Temporal and Frequency Study of the Evolution of the Waveform of the Leakage Current of the Ice-Covered Insulators

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***Abstract*—This research relates to the characterization of the temporal and frequency evolution of the leakage current (LC) obtained from an ice-covered station post insulator during a melting period leading to flashover. Results show that the magnitude and the waveform of the leakage current are directly affected by the establishment of a conductive water film of the ice surface layer. The frequency study of the LC shows that the first two odd harmonics are dominant due to the non sinusoidal waveform of the LC. In particular, it was observed that the magnitude of the third harmonic reach a maximum just before the flashover occurs. In the same way, the study of the phase shift between the LC and the voltage gives us details about the nature of the LC is respectively capacitive-resistive, then purely resistive to finish resistive-inductive very closed to flashover occurrence. Both temporal and frequency analyses have led to establish two LC regimes: transient and permanent. The transition between these regimes occurs at a threshold value clearly identified by both temporal and frequency analyses.**

I. INTRODUCTION

Flashover of an ice-covered insulator is an extremely complex phenomenon resulting from the interaction between the following factors: electric field, wet and polluted ice surface, air gaps at the ice surface, environmental conditions, and the complex geometry of an ice-covered insulator [1, 2]. However, it is well established that several ice parameters have a significant influence on the flashover voltage of ice-covered insulators [1-3]. These parameters are referred to as the type, density, thickness, and distribution of the accumulated ice layer, the conductivity of the freezing water forming the ice as well as the dynamic behavior of the leakage current (LC) flowing at the ice surface.

In order to develop some flashover mathematical predictive models of ice-covered insulators, a large number of investigations were carried out on the static and dynamic modeling of the electrical arc behaviour at the ice surface [4-5]. However, little research has been dedicated to the analysis of the evolution of the leakage current (LC) during flashover processes. Some studies were carried out on the leakage current (LC) of polluted insulators [6-10]. All these studies agree that the measurement and the study of the leakage current (LC) provide a good source of information of the state of pollution on the surface of insulators [7, 9]. Moreover, some of these studies showed that the frequency and the temporal analysis of the leakage current could be used in the development of predictive models of flashover of polluted insulators [5, 8, 9]. In particular, the results obtained highlight that the magnitude of the first odd harmonics of the LC seems to have a direct relation with flashover probability [5, 8, 9].

As ice accumulation can be considered as a severe type of pollution [1], similarities may exist in LC behavior between polluted and ice-covered insulators. In this context, and based on few studies done on the polluted insulator LC, it could be possible to develop a flashover predictive model based on the LC analysis of ice-covered insulators. However, to the best of our knowledge, no systematic research has been carried out concerning the temporal and frequency evolution of the leakage current during ice-covered insulator flashover tests. In this context, this paper presents some preliminary results on the evolutionary parameters of the LC recorded during experimental flashover tests. For this, the temporal and frequency analysis of the LC at the bottom and middle sections of the test insulators covered with wet-grown ice was carried out. This type of ice, also called glaze ice, is considered to be the most dangerous type [1]. The test insulators consisted of three units of standard station post insulator, as used on the 735 kV Hydro-Quebec network. The choice of post insulator is mainly based on the fact that most insulator flashovers observed in Quebec have occurred on this type of insulator [3] during melting periods. The results obtained will be particularly useful to get a better understanding of the LC parameters involved in the mechanisms preceding flashover occurrence.

II. EXPERIMENTAL SETUP

Wet-grown ice was artificially formed on the insulator string at the UQAC facilities, in a 6 m × 6 m × 9 m cold room specially designed for testing of full-scale, ice-covered insulators. The ice accretion procedure and the set-up used were described in [2] and may be summarized as follows: Ice was formed from super-cooled droplets produced by an oscillating nozzle system that sprays water into a relatively uniform airflow produced by a system of sixteen fans placed in a tapering box with a diffusing honeycomb panel, as shown in Fig. 1. High voltage was supplied by a 350 kV transformer. For each test, wet-grown ice was accreted on the insulator using icing parameters shown in Table I.

The experimental procedure used in these tests is based on the procedure described [2]. To summarize, the accumulation of wet-grown ice on the insulators is carried out under service voltage. Once the accumulation is finished, the ice deposit is cooled to -12°C during 20 min, with the voltage turned off so as to improve ice adhesion and hardening. Finally, a melting period is carried out by increasing the air temperature from subzero temperatures to a melting temperature. The average heating rate corresponds to around 14ºC/h until a temperature of -2ºC is reached, and then the rate is changed to 3ºC/h until the end of the test. During the melting period, the LC, applied voltage, and room temperature are recorded.

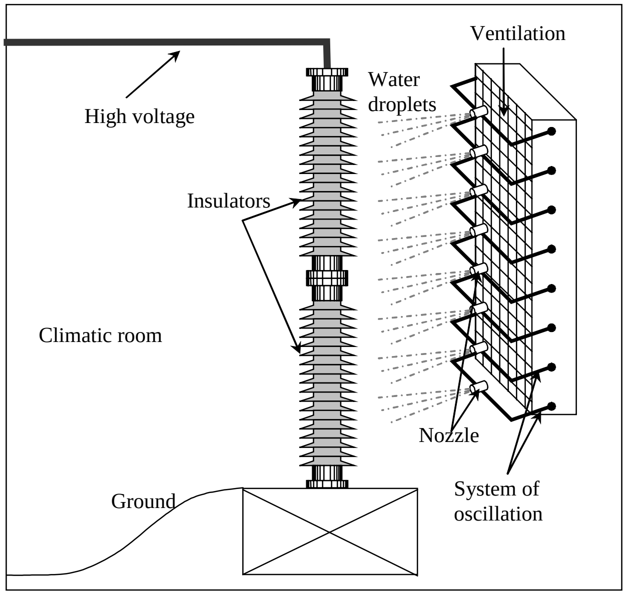


Figure 1: Climatic room.

The insulator used for this study is the bottom and middle section of a three-section station post insulator, used on the 735 kV Hydro-Quebec network (Fig. 2). Each section has a 3500-mm leakage distance and a dry arcing distance of 1390 mm. The two sections were tested under a voltage gradient of 105 kV_{rms} per meter of dry arcing distance, which corresponds to the normal service voltage gradient on the Hydro-Quebec post station insulators.

TABLE 1
EXPERIMENTAL PARAMETERS

Air temperature(°C)	-12
Average droplet size (µm)	80
Wind speed(m/s)	3.3
Freezing water conductivity at 20 °C (µS/cm)	30
Ice thickness (measured on the Witness cylinder) (cm)	1.5
Applied voltage (kV_{rms}/m of arcing distance)	105

The acquisition system, to record and visualize the LC and the applied voltage, was developed under Matlab environment. Matlab is the most common technique offering great flexibility for data treatment and displaying graphic control objects. Moreover, the frequency and temporal investigations of the LC records obtained during this research and their integrations in real-time processing are largely facilitated with Matlab.

Height: 1542 mm
Arcing distance: 1390 mm
Creepage distance: 3500 mm

Higher part
Internal diameter : 154 mm
External diameter : 246 mm

Lower part
Internal diameter: 168 mm
External diameter: 262 mm

Shed
Numbers: 26 for the middle unit and 25 for the bottom unit.
Step : 50 mm
Range: 45 mm
Higher angle: 24,5°
Lower angle: 6°

Fig. 2: Geometrical characteristic of the insulator tested

The leakage current is recorded through the 5Ω shunt and the voltage by means of a capacitive divided voltage, as seen in Fig. 3. The data are recorded on a PC through an acquisition card (NI) controlled by MATLAB.

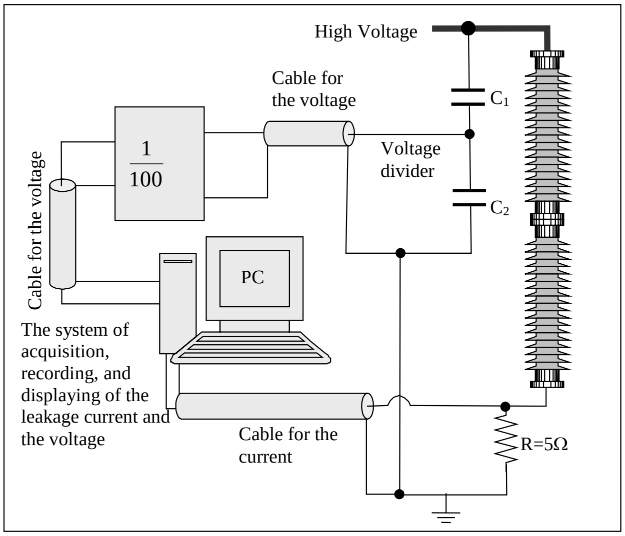


Fig. 3: Acquisition and measurement system of the leakage current and the voltage.

III. TEMPORAL ANALYSIS OF THE LEAKAGE CURRENT

The general observation of the temporal evolution of the LC shows that its magnitude and waveform varies during the melting period, as the state of the surface changes. Fig. 4 illustrates a typical temporal evolution of the envelopes of the leakage current and air temperature during the melting period leading to flashover. Both the negative and positive envelopes are calculated through the minimum and maximum values of the leakage current in a time period of one second. This temporal LC evolution envelope shows that flashover occurs at a very high temperature of about -0.5°C. This demonstrates that the flashover of an ice-covered insulator is a long process governed by the establishment of a conductive water film, mainly due to the melting of the ice surface generated by the local arcs, and also by the lesser effect of air temperature.

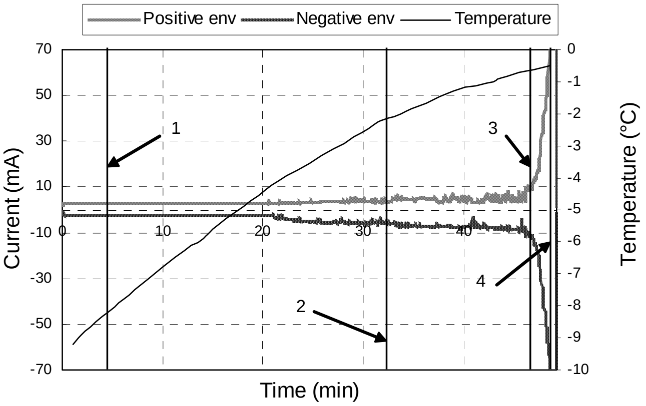


Fig. 4: Evolution of the envelopes of the LC and the climate room temperature for the melting period in the case of a flashover

Figs. 5 to 8 display a snapshot of characteristic LC waveforms in a time window of five cycles extracted from the LC evolution of Fig. 4. Each snapshot is located by a temporal cursor numbered from 1 to 4, as shown in Fig. 4. Each time cursor represents a characteristic step in the evolution of the LC waveform during a melting period.

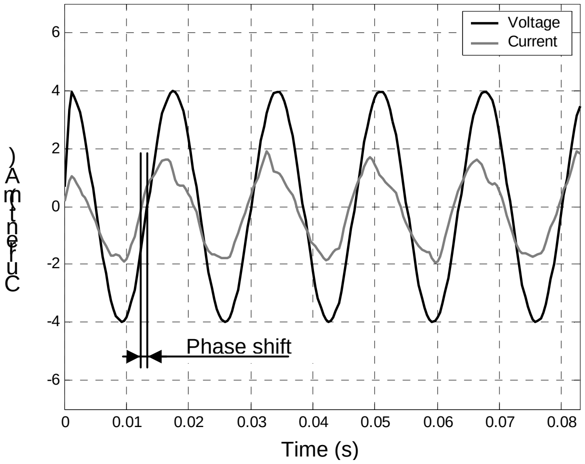


Fig 5: Applied voltage and LC waveform before the appearance of the partial discharges (cursor 1)

Fig. 5 shows that the magnitude of the LC is very small (about 2mA) and the LC is not in phase with the applied voltage. At this moment, which corresponds to the start of the melting period, the water film is not yet present at the ice surface. Under these conditions, the LC is capacitive, as indicated by the phase shift in Fig.5. Since the ice has a relative permittivity of about 90 [10], thus the deposit of ice adds a significant capacity to the insulating column, and hence increases the capacitive value of the LC when there is no conductive water film [11].

With the increase in air temperature, the state of the ice surface is modified as it starts to become wetted. In this condition, a redistribution of the potential occurs along the insulator and the voltage drop along the different air-gaps increases, leading to the discontinuous appearance of partial discharges along the air-gaps [13], as shown in Fig. 6. Air gaps are the insulator parts which are not covered by ice, and are similar to the dry bands of the polluted insulators. The appearance of discharges is correlated with the peak value, or maximum value, of applied voltage, and the phase shift between the LC and the voltage decreases.

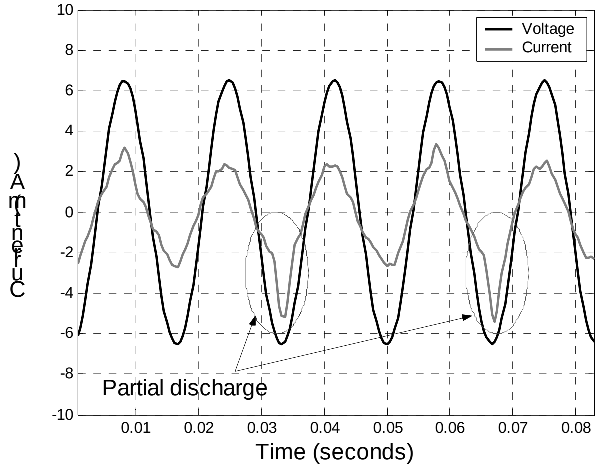


Fig. 6: Applied voltage and LC waveform after the appearance of the first partial discharges (cursor 2)

The heating effect, mainly due to the partial discharges combined to the raise in air temperature (as shown in Fig. 4), accelerates the formation of the water film at the ice surface. This leads to an increase of the voltage drop along the air-gaps, and hence an increase in the activity of the partial discharges, as shown in Fig. 7. In this step, partial discharges appear at each half cycle at the maximum value of applied voltage, and the LC is quite in phase with the applied voltage. Thus, the resistive nature of the LC seems to be correlated with the presence of partial discharges along each air gap, and the establishment of a conductive water film at the ice surface. However, the conductivity of the water film remains low, as illustrated by the small magnitude of the LC (~10mA). This step is a transition between the “transient regime” illustrated by Figs. 5 and 6, which is characterized par the random apparition of the partial discharges and the “steady regime” illustrated by Fig. 8, which preceded flashover.

In the last stage, close to flashover, the water film is well established along the insulator, in part caused by an increase in air temperature and also by the local melting of ice by partial discharges. In this case, partial discharges (violet color) are replaced by partial arcs (white color), as the LC value increase, as shown in Fig. 8. In that case, the establishment of the partial arcs along the different air-gaps leads to an increase in LC value and a decrease in the reignition time of partial arcs, which occurs at a very low voltage. This characterizes the “steady regime”. In this regime, the current becomes

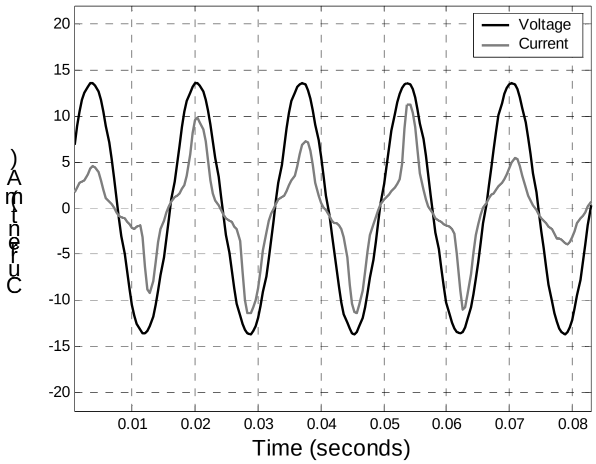


Figure 7: Applied voltage and LC waveform when the partial discharges are established (cursor 3)

purely resistive and its value is only limited by the applied voltage and conductivity of the water film. From experimental observations, it was noted that the passage from the "transient regime" to the "steady regime" takes place for a peak value of LC, around 20 mA for both cases; flashover and withstand. This particular value was taken as a critical threshold of occurrence of flashover during the various tests [1]. In the "steady regime", it is generally the melting of ice by partial arc, which contributes to increase the temperature and conductivity of the water film, leading to an increase of LC value. In the absence of ice shedding, leading to the increase of air-gap length, LC value can increase rapidly until flashover, as illustrated by Fig. 4.

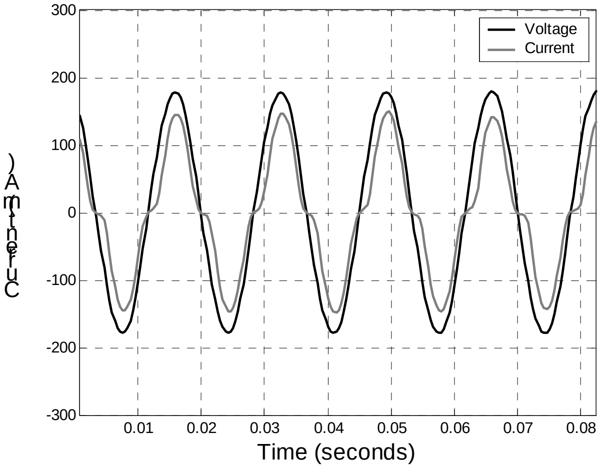
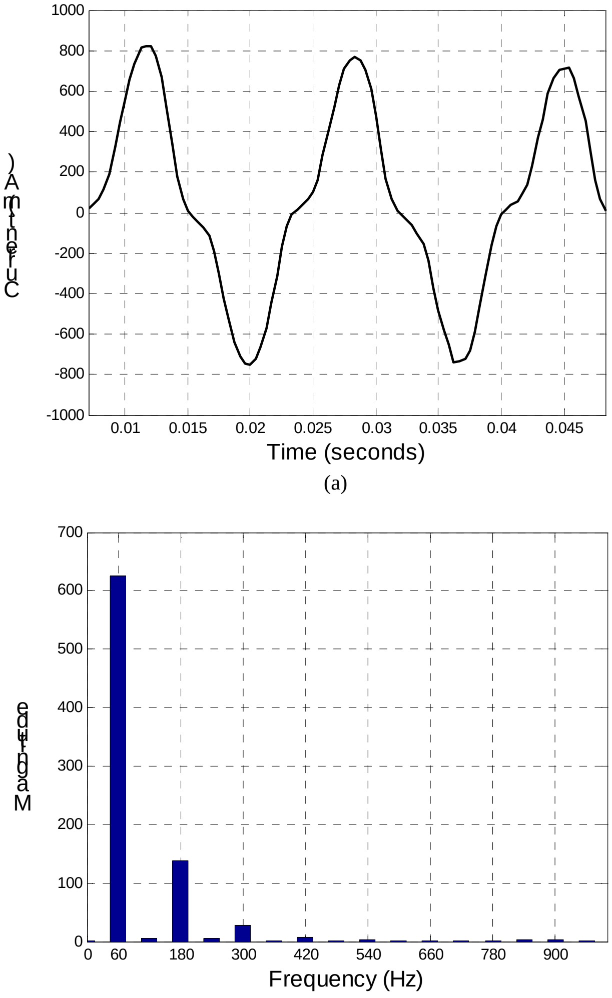


Figure 8: Voltage and LC waveform preceding the flashover (cursor 4).

IV. FREQUENCY ANALYSIS OF LEAKAGE CURRENT

According to the results presented previously, the leakage current is not completely sinusoidal, as demonstrated by the waveform of Fig. 9-a, which corresponds to the "steady regime" as discussed previously. Thus, this quite sinusoidal wave form yields to additional harmonics than the fundamental component of 60Hz. This is clearly illustrated by Fig. 9-b, which corresponds to the FFT of the LC waveform of Fig. 9-a. The results show that the third (180 Hz) and fifth (300 Hz) harmonics are dominant, as reported in polluted insulator studies [6-9]. These results confirm that a similarity exist between the electrical behavior of polluted and ice-covered insulators during a melting period. In that case, it was decided to compute the temporal evolution of each harmonic magnitude during a flashover test, as shown in Fig. 10. To achieve this, the ratio of the third harmonic on the fundamental and the ratio of the fifth harmonic on the fundamental were computed and plotted with the corresponding temporal evolution of the LC envelopes.



(a)

(b)

Figure 9: a) Waveform of the leakage current in steady regime b) Frequency representation of the module of the leakage current.

Results show that the temporal evolution of the third and fifth harmonic exhibit random fluctuations, but with a tendency to increase as flashover approaches.

At the beginning of the melting period, the magnitude of the third and the fifth harmonics are relatively low. At this moment, LC current is quite capacitive and has an almost sinusoidal form, as shown by Fig. 5. With the appearance of partial discharges (Fig. 6 and 7), LC waveform changes and becomes less sinusoidal, leading to an increase in the harmonic magnitude (circle no. 1 on Fig. 10). The same

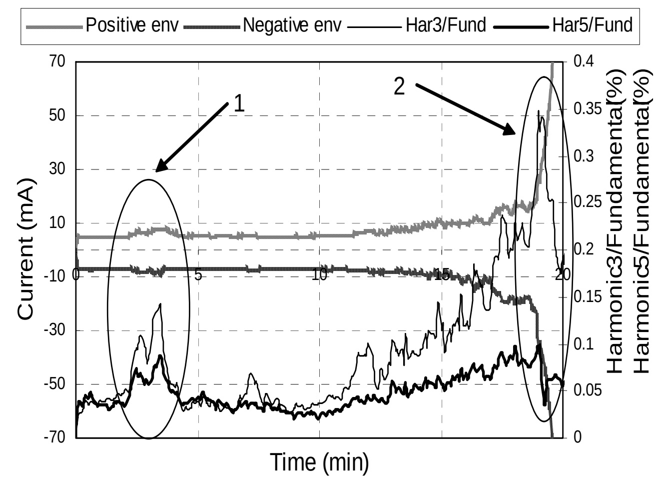


Figure 10: Temporal evolution of the third harmonic/fundamental and the fifth harmonic/fundamental of the current and its envelopes.

observation can be made in the steady regime with the partial arc establishment. The third harmonic presents a peak value at an LC value of around 20 mA, which corresponds to the shift from the transient to the steady regimes, as exposed previously. With LC magnitude higher than 20 mA, the reignition time of partial arcs starts to decrease and the LC waveform becomes more sinusoidal. In this condition, the third and fifth harmonic magnitudes start to decrease (circle no. 2 on Fig. 10) until flashover occurs.

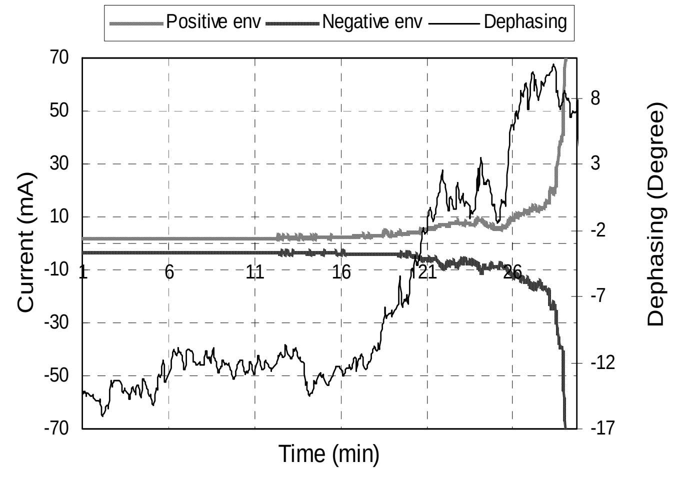


Figure 11: Evolution of the envelope of the LC and its phase angle during meting leading to a flashover

Other information can be extracted by the frequency analysis from the LC like the phase shift between the fundamental and the voltage. Fig. 11 shows the evolution of the phase shift of the LC during a melting period leading to flashover. The results show that the value of the phase shift is about -15° at the beginning of the melting period. This confirms than the LC is not resistive, not totally capacitive, but rather capacitive-resistive. This also indicates that a small resistive path exists at the surface of the ice at the beginning of the melting period. In fact, ice surface is more conductive than bulk ice. This is due to impurities rejected to the ice-air interface during accumulation, and the presence of a quasi-liquid layer of a few nanometers [10]. So, it can be concluded that the small resistive value of the LC is mainly due to the small thickness of this quasi-liquid layer. With the increasing of the discharge activity, the melting of the ice surface is accelerated, which contributes to the increase of water film thickness and leakage current value (starting at 18 min on Fig. 11). The combination of partial arcs and water film leads to a rapidly increase in the LC magnitude, which is characterized by the establishment of a resistive path at the ice surface and a corresponding phase angle equal to zero on Fig, 11. Close to the flashover instant, partial arcs extend along the ice surface and a positive phase angle appears. This small positive phase angle can be ascribable to the electric arc inductance in series with the water film resistance [3].

V. DISCUSSION

The temporal analysis of the LC shows that the magnitude and the waveform of the leakage current change with the variation of the ice surface quality. During the melting period, the evolution of the leakage current until flashover follows four steps. These steps can be classified into two different regimes, one of which is a transient regime and the other, a steady regime. The transient regime gathers the first three steps, which correspond to the appearance of the partial discharges. The steady regime is characterized by the last step corresponding to the establishment of the partial arcs along the different air-gaps and, under certain conditions, by the flashover.

The frequency study of the LC shows that there is a correlation between the temporal evolution of the LC peak value and the magnitude of the first two odd harmonics, which are dominant. Moreover, it is also possible to distinguish the transient and steady regimes using the temporal evolution of the harmonic magnitudes. The transition between the transient regime and the steady one is characterized by the peak value in the third harmonic magnitude.

In the same way, the study of the phase angle between the LC and the applied voltage provide some interesting information on the state of ice surface and about the temporal evolution of the LC as well. Thus, in the transient state, the current is either capacitive-resistive or resistive with the intensification of the partial discharges In that case, phase angle is negative or nearly equal to zero. When the permanent regime appears, the phase angle becomes positive and sometimes it decreases slightly in the vicinity of flashover.

The temporal frequency analysis of the leakage current shows the existence of a threshold corresponding to the passage from the transient regime to steady regime. In the studied cases, the correlation of different analyses shows that the threshold value is about 20 mA.

Finally, the analyses show that in the event of ice falling, the leakage current decreases abruptly and this sudden change is clearly identifiable by the harmonics and phase angle.

VI. CONCLUSIONS

All the results presented previously show that the information obtained through the LC analysis during the melting period constitutes a very important tool in the study of the electric behavior of the ice-covered insulators. These tools give us some information about the state of the ice surface, on the appearance of the partial discharges and also on the establishment of the electric arcs.

It was proved that the period of melting could be divided into four characteristic steps, which can be gathered into two main groups, namely transient and permanent regime. These two regimes are clearly identified by the frequency and temporal study of the LC. These studies led to the establishment of a critical threshold LC of 20 mA, which could be used as preliminary criteria for predicting the imminence of flashover.

However, the results obtained show that there are still many studies that can be made on the LC of the ice-covered insulators. These studies are very difficult to perform because of the random fluctuation of the LC compared with that of polluted insulators. This is mainly due to the random change in the ice accretion geometry and its surface state.

Finally, the influence of the parameters, such as the conductivity of the freezing water, the ambient temperature, and the thickness of the ice accretion on the evolution of the leakage current must be taken into account in future studies. That will be necessary in order to develop a real-time model for the monitoring and prediction of flashovers of ice-covered insulators.

VII. ACKNOWLEDGMENTS

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VIII. REFERENCES

[1] Task Force 33.04.09, “Influence of Ice and Snow on The Flashover Performance of Outdoor Insulators, Part I: Effects of Ice”, ÉLECTRA, No. 187, pp. 91-111, December 1999.

[2] M. FARZANEH (Chair) et al., “Insulator Icing Test Methods and Procedures”, A Position Paper prepared by the IEEE TF on Insulator Icing Test Methods, IEEE Transactions on Power Delivery, Vol. 18, No. 4, pp. 1503-1515, October 2003.

[3] M. FARZANEH, “Ice Accretion on H.V. Conductors and Insulators and Related Phenomena”. Invited article, Philosophical Transactions, The Royal Society, London, no. 358, pp. 1-35, 2000.

[4] M. Farzaneh, I. Fofana, C. Tavakoli & X. Chen, “Dynamic Modeling of DC Arc Discharge on Ice Surfaces”, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 10, June 2003, pp. 463-474.

[5] J. Zhang & M. Farzaneh, “Propagation of AC and DC Arcs on Ice Surfaces”, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 7, No. 2, April 2000, pp. 269-276.

[6] F. Amarth, “Electric Transmission Line Flashover Prediction System”, Ph.D Thesis and Final Report, Arizona State University, PSerc Publication 01-06, May 2001.

[7] E. Thalassinakis, C.G. Karagiannopoulos, “Measurements and Interpretations Concerning Leakage Currents on Polluted High Voltage Insulators”, Measurement Science and Technology, 14, pp 421-426, 2003.

[8] P. Cline, W. Lannes and G. Richards, “Use of pollution monitors with a neural network to predict insulator flashover”, Electric Power Systems Research, no. 42, pp. 27-33, 1997.

[9] M. Fernando, “Performance of Non-ceramic Insulators in Tropical Environments”, Ph.D thesis, Chalmers University of Technology, Sweden, 1999.

[10] T. Suda, “Study of the Frequency Characteristics of Leakage Current Waveforms of Artificially Polluted 12t Suspension Insulators by the Clean Fog Method”, ISH 99.

[11] V.F. Petrenko., « Electromechanical Phenomena in Ice », Special Report 96-2, U.S Army Cold Regions Research and Engineering Laboratory, February 1996.

[12] K. Kannus, “Aspect of the Electrical Performance of High Voltage insulator and Metal Oxide Surge Arresters under Various Environmental Stresses”, Tamplere University of Technology, Publications 229, 1998.

[13] C. Volat, M. Farzaneh et A. Gakwaya, “Dynamic variations of potential and electric field distributions around an ice-covered insulator during ice accretion”, Proceedings of the 10th International Workshop on Atmospheric Icing of Structures, paper 6.8, Brno, Czech Republic, June 2002.