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Detection and Classification of Partial Discharges in Insulators Based on Acoustic Signals

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Detection and Classification of Partial Discharges in Insulators Based on Acoustic Signals

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Abstract. Acoustic inspection is an effective method that enables the detection of early-stage defects in equipment, thereby facilitating predictive maintenance. In recent years, the practice of identifying partial discharges through ultrasonic sensors has expanded significantly. However, interpreting acoustic signals remains challenging and requires extensive experience and knowledge related to equipment configuration. To address this issue, an approach based on evaluating the fundamental frequency has been proposed to standardize insulator diagnostics. In the experiment, a database of more than ten acoustic signals with frequencies ranging from 0 to 120 kHz was created, and various contamination levels and defects were introduced into the insulator string. Using the proposed method, it is possible to detect the occurrence of partial discharges and classify their types, such as corona or surface discharge. This advanced diagnostic approach simplifies the process and provides valuable insights into the severity of phenomena observed under operating conditions.

INTRODUCTION

Partial discharges (PDs) are spatially localized and incomplete dielectric breakdown events in which the voltage gradient is sufficiently high only around the initiation point to generate and sustain electric charge [1-5]. PDs occur in localized regions of the insulation system and, over time, may lead to material degradation. In general, four main types of PDs are distinguished: corona discharge, internal discharge, surface discharge, and treeing discharge. Each type is formed depending on local electric-field intensification, insulation geometry, or the physicochemical properties of the surrounding medium, and they possess distinct physical mechanisms, spectral characteristics, and diagnostic signatures. As illustrated in Fig. 1a, corona discharge occurs when the electric field in the surrounding medium is sufficiently non-uniform. This type of partial discharge typically appears near sharp geometrical points or around curved conductors in transmission lines. Corona discharges may manifest as bluish luminescence accompanied by ultrasonic and audible acoustic emissions. Furthermore, their temporary or persistent development can lead to gradual degradation of the insulation material. Internal discharge, shown in Fig. 1b, arises within voids located in layers of the insulator where the dielectric strength is reduced. The sustained presence of such discharges within a solid dielectric medium may cause the formation of severe defects in the material structure, particularly the development of conductive paths (tracks). The progression of this process may eventually lead to treeing discharge, illustrated in Fig. 1c. Surface discharges, depicted in Fig. 1d, occur when the tangential component of the electric field along the dielectric surface becomes significantly high [6-9].

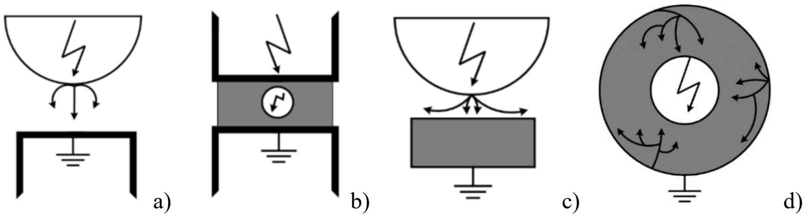

FIGURE 1. Types of electrical discharges: a) corona discharge, b) internal discharge, c) surface discharge, and d) treeing (root-like) electrical discharge

EXPERIMENTAL RESEARCH

In this article, a method for determining the fundamental frequency in the evaluation of partial discharges (PDs) is used, which is based on the power spectral density (PSD) approach to frequency estimation. The process of determining the frequency is carried out through the power spectrum of the signal. The power spectral density technique represents how the signal power is distributed over frequency. The power spectrum is obtained by applying the Fourier transform to the autocorrelation function of the acoustic signal.

The autocorrelation function is an effective mathematical tool for identifying repeating patterns in unknown periodic signals masked by noise. It also makes it possible to determine the fundamental frequency of the signal and its harmonics by analyzing the linear relationship between delayed values in time-series data [10-15].

For random signals, the periodogram is used as a method for estimating the power spectral density (S_x), and it is expressed by equation (1).

$$S_x\left(e^{jw}\right) = \lim_{N\to\infty} E\left\{\frac{1}{2N+1}\left|\sum_{n=-N}^{N} x(n)e^{-jwn}\right|^2\right\} \quad (1)$$

here, E denotes estimation, i.e., mathematical expectation.

Considering a finite amount of data with lengths equal to $N-1$, equation (1) can be transformed into equation (2).

$$S_x\left(e^{jw}\right) = \frac{1}{N}\left|\sum_{n=0}^{N-1} x(n)e^{-jwn}\right|^2 = \frac{1}{N}\left|X\left(e^{jw}\right)\right|^2 \quad (2)$$

here, $X(e^{j\omega})$ is the discrete-time Fourier transform (DTFT) of the signal, which in turn is given by (3). The rectangular input signal has the same length and the frequency sampling is equal to 250 kHz.

$$\omega = \frac{2\pi k}{N}, k = 0,1,2,\dots N-1 \quad (3)$$

Using the expressions above, it is possible to calculate the fundamental frequency and harmonic characteristics of partial discharge (PD). The methodology of the laboratory experiments is shown in Figure 2. The equipment shown in Figure 2 consists of the following components:

1. Resonant controller;
2. Power transformer;
3. Resonant source;
4. Device under test — insulator string (IS);
5. Capacitive divider;
6. Digital ultrasonic testing device located 12.5 m away from the device under test;
7. Oscilloscope;
8. Receiving system of the capacitive divider;
9. Computer.

In the tests, a string of three-element high-voltage glass insulators was used, to which various types of artificial pollution were applied. The technical datasheet of the insulator is provided in [16-21].

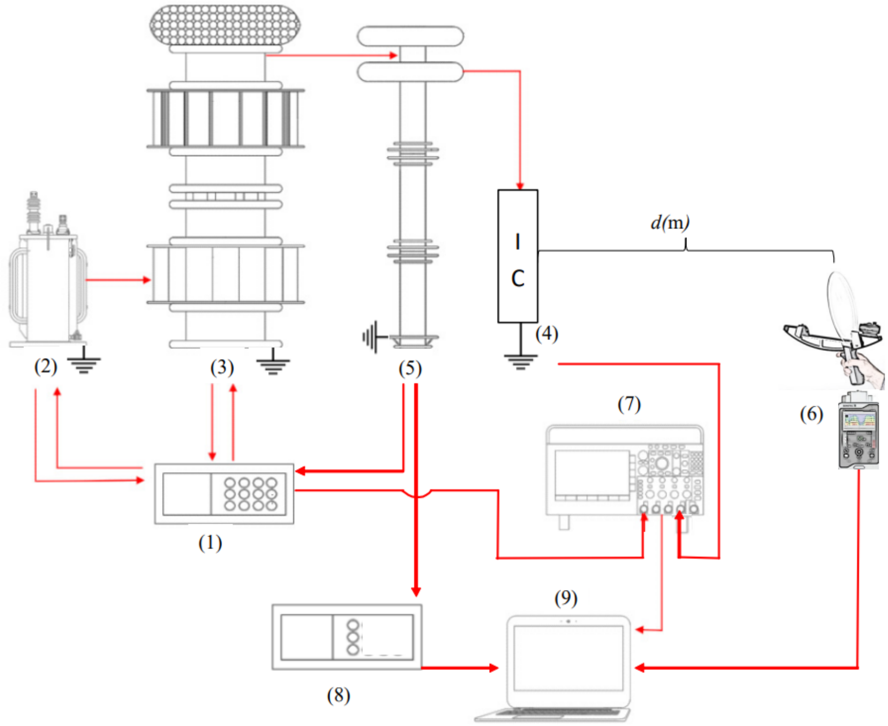

FIGURE 2. Organization of the experimental method

RESEARCH RESULTS

The tests were carried out in a way aimed at recreating the real operational conditions that insulators could encounter. This took into account the formation of permeable microfilming, which occurs under the influence of rain, wind or other environmental factors, the presence of a layer of clay that can arise as a result of dust and bird droppings, as well as cases of partial damage and degradation he tests were carried out in a way aimed at recreating the real operational conditions that insulators could encounter [33-62]. This took into account the formation of permeable microfilming, which occurs under the influence of rain, wind or other environmental factors, the presence of a layer of clay that can arise as a result of dust and bird droppings, as well as cases of partial damage and degradation. The insulator is characterized by a conductive microfilm produced by contamination that is partially or completely scattered along its surfaces. Also applied was clay contamination consisting of a mixture of soil and water. After that, partial mechanical damage was created on the surface of the insulator. Small cracks are observed on the surface of the insulator. Figure 3 presents the general condition of the insulators and the range of voltages applied in laboratory experiments. The insulator chain was tested at voltages ranging from 10 kV to maximum values provided by a laboratory resonance source, until the over-current protection system came into operation [22-25].

Below, the maximum voltage levels depend on the condition of the insulator (pollution level) and environmental conditions, as humidity and temperature affect the occurrence of PDs due to favorable or unfavorable ionization conditions in the air. Therefore, laboratory tests carried out on days with different environmental conditions with the same insulator chain can partially lead to different maximum voltage levels required for dielectric breakdown [26-32].

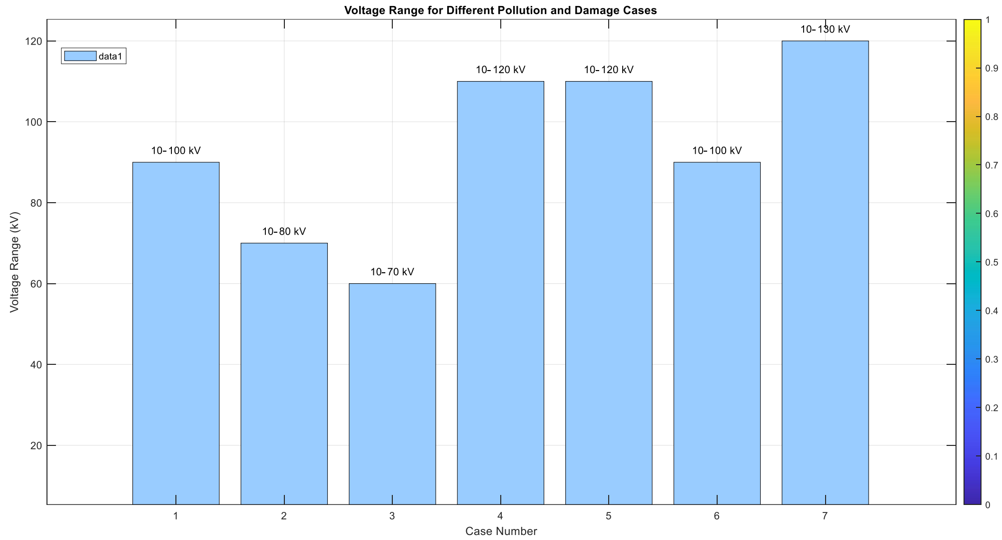

FIGURE 3. The condition of the insulators and the voltage range used in laboratory experiments.

Ultrasonic measurements were carried out at a distance of 12.5 m for 10 seconds with a sampling rate of 250 kHz. The measurements consisted of a raw audio signal measured in microvolts and in the frequency spectrum, both of which vary over time. Figures 4 show the amplitude and frequency spectrograms at different voltage intensities for each test condition.

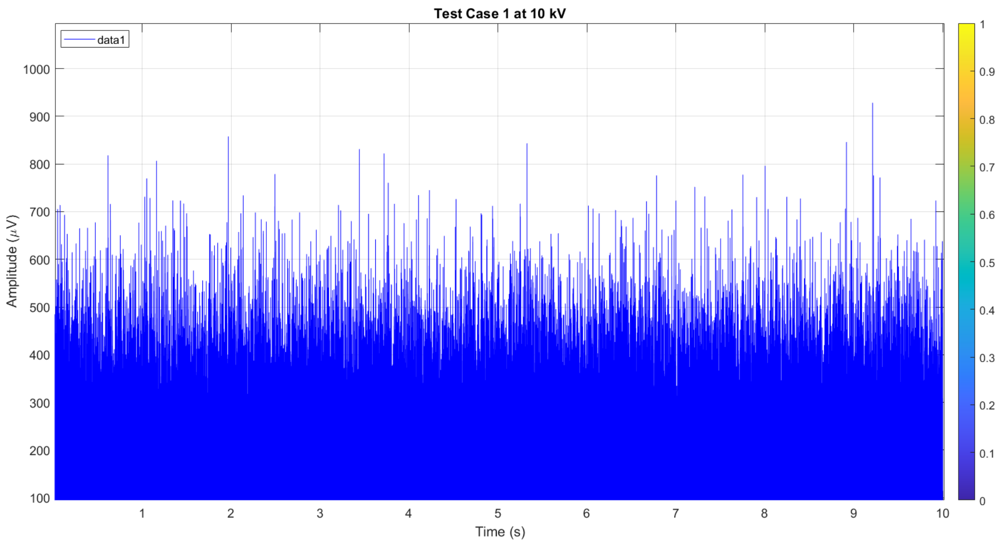

FIGURE 4. Amplitude and frequency spectrogram of the ultrasound signal for the test state at a voltage of 10 kV.

An experimental test showed that the measurement time of 10 seconds was sufficient to determine the occurrence of PDs. This duration allows the operator to control the digital ultrasound Tester without noticing fatigue or vibration along the insulator chain, thus facilitating experimental measurements.

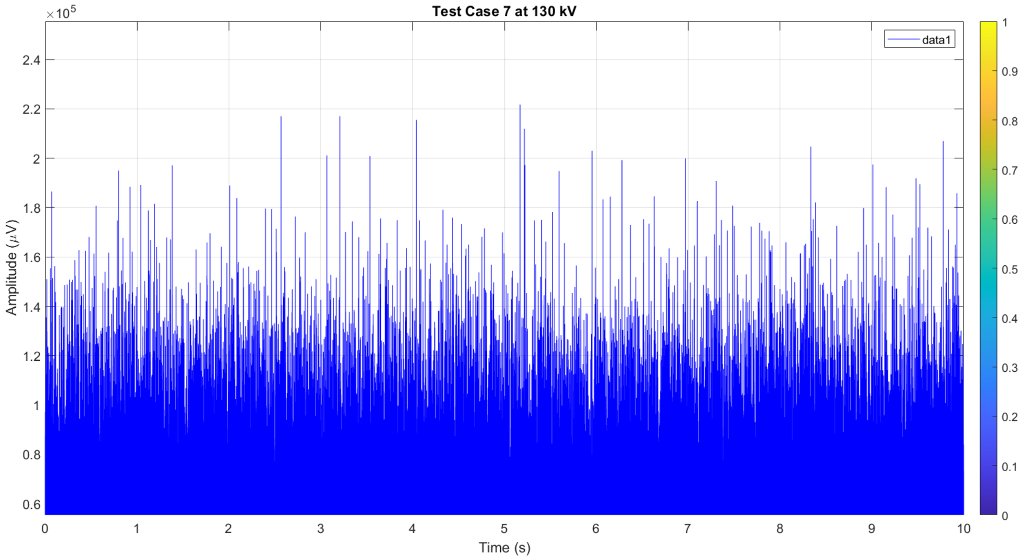

FIGURE 5. Amplitude and frequency spectrogram of the ultrasound signal for the test state at a voltage of 130 kV.

The measurement time of 10 seconds was shown to be sufficient to determine the occurrence of PDs. This duration allows the operator to control the digital ultrasound tester without noticing wear or vibration along the insulator chain, and thus facilitates experimentalof the dimensions.

CONCLUSIONS

Identification and classification of PDs by acoustic inspection can be a powerful predictive maintenance tool. Acoustic signals, without pre-processing and covering a wide frequency range (0 to 120 kHz), contain large amounts of data both in the audible spectrum (<20 kHz) and in the ultrasound spectrum (>20 kHz). When appropriate techniques are used, they allow a more accurate diagnosis of PDs. A test case of artificial contamination was performed on high-voltage glass insulators, resulting in various physical conditions and different levels of tension, such as mud accumulation, conductive microfilm formation, and damage. Thus, some conditions have been partially illuminated by the results of the following test to determine the formation of PDs and predict the working condition of the insulators through modern structures.

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