An Experimental Investigation of Leakage Current on High Voltage Contaminated Insulators

Panagiotis T. Tsarabaris, Constantinos G. Karagiannopoulos, Perikles D. Bourkas, and Nikolaos J. Theodorou

Abstract—**This paper deals with results of leakage current measurements on 20 kV porcelain insulators. The measurements were performed in a time frame of one period (50 Hz) and the insulators were contaminated from a compound of salt and kaolin. The study was made via I-U characteristic curves plotted for one cycle of voltage application. The investigation of the observed phenomena showed that the response to the applied voltage is linear at first and thereafter takes the form of current pulses. Partial discharges (streamers), short and long duration arcs are the most likely physical phenomena detected experimentally. This assumption is convincingly supported from calculations of the average energy per pulse, which was found to be close to values reported in the related literature.**

Index Terms—**Insulators, leakage current, partial discharges.**

I. Introduction

Flashover is probably the major failure of insulators, which damages power quality, diminishes system reliability and results in considerable power loss. This effect usually appears on insulators that operate under adverse conditions, such as industrial areas, near the sea, in a desert or in snow [1]-[8]. Wind is generally the main factor which causes the deposition of contaminants on the insulator surface. The probability of a flashover occurring on a contaminated insulator depends mainly on the level and nature of the insulator surface's contamination, and on the wetting condition [9]. Scientists, all over the world, have investigated this phenomenon for many years. Test methods have been developed and many research papers were published. Researchers have studied flashover on contaminated insulators, (especially from salt contaminants) and most have worked on the correlation of the voltage level at which flashover occurs either with the number of units on the insulator string or with the equivalent pollution density [2], [4], [5], [9]-[13]. Other researchers have been investigating the correlation of the precipitation rate with the equivalent salt deposit density [12].

Flashover is the result of a series of other effects, which occur in the following order: insulator contamination, wetting of contaminants, generation of a thick electrolytic solution, occurrence of partial discharges (frequently called streamers), increase of the leakage current, increase of the temperature, formation of a dry band, occurrence of arcs, and finally the flashover [1]. However, it is commonly accepted [14], [15] that ageing and breakdown in the dielectrics are affected by four basic factors: joule losses, coulomb forces, partial discharges and ambient temperature. The above factors combine with different significance according to the situation and different local conditions (i.e., fields strength, contamination of the environment) so that the reduction in dielectric strength of the dielectric is the result of the combination of these [16]-[18]. More information about the ageing and breakdown of insulation has been studied, considering the energy of the free electrons and it has been experimentally proved that the spectrum of the emitted radiation during ageing may extend up to the ultraviolet range [19]-[21].

To better understand the progression of insulators from a healthy state to failure the leakage current has to be studied and therefore a large part of the bibliography concerns leakage current [3], [6], [7], [12], [22]-[26]. Leakage current of the contaminated insulator has been studied in relation to the salinity [6], for salt pollution in relation with time [23], as well as the exposure time in foggy places [12]. Also recorded has been the leakage current on insulators polluted by a combination of salt and desert dust [7], and also for insulators exposed in a coastal area having snow deposited on their surface [22]. Furthermore, a measurement method for the leakage current has been proposed, for the calculation of the RMS value of the leakage current [3]. The form of interference in radio and television sets with respect to the form of the leakage current for DC [25] and AC [23], [24] voltages has also been investigated.

In this work, measurements of the leakage current were performed on 20 kV porcelain insulators contaminated from a compound of salt and kaolin in a time frame of one period (50 Hz), using a high sampling frequency analogue/digital converter. To the best of our knowledge, this type of measurement has not been reported previously. An investigation of the observed phenomena is also attempted with the assistance of I-U characteristic curves plotted for one cycle of voltage application.

II. The Measurement System

The measurement circuit is provided schematically in Fig. 1. The voltage step-up transformer is supplied by a variable autotransformer, resulting in a controlled gradual voltage increase. The transformer's secondary coil

Manuscript received July 8, 2002; revised April 3, 2003.

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Publisher Item Identifier S 1682-0053(03)0165

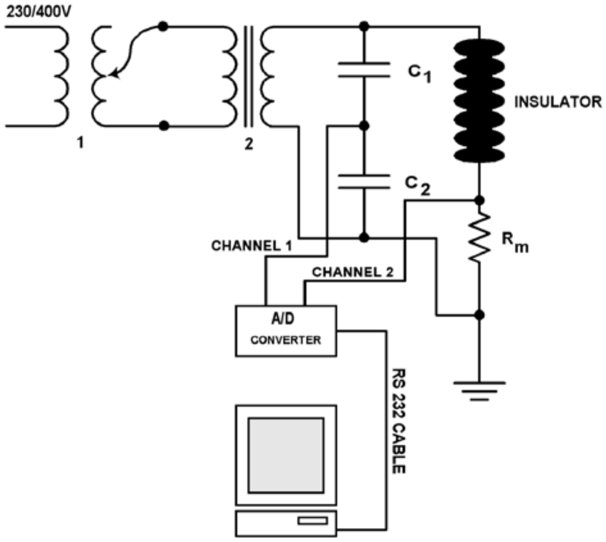


Fig. 1. Measurement circuit 1: variable autotransformer, 2: high voltage transformer, C_1 - C_2 : voltage divider, R_m : measuring resistance.

is connected in parallel with a capacitive voltage divider composed of capacitors C_1 and C_2 (Fig. 1). In parallel with the voltage divider the series connection of the insulator and the measurement resistance R_m is coupled. The voltage source as well as the circuit have been checked and fill the specifications [27], [28] required for their right use in artificial pollution tests. The voltage across C_2 and R_m is measured with the use of an A/D converter. The data is transferred from the A/D converter via an RS 232 connection to a computer where they are recorded and visually displayed with the use of appropriate software. The technical characteristics of the capacitors C_1 and C_2 were 224 pF, 100 kV / 50 Hz and 2 µF, 1000 V / 50 Hz, respectively. Prior to the use of the measuring capacitor C_2 the following tests were performed: an impulse voltage 1.2/50 µs with peak value of 500 V was applied to every capacitor and the response was observed on an oscilloscope. The exact capacitance was also determined using a Schering Bridge. The capacitors have shown ideal behavior. The value of the above-mentioned capacitor determines the appropriate voltage division ratio, as the maximum voltage across C_2 must not exceed the permitted input voltage of the A/D converter. In this case, this maximum value was 5 V. The resistance R_m, had zero self-inductance and its maximum permitted power was considerably higher than that imposed by the measured leakage current. The thermal factor, α , of the resistance was negligible. Coaxial 50 Ω cables with low interference capacity of the order of 50 pF/m were used to transfer the signals from the circuit to the A/D converter. Applying high voltage techniques the electromagnetic interference from the high voltage components was eliminated and with careful screening low induced voltages caused by stray magnetic fields was minimized. Besides it has been reported [28] that the influence of capacitive effects concerning the fittings does not affect the results significantly.

The whole sampling system was specifically designed and released for measuring fast rising voltage profiles and was capable of detecting voltages as low as ±1 mV with a typical error 0.1% when the input voltage to be measured was 1 V. The 12 bit A/D converters were of the successive

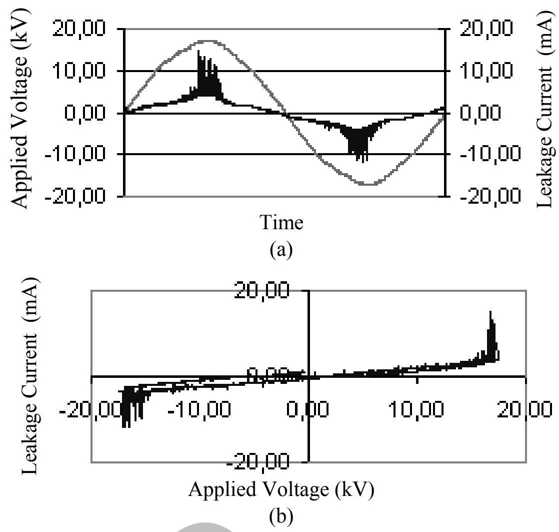


Fig. 2. (a) Waveforms of leakage current and applied voltage with respect to time for one cycle of voltage application, (b) I-U characteristic curves that have been obtained after the elimination of time from the previous measurements.

approximation type with a fast conversion rate of 0.020 µsec (2×50 MSPS). The input signals varied between ±5 V. The data were stored in tables in ASCII format. The insulator under test was a strut type multicone 20 kV insulator made of porcelain, having a leakage distance of 480 mm, the contamination (a compound of salt and kaolin) was 0.1 mg/cm^2. The solid layer wetting process of the specimen under test was in accordance with the specifications of the IEC 60507 standard.

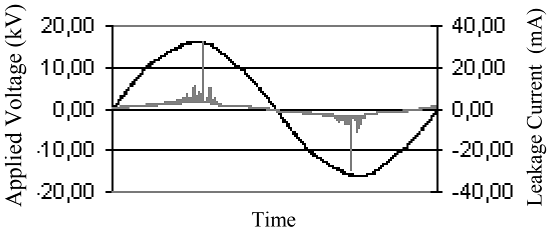
III. Results

Using the above circuit many measurements were performed. The tests were repeated on the same sample with contaminant layer each time renewed. Figs. 2 to 5 present indicative measurements acquired for an applied voltage $20/\sqrt{3}$ kV. In Figs. 2(a) to 5(a) the waveforms of the leakage current and of the applied voltage are given as a function of time. Every waveform of the applied voltage and the leakage current provided in Figs. 2(a) to 5(a) was drawn from 5000 points, the sampling frequency was 0.25 MHz and each point corresponds to one measurement.

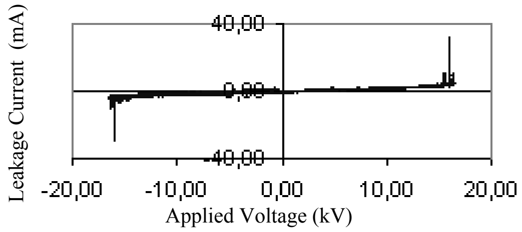
The voltage values are indicated on the left vertical axis and the leakage current values on the right one. It is noted that the waveform with pulses represents the leakage current measured across R_m, while the sinusoidal waveform represents the applied voltage measured across C_2. In Figs. 2(b) to 5(b) I-U characteristics, after the elimination of time from the previous measurements are given. Those characteristics clearly show that the insulator acts as a non-linear, high resistance conductor.

IV. Discussion

The predominant opinion of many authors in the bibliography is that the leakage current in the time frame of one period (50 Hz) is initially practically zero and attains a significant value only close to the maximum of the applied sinusoidal voltage [6]. It is also documented that the leakage current waveform always consists of pulses appearing randomly [25]. From the measurements provided in this study one can see that leakage current increases in

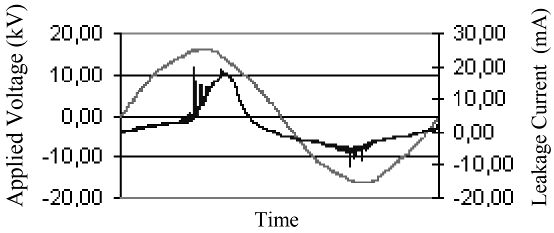


(a)

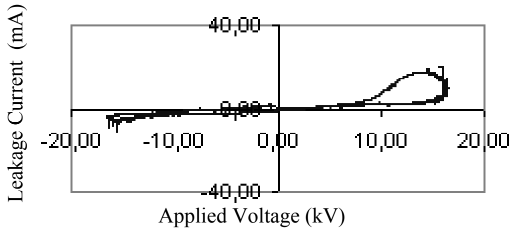


(b)

Fig. 3. (a) Waveforms of leakage current and applied voltage with respect to time for one cycle of voltage application, (b) I-U characteristic curves that have been obtained after the elimination of time from the previous measurements.



(a)



(b)

Fig. 4. (a) Waveforms of leakage current and applied voltage with respect to time for one cycle of voltage application, (b) I-U characteristic curves that have been obtained after the elimination of time from the previous measurements.

proportion with the applied voltage. This contradiction is further discussed and analyzed.

By examining on one side the leakage current values that resulted from the measurements and on the other side observing the waveforms of the leakage current in relation to the applied voltage as well as the corresponding I-U characteristic curves (Figs. 2 to 5), we can distinguish three phases in the development of the phenomena. Those phases are labeled with letters A, B, C and D in Fig. 6. Initially, the leakage current is very small for values of the applied voltage close to zero (point A).

This is expected, as the potential difference at the edges of the insulator is low and therefore the corresponding field is also low. During the first phase, the current rises linearly with the increase of the applied voltage up to a point B. This linearity is obvious in the I-U characteristic curve and is labeled I in Fig. 6. This implies that in the A-B area, conductivity probably appears on the insulator. The observed conductivity can be mainly attributed to the conductivity of the deposits on the insulator's surface but also to the low conductivity of the solid insulating material of the insulator (porcelain). The deposits' conductivity is due mainly to the conductivity of the dense electrolytic solution (for instance NaCl), which is formed among the substances on the insulator's surface pollution and the water concentrated on its surface. The ions of the diluted substance become more mobile under the influence of the strong electric field, causing the appearance of conductivity [29]. The value of the resistance was estimated from the measurements as 5 MΩ.

In the second phase (area II of Fig. 6) we observe that there is a point in the leakage current waveform, where the current increases instantaneously, having the shape of high amplitude - negligible width, pulses. The pulses vary in number and amplitude for different periods, and they do not appear periodically. The leakage current pulses, which appear randomly, are assumed to be caused by partial discharges on the insulator's surface, as well as by arcs on the insulator's surface across dry bands or on different disks. This is reasonable because it is documented that the occurrence of partial discharges is followed by rapid current fluctuations of the order of a few tenths of μs [30], [31]. Therefore, a dense spectrum of current pulses may imply that on the insulator' surface there was a high partial discharge activity and arcs. Examination of the leakage current waveforms of Figs. 2(a) to 5(a) shows that the current pulses can be divided into three categories. The first category consists of pulses with amplitude of up to 10 mA and with negligible width (of the order of a few μs). The second category contains pulses with amplitude of greater than 10 mA and with negligible width. The third category contains pulses with amplitude greater than 10 mA and with significant width, usually of the order of a few thousands of μs. The first category pulses are probably caused by partial discharges, because their amplitudes are small, in contrast to the pulses of the other two categories, whose amplitudes are much higher which are probably caused by arcs. This aspect seems to be true as the number of the first category pulses is greater than that of the other categories pulses. Referring to the second and third category pulses, it is conjectured that momentary arcs cause those with the lower width, whereas long duration arcs cause those that have significant width.

Note that pulses caused by following another arc, Figs. 4(a) and 5(a), generally start close to the maximum value of the applied voltage. Then a long duration pulse builds to a maximum value of approximately 30 mA. Its amplitude then decreases linearly with the applied voltage and becomes zero when the applied voltage is almost zero. This implies that on the insulator's surface long duration arcs were in progress, which extinguish out when the applied voltage reaches a comparatively low value. Note that prior to the occurrence of the current pulses due to long duration arcs, pulses either due to partial discharges (Fig. 5(a)) or due to instant arcs (Fig. 4(a)) occur. This probably implies that ignition of a long duration arc is achieved after the presence of partial discharges or instant arcs that act as triggering mechanisms.

In order to corroborate the above we calculated the energy and the electric charge of the measured current pulses. The data used were available in tables from the software of the A/D converter. From the data tables the

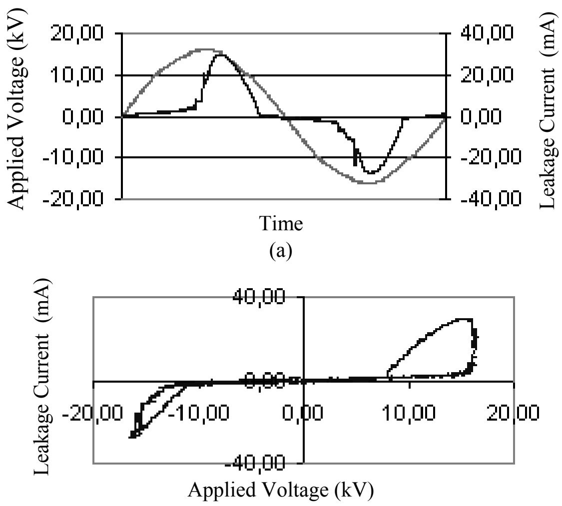


Fig. 5. (a) Waveforms of leakage current and applied voltage with respect to time for one cycle of voltage application, (b) I-U characteristic curves that have been obtained after the elimination of time from the previous measurements.

exact estimation of the leakage current pulses energy and charge were extracted. The calculation was performed using the relations:

$$\Delta W = \int_0^t i\,u\,dt = \sum_0^t [i\,u\,4.10^{-6}] \ \ (J) \qquad (1)$$

$$\Delta Q = \int_0^t i\ dt = \sum_0^t [i\ 4.10^{-6}] \ \ (C) \qquad (2)$$

where u, i are the instantaneous value of the applied voltage (kV) and leakage current (mA), respectively, n is the number of points which form each pulse and 4×10^{-6} represents the time interval (sec) between two successive measurements.

Current pulse energy and charge were calculated for a great number of pulses measured and the average value was estimated. Table I provides those values for the three categories of pulses.

For the charge of the first category pulses it is noted that they are very close to the partial discharge (streamers) charge measured in solid dielectrics stressed with high impulse, AC and DC voltages [32], [33]. The reported partial discharges charge for an applied voltage 20 kV is of the order of 0.1-0.3 μC. Therefore the assumption that the first category pulses correspond to partial discharges on the insulator surface seems to be valid. The charge of second category pulses has calculated values that are triple those of the first category and they don't match with the above charge values. The calculated energy of this category pulses seems to be in the range of non self-supporting discharge energy [34], and this supports the assumption that those current pulses originate from momentary arcs. Finally, the calculated average energy and charge of the third category pulses differ by two orders of magnitude from the values of the first category pulses. For these current pulses the realistic assumption that they originate from long duration arcs can be made, as their average energy is much higher.

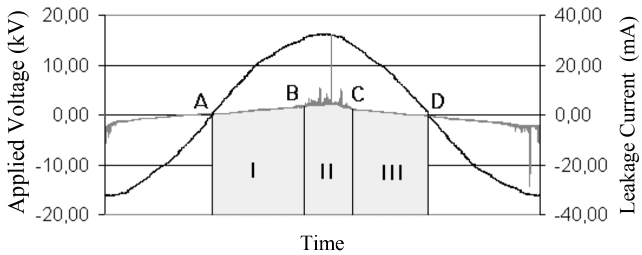


Fig. 6. Waveforms of leakage current and applied voltage with respect to time for one cycle of voltage application.

TABLE I
THE AVERAGE ENERGY AND CHARGE FOR THE THREE CATEGORIES OF PULSES MEASURED.

Pulse Category	1	2	3
Average Energy (J)	$6{,}535.10^{-3}$	$16{,}89.10^{-3}$	1,123
Average Charge (μC)	0,284	0,993	661

1: Pulses with amplitude up to 10 mA and with negligible width.
2: Pulses with amplitude over 10 mA and with negligible width.
3: Pulses with amplitude over 10 mA and with significant width.

V. CONCLUSION

In conclusion, we can say that the predominant opinion that leakage current is initially zero, and retains a significant value only close to the peak of the applied voltage, or that leakage current only exists in the form of negligible amplitude pulses, does not seen to be valid. From the present experimental work, data are presented that support the aspect that the leakage current remains non zero, as long as the applied voltage is non zero. It is shown that its response to the applied voltage is linear at first, thereafter takes the form of pulses, then becomes linear again and finally goes to zero. The measured pulses are divided into three categories by considering their calculated average energy. According to the analysis performed, it is concluded that the three categories of pulses correspond to partial discharges, short duration and long duration arcs respectively.

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