Measurement of Ice Surface Resistance

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Abstract—**In this paper, ice surface resistance, measured on a simplified physical model, was investigated because of its relevance to the flashover of high voltage ice-covered insulators. Special attention was paid to three experimental parameters, electric field, freezing water conductivity, and surrounding air temperature. All experiments were performed by placing the physical model inside a climate chamber kept at the investigated temperatures of -12 and -2°C. From the obtained results, it can be seen that temperature and freezing water conductivity tend to considerably influence ice surface resistance. Possible mechanisms, which control these variations, are discussed.**

I. Nomenclature

DC : direct current
R_{SH} : shunt resistance
R_0 : direct current ice surface resistance
σ : freezing water conductivity, μS/cm
t : time, minutes
T : temperature inside the cold room, °C
E : applied electric field, V/mm
d : electrode clearance

II. Introduction

ICE accretion on transmission lines and outdoor hardware can cause mechanical and electrical damages [1-5]. Particularly, ice accretion on outdoor insulators may considerably decrease the electrical performance of these devices [1-5] leading under certain circumstances to flashover and consequent power outages, as in Canada and other countries [1-10].

The mechanisms of flashover of ice-covered insulators are not yet fully understood. Though tentative explanations have been proposed in the literature [3-5], new 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 factors, including [1, 3, 5, 8]:

- Ice type and density, amount and distribution along the insulator surface;
- Decrease in “effective” leakage distance caused by ice bridging;
- Increase in surface conductivity caused by the presence of a water film resulting from factors such as 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, a rise in air temperature or ice shedding;
- And, finally, the presence of a pollution/impurities layer on the surface of the insulator.

Among those factors, ice surface resistance appears to be one of the most important parameter governing flashover processes. Indeed, the development of leakage current and arcing on an ice surface, whose resistance has been reduced due to the presence of contaminants and impurities, as well as to melting and pre-melting, is responsible for flashover. It is therefore important to accurately characterize the resistance of the ice surface.

Over the years, partial discharge intensity, surface conductivity of various materials has been investigated. However, very little work has been done on ice surfaces under DC voltage. Of considerable interest is In particular, the manner in which the ice surface resistance changes with freezing water conductivity, ambient temperature or electric field is of considerable importance [11]. P. G. Buchan [12] measured the electrical conductivity of ice and its variation with temperature. He found out that wet ice can be considered to have both volume and surface conductivity. H. T. Bui compared ice resistance during icing and de-icing [13]. He found that at the same temperature ice resistance is higher in the former case than the latter.

In order to close gaps on those investigations, the present study focuses on determining the influence of electric field, ambient temperature and freezing water conductivity on ice surface resistance. Since industrial insulators have a complex shape and are difficult to use for fundamental process investigations, a simplified physical model was used as a mould to form ice.

This investigation will help improving our basic understanding of ice surface flashover processes. The results will also be helpful in establishing mathematical models for predicting flashover on ice-covered insulating surfaces.

III. Test Procedure and Experimental Setup

Since ice accreted on insulators is of irregular shape and thus difficult to investigate, it is practical and more convenient to use a simple model to study ice surface resistance, ensuring the formation of uniform leakage current distribution on the ice surface. Figure 1 shows the simplified physical model used in these investigations.

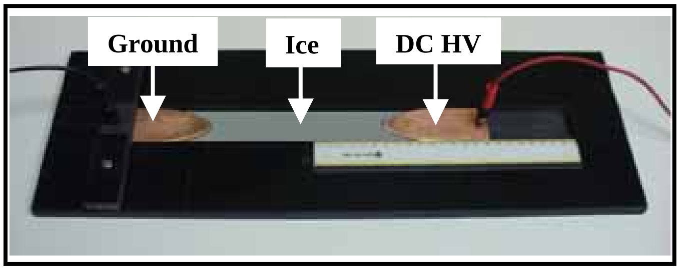


Fig. 1. Simplified physical model used to measure ice surface resistance.

The physical model (Figure 1) consists of a rod-rod configuration aligned with the ice surface, with an adjustable electrodes clearance *d*. The electrodes are fixed into a rectangular Benelex box, which also serves as a mould to form the ice. The ice samples are formed by filling the model with water of controlled conductivity. The mould is then placed in a freezer at -20^{o}C. The freezing water conductivities considered are 30 and 80 µS/cm. All experiments were carried out inside a cold room. Figure 2 shows the experimental setup used to determine the ice surface resistance.

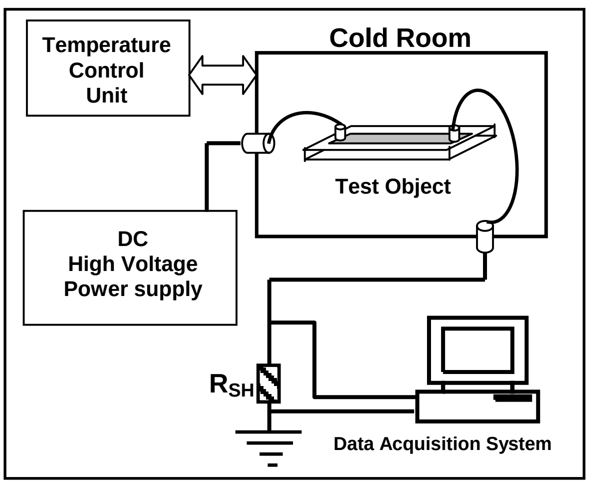


Fig. 2. Experimental setup for measuring ice surface resistance.

Once an ice sample was formed, it was placed at the desired temperatures -12 or -2 °C for a minimum of one hour in order to have enough time to stabilize the surface temperature.

To measure ice resistance, a DC voltage source was used. The applied voltages, 1.5, 2 and 2.5 kV, were chosen to be high enough to allow current measurement, for an electrode clearance *d* = 15 cm, these allowed a voltage gradient variation of 100, 133 and 166 V/cm, respectively. All tests were carried out for 75 minutes, enabling a saturation/stabilization of the resistance value.

The main components of the data acquisition system are a National Instrument DAQ plug-in board in a PC, and LabVIEW^{TM} application software. A LabVIEW graphical software program was used to acquire the data. The current leakage current was sampled at a rate of 1200 samples/s, transferred to a data buffer and stored. The current signal was transferred to a voltage signal using a low resistance shunt of 100 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.

IV. Results and Discussion

Surface resistance is defined in all of the aforementioned literature sources as the ratio of the DC voltage to the current flowing between two electrodes of specified configuration with the same material under test [14].

Surface resistance measurements depend on electrode material and geometry as well as on certain parameters discussed in [14]. As the electrode shape and material was kept the same during the experiment, the effect the macroscopic parameters was reduced to three (electric field, freezing water conductivity, and surrounding air temperature) in this investigation.

The equivalent electrical circuit of ice forming between two electrodes is shown in Figure 3 [15], where R_0 is the direct current resistance, C_∞ is high frequency capacitance and R_1 and C_1 are the relaxation resistance and capacitance.

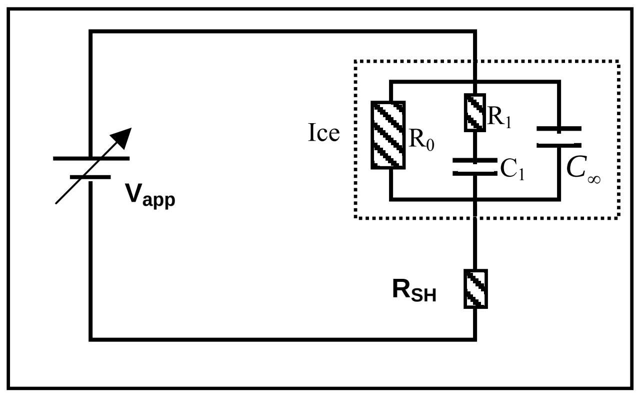
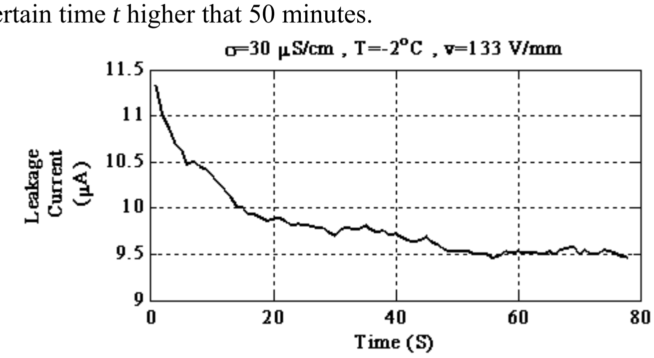


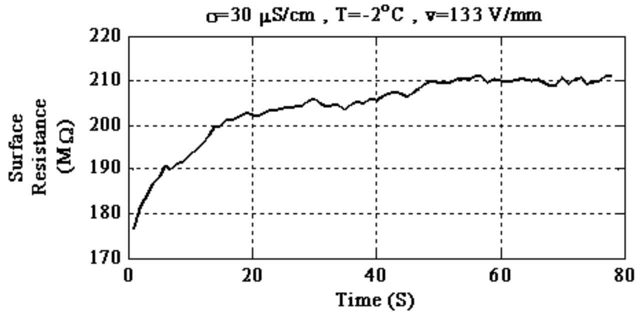
Fig. 3. RC equivalent circuit for ice in series with shunt resistance [15].

Under DC applied voltage or low frequencies, the direct current resistance R_0 of the circuit dominates [15]. R_0 is the ice DC surface resistance and can be determined by measuring the drop voltage of shunt resistance under DC applied voltage.

Figure 4-a and 4-b show typical waveforms obtained from the experiments. The leakage current and surface resistance for σ = 30 µS/cm, *T* = -2°C and *E* = 133 V/mm are represented in these Figures. It can be observed that ice surface resistance increases exponentially and saturates after certain time *t* higher that 50 minutes.



(a)



(b)

Fig. 4. Typical waveforms for leakage current and surface resistance.

A. Effect of electric field

The DC stress used for measuring the ice surface resistance was varied. Three values were considered, 100, 133 and 166 V/mm, while keeping the length of ice specimen at d = 15 cm (see Figure 2).

The results are summarized in Figure 5. From these figures, it can be observed that regardless of σ and T, ice surface resistance decreases as electric field increases. This is because of the fact that large current or field values can cause ~~a~~ temporary partial drying of the ice surface.

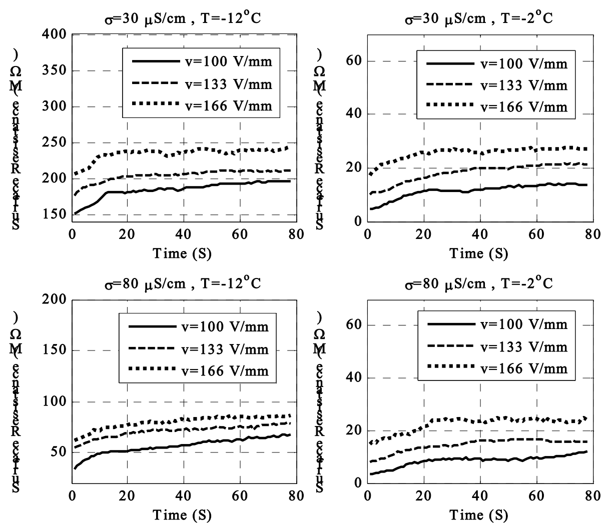


Fig. 5. Surface resistances versus time for various electric field values.

Also, these results show that when electric field increases linearly, the increase in ice surface resistance is non-linear. Current distribution density and uniformity of the water film on the ice surface are the important parameters when ice surface resistance changes under various electric fields.

B. Effect of temperature

A study on surface conductivity of ice crystals showed that surface conductivity increases rapidly as temperature is raised [16].

Our understanding of the melting of the ice surface is based on the modern theory of pre-melting [15, 17–19]. Surface pre-melting refers to a less familiar, but no less common process whereby a liquid film, known by various names as the quasi-liquid layer, liquid-like layer, surface melting layer, or pre-melting layer, is present at the ice surface at temperatures below the bulk melting transition. The film thickness is extremely sensitive to temperature and to the amount of impurities/dopant [15, 17-19]. This layer, which is quite small at lower temperature, becomes thicker with increasing temperature [17].

Materials that are poor conductors of electricity have the ability to store charge on their surfaces. Charge placed on these materials remains on the surface for a long time [20]. The liquid or liquid-like film is an electrolyte solution containing, for example, monovalent ionic species such as NaCl. Salts release strong electrolytes when dissolved in water. At temperatures below the melting point, surface conductivity increases rapidly with rise in temperature, with an increase in the mobility of the different kinds of ions in the solution, thus causing a corresponding increase in the conductivity. This temperature effect on surface conductivity is opposite to that observed in most electric conductors [21].

Increasing the water layer on the ice surface results in lower surface resistance at high temperature, as shown in Figures 6 and 7. As can be observed, the higher the temperature, the lower the ice surface resistance is.

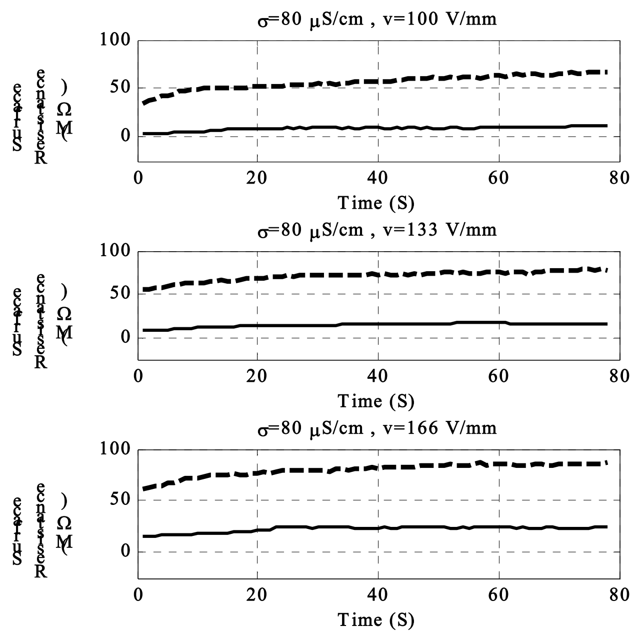


Fig. 6. Surface resistances versus time for σ = 80 μS/cm and two temperatures (Solid line: -2 ºC and dashed line: -12 ºC).

Also, comparing Figures 6 and 7, it is obvious that there is a big difference between low and high temperature resistance for low freezing water conductivities.

C. Effect of freezing water conductivity

The values of freezing water conductivity were chosen in accordance with values recorded during natural icing events [14]. The presence of the different impurities or pollution types contributes to an increase in conductivity of atmospheric precipitations. In the present study, sodium chloride (NaCl) was used to adjust the conductivity of the freezing water. When freezing water conductivity increases, ice surface conductivity increases. It has also been acknowledged that during the freezing process, impurities are rejected from the solid part of ice towards the liquid layer of drops or droplets [2].

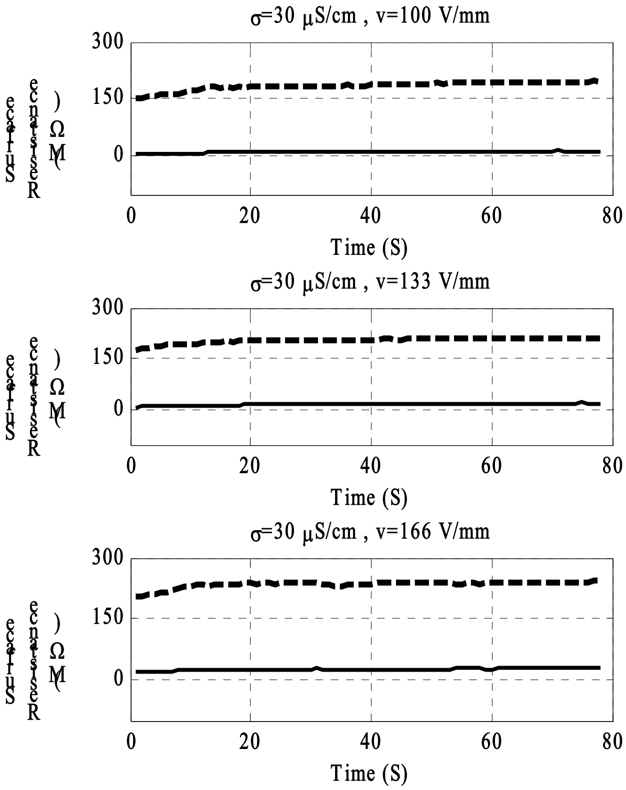


Fig. 7. Surface resistance versus time for σ = 30 μS/cm at two temperature values (Solid line: -2 ºC and dashed line: -12 ºC).

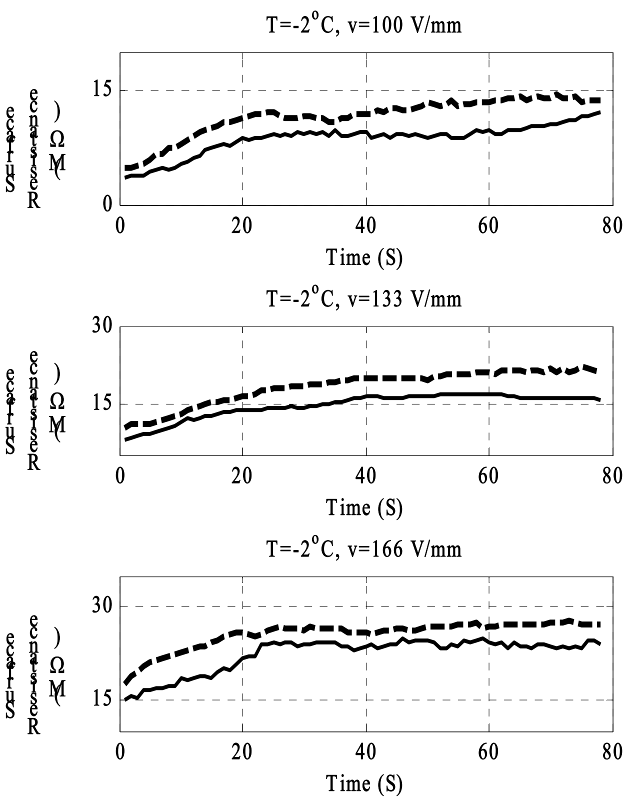


Fig. 8. Surface resistances versus time at -2 ºC at two values of freezing water conductivity (Solid line: σ=80 μS/cm and dashed line: σ=30 μS/cm).

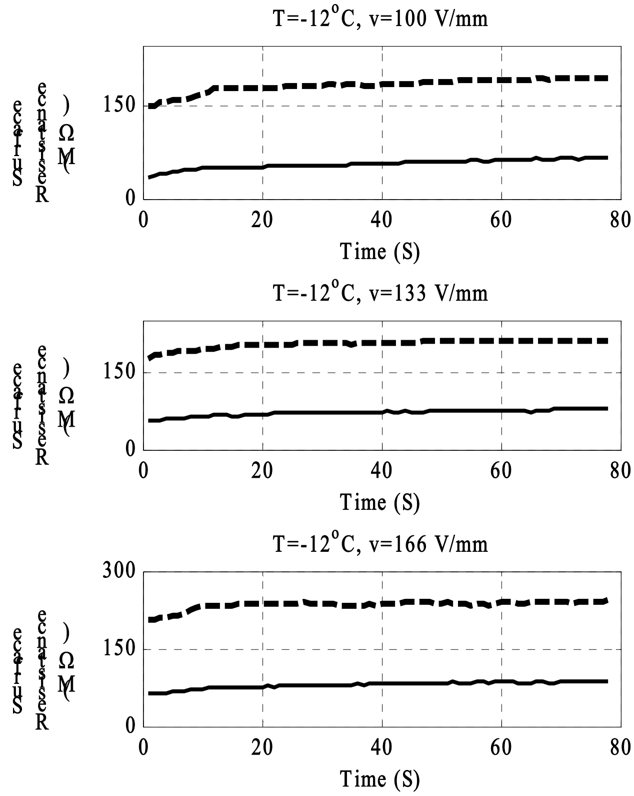


Fig. 9. Surface resistances versus time at -12ºC at two values of freezing water conductivity (Solid line: σ=80 μS/cm and dashed line: σ=30 μS/cm).

Because the impurities are non-volatile and insoluble in ice, small amounts of them can move to the surface increasing the surface conductivity and decreasing the activation energy [17, 19]. Indeed, it is known that the impurity incorporation process influences the surface structural phase transitions by reducing the surface energy [18, 19]. The conductivity of this liquid-like water film, can reach values as high as ten times those of the freezing water conductivity [2].

Figures 8 and 9 show the effect of freezing water conductivity on the ice surface resistance. As mentioned above, any increase in the freezing water conductivity induces a decrease in the ice surface resistance. The difference between both conductivities is high, as temperature decreases.

V. Conclusions

This study was undertaken to investigate resistance of an ice surface, because of its important role in ice-covered insulator flashover processes. The results indicate that ambient air temperature, applied electric field as well as freezing water conductivity may have a considerable influence on the surface resistance. From the obtained results, the following conclusions may be drawn:

- Any increase in the applied electric field lowers the ice surface resistance.
- Any increase in the ambient air temperature lowers the ice surface resistance.

- Any increase in the freezing water conductivity lowers the ice surface resistance.

The authors are engaged in a study to further investigate this matter and develop a mathematical model for predicting the ice surface resistance as a function of temperature, electric field and freezing water conductivity. Such a model could be used to simulate flashover processes on an ice surface.

VI. ACKNOWLEDGMENT

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