −12 °C, at which the surface of the ice remained dry, the negative breakdown voltage was slightly lower than that the value obtained for positive polarity. A similar effect of voltage polarity has already been observed in DC withstand voltage measurements of industrial insulators covered with artificial ice (Farzaneh et al. 1997b). In the case where a water film was present on the ice surface (T=0 °C), smaller values for the 50 % breakdown voltage were obtained for positive polarity. The fact that no secondary electrons exist in the water may explain this phenomenon (Loeb 1956). This might lead to weaker pre-discharges under negative polarity for the same voltage level, compared to the activities under positive polarity, and thus to a higher value of breakdown voltage.

Table 2: 50 % lightning impulse breakdown voltage and standard deviation as a function of the polarity for different temperatures (σ=30µS/cm)

T		+	-
-12 °C	$+V_{50}$(kV)	41.9	39.6
	σ_{50}(kV)	2.8	4.7
0 °C	$+V_{50}$(kV)	24.3	27.3
	σ_{50}(kV)	2.4	1.8

The analysis of the images obtained with the ultra-high speed camera supplies more information on the processes of discharge development on the surface of the ice.

Figure 3 shows the streak recording of an ice sample made with de-ionised water, so that the resistivity of the freezing water, as well as that of the ice, are very high. It can be observed on the image that the first visible discharge activities started in front of the two electrodes. Both partial discharges proceeded into the middle of the space between the electrodes until breakdown occurred after about 22 ns. For the ice sample produced with water at higher conductivity, the visible discharge activity also started at the electrodes (Figure 4). But the discharge bridged the whole interval between the electrodes very quickly, and total breakdown of the ice surface occurred after 7 ns. For highly conductive ice, the discharge seemed to start somewhere on the surface of the ice and at several places at the same time (Figure 5). The duration, from the start of the first visible discharge activity to total breakdown, was about 5 ns. These results are in good concordance with ultra-high speed photographic investigations using shorter sweep duration (Farzaneh et al. 1999a).

Figure 7 shows the periods of time to breakdown, derived from the recordings with the streak camera, for the different ice surface conditions. It can be observed that the time to breakdown became shorter as the conductivity of the freezing water increased (7 ns in the second case compared to 22 ns in the first case). Where a water film on the surface of clean ice existed, the time to breakdown was about as long as it was for a dry ice sample formed with highly conductive water (5 ns in the third case compared to 7 ns in the second case). In general, the experiments showed that the time to breakdown was accelerated in the same cases where decreased breakdown voltage was measured in the first series of experiments. So it might be concluded that lower breakdown voltage is concurrent to a faster discharge development, as represented by a shorter time to breakdown.

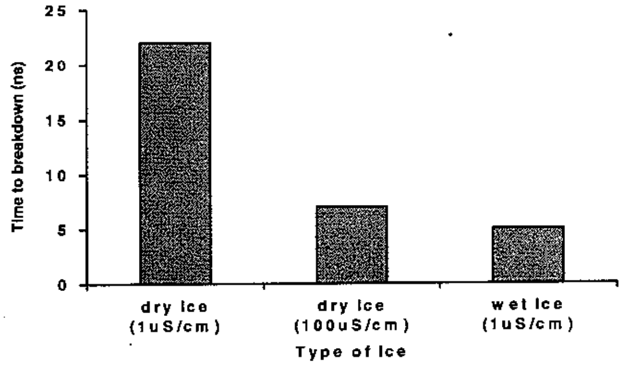

Figure 7. Time to breakdown for different ice surface conditions

CONCLUSIONS

A laboratory investigation was carried out to study the influence of different parameters on the 50 % lightning impulse breakdown voltage of an ice surface placed between two metallic electrodes. The results lead to the following conclusions:

1) The 50 % breakdown voltage of the ice surface tested decreased as air temperature increased. This may explain that an important number of failures in power networks have been observed during a period of rising air temperature after an icing event, when the ice cover started to melt and a water film was present on the ice surface.
2) The 50 % breakdown voltage of the ice surface tested decreased as freezing water conductivity increased. This illustrates that precipitations containing pollution can cause a significant loss of insulation capacity of the power network equipment. In particular, the combination of higher conductivity of the surface of the ice built-up with rising temperatures might cause critical situations for power network equipment, leading to power failures.
3) The streak images revealed that the time to breakdown decreased with increasing freezing water conductivity, as well as increasing ambient air temperature. This suggests that the decrease of the 50 % breakdown voltage for theses two cases is interconnected to faster discharge development until breakdown. Depending on ice surface conditions, visible discharges may be initiated on the surface near the electrodes, or at a location on the ice surface between the electrodes.

In order to have a better understanding of the breakdown processes on ice surfaces, additional research work using various ice samples with different ice surface conditions is planned for the future. The understanding of these physical processes of discharge initiation and development is necessary to create numerical tools for voltage and electrical field calculations and might help in the future to improve the design of high voltage insulators destined to the power lines in cold regions.

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