Application of Wavelet Analysis to Feature Extraction of Noisy Corona Discharge Signals

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Abstract

As transmission line voltages increased in time, corona occurring on conductors had more importance in terms of both corona losses, their impact on power transmission as well as leading to electromagnetic interference. One of the major challenges of corona discharge measurements is separation of corona signals from different type of noises resulting from measurement circuit or surrounding environment. In this paper, wavelet analysis based de-noising was used to separate corona discharges from noisy data obtained during the measurements. For that purpose, necessary procedure for accurate de-noising of corona discharge signals was defined. Obtained results by following the wavelet based de-noising procedure indicate that de-noising and future extraction of corona signals acquired from high-voltage devices by using the proposed method is successful to remove noise from the measured data as effectively as possible while preserving the signal features.

1. Introduction

Partial discharges (PD) are localized electric discharges that do not bridge the whole distance between electrodes, which can be classified in three different groups because of their different origins: (1) corona discharges, (2) internal discharges and (3) surface discharges [1]. Like the other discharges, recognition and evaluation of corona discharges is of great importance, because corrective actions can be planned and implemented, resulting in reduced losses and unscheduled downtime.

Discharge monitoring is an effective on-line predictive maintenance test for high voltage equipment. Condition monitoring based decision-making processes has also found wide application in recent years. The benefits of on-line testing allow for equipment analysis and diagnostics during normal operation. An understanding of the relationship to early detection of such discharges is required to properly evaluate the data obtained during such monitoring and testing purposes. It is known that during the all mentioned applications it is not always possible to reach the correct outcome with time domain evaluation and sometimes necessary to use special data processing and evaluation techniques. Moreover, there are factors (environmental conditions, material properties, voltage-current characteristics) that may affect the signals emerging during testing or being under operation for high-voltage equipment. Therefore, understanding and evaluation of those signals are an important process [2].

Data acquired by experiment and measurements may contain a certain amount of noise that relies on measurement set-up or external factors. Sometimes the noise level may be high enough to mask the main signal. The major challenge for discharge measurements is separation of corona signals from the noise interfacing with the measured data. The most dominant noise components are white noise, sinusoidal continues noise and pulse-like noise. When the noise level is high enough, it might not be possible to distinguish PD signal parameters from the recorded data. In this case, noise component should be suppressed as possible and separated from the main data.

This paper will present an implementation and measurement techniques that have evolved in the industry for corona discharge recognition systems. For that purpose, a set of tests was performed at Istanbul Technical University - Maslak High Voltage Laboratory and the obtained data were analyzed with the proposed wavelet de-noising method.

Wavelet analysis is used to as a good measure for de-noising noisy PD data [3, 4, 5]. However, it is necessary to be so careful when dealing with noisy discharge data in order not to distort main pulses and effectively define the basic parameters of them. In this study, the wavelet analysis is used in order to increase the effectiveness of de-noising of corona discharge data. During the de-noising process of discharge data, major difficulties are selection of mother wavelet, decomposition level and thresholding rule & function, which affect the evaluation of discharge characteristics [6].

The aim of this research is to study the effectiveness and appropriateness of wavelet analysis for de-noising of noisy corona discharge data. Throughout the simulation tests for corona discharges under high voltages, the discharge events were recorded and stored together with the instantaneous value of the test voltage. After applying the proposed de-noising procedure, results indicate more visible corona discharges with measurable basic parameters such as discharge amplitude, discharge duration and time of occurrence.

2. Wavelet Analysis

Wavelet analysis is an effective time-frequency signal processing tool. Similar to Fourier transformation that produces the projection of signal in frequency domain, wavelet analysis is the projection in time-frequency domain. Continuous Wavelet Transform (CWT) of $x(t)$ is given by (1), where the transform breaks up the signal into shifted and scaled versions of a mother wavelet $\psi(t)$ [7].

$$CWT(\tau,a)=\frac{1}{\sqrt{a}}\int_{-\infty}^{\infty}x(t)\psi^{*}(\frac{t-\tau}{a})dt \quad (1)$$

τ and a are translation and scaling parameters, respectively. The discrete form of the CWT is obtained by sampling the time-scale plane. DWT is expressed by (2) where n, b and a are the discrete versions of t, τ and a, respectively [8].

$$DWT(a,b)=\frac{1}{\sqrt{a}}\sum_{n}x(n)\psi^{*}(\frac{n-b}{a}) \quad (2)$$

The general form of discrete wavelet the approximation and detail sequences at level $j+1$ are related to earlier sequence that is level j. Equations (3) and (4) give approximation and detail coefficients at higher level, where $h_0(k)$ and $h_1(k)$ are wavelet and scaling filters, respectively.

$$c_{j+1}(k)=\sum_{m}h_0(m-2k)c_j(m) \quad (3)$$

$$d_{j+1}(k)=\sum_{m}h_1(m-2k)c_j(m) \quad (4)$$

3. Corona Discharge Measurement Set-up

A typical partial discharge measurement circuit where the test object is grounded directly is given in Fig. 1 [1]. In this figure HVT is a High Voltage Transformer, U is applied voltage, C_a is a test object (basic electrodes producing discharges at some specific voltage levels), C_c is the coupling capacitance, Z_m is the measuring impedance, Z_n is a resistance protecting the circuit from high currents. When the capacitance of test object is low and isolated from the ground, measuring circuits in which the test object is connected to measuring impedance in serial arrangement can also be used. During the measurement signal obtained from the measuring impedance with four terminals was connected to an oscilloscope in order to record the data for further processing.

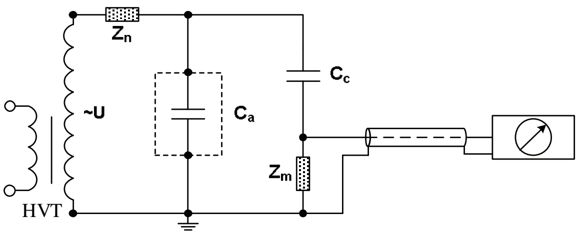
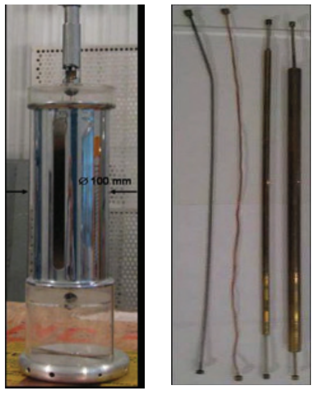


Fig. 1. Partial (corona) discharge measuring circuit.

During the tests, in order to investigate different sources of corona discharges, a coaxial electrode system with wire electrodes (simulating corona discharges) has been used. Those electrodes and the housing are shown in Fig. 2. Fig. 2a shows the external housing for the coaxial arrangement having 100 mm diameter. It is possible to use different wire electrodes having different properties inside this housing for the corona studies as it is shown in Fig. 2b.



a b

Fig. 2. a) Coaxial electrode system; b) Wire electrodes.

Figure 3 below gives the dimensional and material based characteristics of the wire electrodes used in the coaxial arrangement.

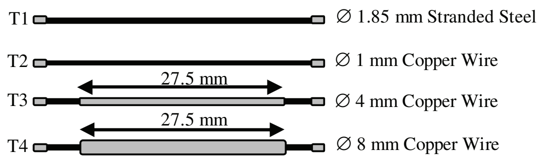


Fig. 3. Stranded steel and copper wires used for the tests.

The overall test set-up at Istanbul Technical University Maslak High Voltage Laboratory is shown in Fig. 4. High voltage is applied to wire electrode inside the coaxial electrode and housing is connected to the ground via serial measuring impedance. 100 kV High Voltage Transformer is used to apply high voltage to test object.

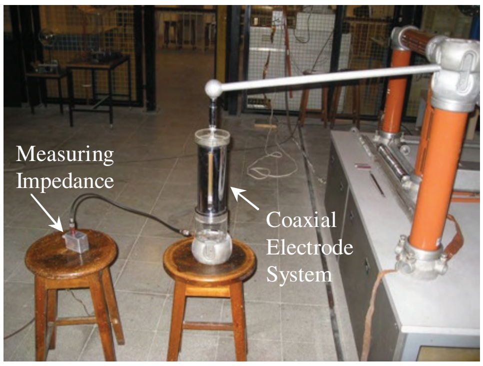


Fig. 4. Test set-up.

3. Measurements

After placing the test objects between the high voltage source and measuring impedance, high voltages with increments applied to wire electrodes and all necessary data for the evaluation were recorded usually more than 2 AC cycles.

Although the tests were repeated for all wire electrodes explained earlier (Fig. 3), obtained voltage vs. time from the leads of measuring impedance, when the stranded wire electrode ∅ 1.85 mm (T3) is used inside coaxial cylinder arrangement, is given in this study. An oscilloscope with sampling frequency of f_s = 4 MHz was utilized to record the data. When the voltage was increased the first remarkable discharge value was obtained at 12.2 kV, which is the inception voltage level. When reducing the voltage back to zero level, 12 kV voltage level was recorded as extinction level. Three different voltage levels were used to record corona discharge waveforms as 14.9 kV, 16 kV and 17 kV. Figure 5 indicates the obtained noisy corona discharge waveforms. In order to see the noise interference better, a close view of noisy signal at 17 kV for the duration between 10 ms and 35 ms is given in Fig. 6.

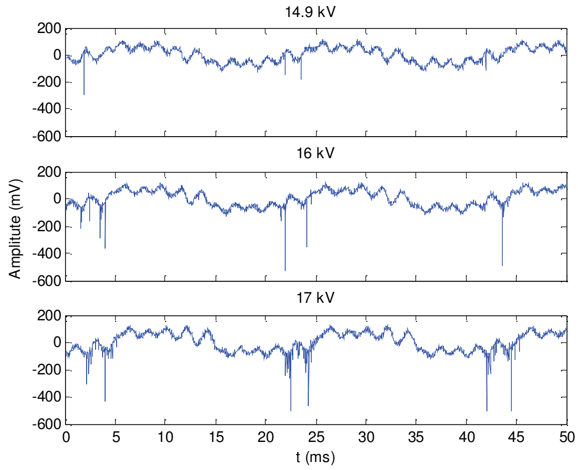


Fig. 5. Noisy corona discharge signals.

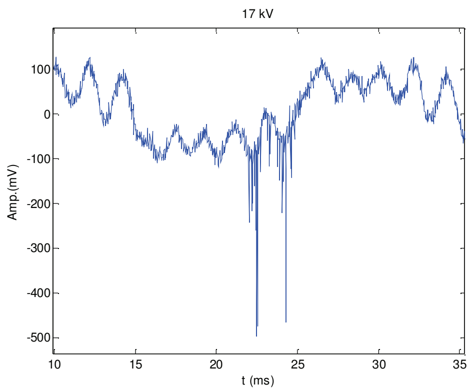


Fig. 6. A close view of 17 kV noisy discharge waveform.

As it is seen from the figures given in Fig. 5 and Fig. 6, it is necessary to separate corona discharge pulses from the existing noise interference in order to define the exact parameters such as magnitude, duration and time of occurrence of discharge pulses. A conventional filtering method based on such as Fourier Transform will not be a good solution since noise frequency spectrum covers the all frequency axes as shown in Fig. 7. Therefore it is necessary to use time-frequency signal processing tool like wavelet analysis.

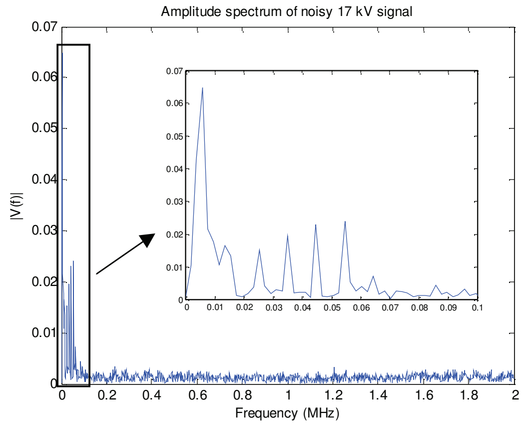


Fig. 7. Frequency spectrum of noisy corona discharge waveform obtained at 17 kV.

6. De-noising Procedure and Results

An adequate noise suppression method should guarantee the extraction of signal of interest with the minimum attenuation and distortion. Wavelet based de-noising procedure was defined in our earlier study [6]. The procedure can be defined as the following steps;

- *Decomposition:* Defining a suitable mother wavelet and maximum decomposition level and then computing the wavelet coefficients in each level.
- *Thresholding:* Defining threshold values for each level and applying appropriate threshold on coefficients.
- *Reconstruction:* By using the modified wavelet coefficients reconstructing the signal with inverse wavelet transform.

Mother Wavelet

The first step of wavelet de-noising process is to select wavelet function. The right mother wavelet enables better reconstruction and enables more accuracy. If selected wavelet matches well with the shape of the signal of interest, larger wavelet coefficients associated with the corona signal are obtained. Correlation between the corona pulses and mother wavelet has been used in order to define the best suitable mother wavelet for the analysis. A total of 23 wavelet functions from different families such db, sym and coif are used during the evaluations and the highest correlation value was achieved with coif2.

Decomposition Level

The sampling frequency of simulation was f_s = 4 MHz. Generally, it is not necessary to fully decompose the signal if the signal energy is concentrated in part of the frequency spectrum. In this context, by using selected coif2 wavelet, energy distribution of signal to the decomposition level of 10 has been calculated and realized that decomposition level of 5 provides sufficient performance for the decomposition of noisy discharge waveform.

Thresholding Rule and Thresholding Function

The objective of wavelet de-noising is to estimate the signal of interest $s(n)$ from the noisy signal $f(n)$, where $e(n)$ is the noise component (5).

$$f(n) = s(n) + e(n) \tag{5}$$

Level Dependent Threshold (LDT) proposed by X. Ma et al all [3] had been found the most suitable thresholding rule in our study [6].

$$\lambda_j = \frac{m_j}{0.6745}\sqrt{2\log(n_j)} \tag{6}$$

In (6) λ_j is threshold value at level j, m_j is the median value of the coefficients at level j, n_j is the number of coefficients associated with level j [3]. Best thresholding function was combined thresholding function as it was given in [6].

Following above given steps and defined de-noising parameters obtained results are given in Fig. 8. As it seen from these figures, it is now feasible to define waveform parameters such as discharge amplitude, discharge duration and time of occurrence more accurately. Even small corona discharges are detectable by using this method.

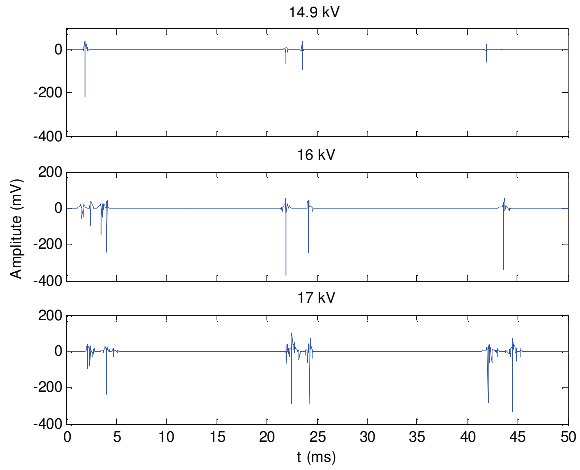


Fig. 8. De-noised corona discharge waveforms at three different voltage levels (De-noised version of Fig. 5).

Since there is no reference signal in recorded data to compute SNR (Signal to Noise Ratio) in order to quantify the de-noising performance, we can only talk about the reduction in noise level (RNL), where NS represents the noisy signal, DS represents the de-noised signal, N is data length. The related expression is given in (7).

$$\text{RNL (dB)} = 10 * \log \Sigma\ (1/N * (NS(i)-DS(i))^2) \tag{7}$$

High RNL indicates better noise suppression. For the 17 kV corona discharge signal improvement in SNR (RNL) value was defined as 41.89 dB, which is remarkably high value indicating better de-noising performance while preserving the original signals as much as possible.

6. Conclusions

In order to understand the basic discharge characteristics of corona occurring on high voltage transmission lines as well as other high voltage equipment and detect their existence with suitable measuring devices, a set of corona discharge measurements were performed at Istanbul Technical University Maslak High Voltage Laboratory.

Simulation tests for corona discharges by using the basic electrode configurations under high voltages revealed that during the tests discharge waveforms were affected by noise. Especially on site measurements are affected by electromagnetic interference which makes sensitive corona measurement more difficult. For those reasons, it is necessary to have a de-noising tool or algorithm that deals with this problem. In this study, a wavelet-based de-noising procedure was proposed and applied to noisy corona discharge data.

For this purpose mother wavelet, decomposition level and thresholding rule & function were defined for the efficient feature extraction of noisy corona discharge signals obtained from a test set-up or online condition monitoring systems. All these defined parameters were used in Discrete Wavelet Transform and signal having remarkable noise before the analysis turned to clear signal revealing corona discharge pulses after the analysis. Improvement in SNR was 41.89 dB.

Results show that de-noising and future extraction on signals acquired from high-voltage devices by using the proposed method is effective. This procedure can also be used for other common type of signals in high-voltage area. In that case, optimum parameters of analysis should be defined for the signal of interest by following the steps defined in this study.

7. References

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