Recurrent Plot and Quantification of Leakage Current for Monitoring the Insulator Surface State under Non-uniform Desertic Pollution

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Abstract— This work is devoted to study the influence of the increasing of the width of the polluted band on insulators used in desert regions, by measuring the leakage current through the insulators surface. The Recurrent Plot technique (RP) is used to analyze the leakage current (LC) signal for monitoring the insulators surface state. This technique is applied directly on the leakage current waveforms, and the high frequency components are extracted from the leakage current signal using the wavelet transform technique. We also used the Recurrent Quantification Analysis (RQA) technique to quantify the RP characteristics of the LC signal and high frequency components, by computing the Recurrence Rate (RR), the Determinism (DET) and the Laminarity (LAM).

Keywords—Desert pollution, Leakage Current, Recurrent plot, Recurrent Quantification Analysis (RQA);

I. INTRODUCTION

In desert regions, the sand recovering the insulating surfaces of high voltage insulators is carried away by wind, mainly in periods of sandstorms. The pollution layer formation begins at the lower surface of the insulators, i.e. at the high voltage electrode side [1]. Different researchers found that this polluted band often goes on towards the opposite ground electrode. The large difference of the temperature between the day and the night in desert regions leads to the formation of the dew in the morning humidifying the pollution layer, which damages the insulators performance.

Different investigations on the insulators pollution domain are carried out in the laboratory to investigate the influence of the pollution layer on the insulators behavior, based on studies of the flashover voltage and the leakage current through the insulators surface. To study the increasing of the polluted layer width, and its effect on the insulators performance, Douar et al [2] used the wavelet transform technique to extract the different harmonics components of the leakage current. They computed the standard deviation (STD) of these components to estimate the importance of the pollution layer width and detect its position on the insulator. Liu et al. [3] focused on the leakage current analysis to study the flashover process. They used RP and RQA techniques applied to the high frequency components extracted from the leakage current, for tracking the flashover process. Chao et al. [4] used the Recurrent Plot Quantification (RPQ) to extract the different parameters of the RP, for classification of the pollution severity. Megriche et al [5], investigated the frequency analysis of the leakage current to monitor the insulators surface, using FFT (Fast Fourier Transform), and wavelet transform technique.

In this work, we are interested to study the influence of the increasing of the polluted layer width on the insulators behavior in desert regions. The study is performed on the plan model, having as leakage path between electrodes 29.2cm; similar to that of the insulators 1515L widely used by SONELGAZ. This insulator model is subjected to moistened desert pollution under 50 Hz AC voltage. To control the increasing of the pollution layer width, we analyze the leakage current signal through the insulators surface.

We used RP technique to analysis the leakage current signal. The RP is directly applied on the leakage current waveforms, and the high frequency component. This component extracted from leakage current using wavelet transform technique. Which allows detecting the increasing of the pollution layer width and the intensity of the partial discharges on the insulator surface. The RQA is used to quantify the RP structure of LC and high frequency components. The variation of the computed of different parameters extracted from tensor of the RP, which represent the mean of total recurrence points (RR), and the mean of the diagonal line (DET), and the mean of the vertical lines (LAM) of different RP structures.

II. EXPERIMENTAL SETUP

The experimental tests are carried out in the Ecole Nationale Polytechnique High Voltage Laboratory (Algiers). The test circuit consists of a high voltage transform (500V/300kV), a capacitive voltage divider, a resistor inserted between the insulator and the ground allowing to collect the leakage current, GW INSTEK numerical oscilloscope of 500 MHz bandwidth and personal PC to transfer the data from the oscilloscope.

The test object consists of a plan model of (50 cm x 50 cm x 0.5 cm); desert sand collected from Algeria desert is used as pollution layer and aluminum electrodes having rectangular form (50 cm x 3 cm). The distance between electrodes is 29.2 cm, similar to the leakage path of the 1512L insulator.
As we consider non-uniform case of pollution, and to obtain clean and polluted bands, we first recover the clean bands by plates of plexiglass, and then we spray a desired sand quantity, as uniform as possible using a sprayer. The considered widths of the pollution bands are 10 cm, 15 cm, 20 cm and 25 cm. The quantity of the sand used for the polluted layers is the equivalent of 15 g for each width of 10 cm. Finally, we use distilled water for humidification of these polluted layers.

The leakage current (LC) waveforms are recorded through a resistor $R$ of $1 \, \text{M} \Omega$, inserted between the insulator and the ground by an oscilloscope. The data are transferred to the PC for further processing.

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**III. RECURRENT PLOT ANALYSIS**

The RP analysis is generally used to study the dynamic of complex and non-stationary systems [6]. It can define the characteristics of the signal, detect and locate the transition peaks in the signal. The Recurrent Plot formed by comparing all the phase spaces of $N$ dimension and $m$ embedding, with threshold fixed distance of value $\varepsilon$.

RP is computed as below:

$$x(t_i) = [s(t_i), s(t_i - \tau), ...., s(t_i - (m-1)\tau)] \quad i = 1, ..., N \quad (1)$$

$$R_{ij}(\varepsilon) = \Theta(\varepsilon - ||x_i - x_j||) \quad i, j = 1, 2, ..., N \quad (2)$$

$\Theta$ : is the Heaviside function, $\varepsilon$ is a threshold distance, $R_{ij}$ : is a tensor representing recurrence plot, $\varepsilon$ is taken by different researches equal to 0.25 $\sigma$, where $\sigma$ represents the Standard deviation of the signal. $\|\|$ is the Euclidian norm, and $s$ is a signal.

**IV. RECURRENT PLOT QUATIFICATION**

The recurrent plot allows measuring the complexity of the System. Which is highly dependent on the sequential organization of the time series. The results of RR, DET, and LAM, are consistent with the variations of RP topological structures [3].

The recurrent rate represents the density of the recurrence points in the RP structure, and is calculated by the following expression:

$$RR(\varepsilon) = \frac{1}{N^2} \sum_{i,j=1}^{N} R_{ij}(\varepsilon) \quad (3)$$

Determinism (DET) is the ratio of the recurrence points on the diagonal structure to all recurrence points. The variation of DET indicates the characteristics of deterministic ingredients of the signal. It is calculated by the following expression:

$$DET(\varepsilon) = \frac{\sum_{i,j=1}^{N} IP(1)}{\sum_{i,j=1}^{N} IP(1)} \quad (4)$$

Laminarity (LAM) is analogous to determinism except that it is defined by the ratio of recurrence points forming vertical structures to all recurrence points. The LAM indicate state laminarity of the signal. It is calculated by the following expression:

$$LAM(\varepsilon) = \frac{\sum_{i,j=1}^{N} vP(v)}{\sum_{i,j=1}^{N} vP(v)} \quad (5)$$

**V. RESULTS AND DISCUSSION**

Figure 2 shows the LC waveforms and their corresponding high frequency components. The distortion of LC waveforms are due to the capacitive effect of clean bands, which amplify the magnitudes of the leakage current [2]. We observe also the presence of some pulses in waveforms of the leakage current, which indicate the activity of partial discharges. For the pollution layers with 5 cm and 10 cm of width, figure 2a and 2b, show the presence of some pulses on LC waveforms that shows for the high frequency component low pulses are observed. for width of 15 cm (Fig. 2c), we observe the increasing of the intensity of these pulses, which are more important at the ground electrode side. For the bands width of 5 cm, 10 cm and 15 cm, the important capacitive effect don’t allows the apparition of arcs, these pulses represent partial discharges initiated in air near the ground electrode (clean band side). For the bandwidth of 20 cm, we observe in figure 2d an important increasing of pulses intensity on the LC waveform that shows on the high frequency component a presence of many large pulses, which announce the initiation of apparition of arcs. In the case of pollution layer with width of 25 cm, figure 2e shows a more accentuated distortion of LC waveform, and a presence of intense pulses of high magnitude, the LC waveform represents the waveform when the arcs short-circuit the clean band. In this case, the importance of the polluted layer leads to the apparition of arcs in the clean band.
Figure 2 Leakage current waveforms and the corresponding high frequency components for different polluted layer widths (a) layer of 5 cm (b) layer of 10 cm, (c) layer of 15 cm, (c) layer of 20 cm, (e) layer of 25 cm at 30 kV

Figure 3 shows the RP structure applied on the LC signal under different polluted layer widths. For each width of the pollution layer corresponds a specific topology. The structure shows the periodicity of the leakage current signal with regard to the diagonal line on LOI. In the diagonal line, the concentration points indicate the approaching of the apparition of peaks. These peaks represent the different deformations caused by the harmonic components contained in the signal.

The number of the concentration points depends upon the magnitude of the harmonics contained in the signal and the harmonic frequency ratio relative to the fundamental one [6], most the number of these concentration point important shows the important of the harmonic of the frequency superior. The most frequently present harmonics components in the leakage current in the case of the capacitive behavior are the third, the fifth and the seventh one [5].

In the figures 3a, 3b, and 3c corresponding to 5 cm, 10 cm and 15 cm of pollution layer widths, the important number of the concentration points, shows the important magnitude of the seventh and fifth harmonics. When the polluted layer bandwidth increases, the number of the concentration points decreases that show the important increasing of the third harmonic magnitude for 20 cm and 25 cm of width of polluted bands. Insolated points represent the intense presence of pulses on the leakage current. In figure 3e, case of 25 cm of the polluted layer width, we observe the presence of some isolated points in the diagonal line, which represent an intense pulses present in the leakage current waveforms (Fig. 2e).
Figure 4 shows the RP structure applied on the high frequency components extracted from leakage current signal using wavelet transform technique, for different polluted layer widths. Denser points grouped into rectangles, isolated points, and white band compose the structure. For the polluted layer band with 5 cm and 10 cm of width, we note in figure 4a and 4b that the recurrence points are low, represented into many small rectangles, and isolated points indicating the occurrence of transients pulses. For polluted layer widths of 15 cm and 20 cm, the accentuation of the recurrence point intensity shows that the activity of partial discharges increases. In the case of 25 cm of pollution layer width, figure 4e shows very dense points into rectangles form, and large white bands indicating the presence of arcs on the insulating surface.

![Figure 4](image1)

Figure 4 shows the RP structure for different polluted layer widths. For a) layer of 5 cm, b) layer of 10 cm, c) layer of 15 cm, d) layer of 20 cm, and e) layer of 25 cm at 30 kV.

Figure 5 shows the variation of different characteristics of the RP structure. In figure 5a, we observe only the increasing of the recurrent rate (RR) with the polluted layer width, which indicate the increasing of the recurrence point with the polluted layer width. The value of the DEL, and LAM, are near to equal value 1, that indicate low isolated points on RP structure applied on the leakage current waveforms.

![Figure 5](image2)

Figure 5 Characteristics of RP structure for (a) LC signal, (b) high frequency components.

The variation of the RR, DEL, and LAM, are very significant in the RP structure for the high frequency components (Fig.5b). They increase with the polluted layer width. The increasing of the DEL, and LAM, with the increasing of the polluted layer width, shows more deterministic of the signal and presence transitions zone significant, that indicate the increasing of the discharge activity.

VI. CONCLUSION

In this work, we are interested to study the influence of the increasing of the polluted layer width on the insulator behavior, basing on the analysis of the leakage current waveforms using RP analysis.

1- The increasing of the polluted layer width allows the increasing of the intensity of the partial discharge appearing as pulses on the leakage current waveforms.

2- The high frequency components extracted from the leakage current are in accordance with the discharge activity frequency. This allows us to follow the evolution of the discharge activity on the insulator surface.
The RP structure and the quantification of the high frequency components are very significant to study the discharge activity characteristics, and the importance of the polluted layer width on the insulator surface.

REFERENCES


