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Detection of online PD signals in XLPE cables using the Bhattacharyya distance

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Abstract: Partial discharge (PD) signal detection can be used for insulation monitoring of power system equipment. Online PD detection as a main task of insulation monitoring for different power system equipment is a difficult procedure when environmental noise is taken into account. This paper proposes a new scheme based on the Bhattacharyya distance approach with the main goal of detecting the PD signals in cross-linked polyethylene cables. The proposed method, as a preprocessing tool, can be used for detection of PD signals in a noisy environment. The simplicity and the accuracy of the Bhattacharyya distance approach are the 2 main advantages that grab the attention of the authors in introducing this technique for detection of PD signals in different high-voltage power devices. In order to remove noises between intervals of measurement of PD signals, other simple signal processing techniques should be used as postprocessing tools. Detection of PD signals in a noisy environment, i.e. finding the times of PD occurrences, is the most important and difficult stage in online PD signal monitoring. The Bhattacharyya distance method is a simple approach that can be used for detection of short duration time signals such as PDs.

Key words: Condition monitoring, failure detection, partial discharge, cross-linked polyethylene cables, Bhattacharyya distance

1. Introduction

Online condition monitoring is a mandatory task for fault detection and analysis of power system equipment in an uninterrupted process of measuring quantities such as currents, voltages, active and reactive powers, temperatures, and harmonics. Applying online monitoring, it would be possible to diagnose the main causes of failures occurring in electrical industry appliances. Detection of partial discharge (PD) signals has been introduced as a main task in applying condition monitoring processes in power systems. For most of the failures associated with insulation breakdown in high-voltage devices, the PD can be a sign leading to early diagnosis of failures. It was reported that most of the observed failures in high-voltage devices arise from insulation failures [1]. In the beginning stages of these failures, usually only the PDs occur, although in some cases these failures may result in a total breakdown of the device [2,3].

In condition monitoring processes, based on the magnitude and occurrence rate of the PDs, the condition of the device insulation can be determined and sudden insulation outages in the power system can be prevented. The PD signals are current impulses with high frequency content and very short pulse width. In cross-linked polyethylene (XLPE) cables, the PDs occur in the air-filled cavities, and in oil power transformers they occur in the bulbs filled with air, humidity, and voids in the paper insulation [4]. The insulation strengths of these cavities and bulbs are less than in other parts of the insulation and result in the PD occurrence.

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For detection of the PDs, electrical and nonelectrical techniques can be used. It has been shown that electrical methods are usually more sensitive than nonelectrical ones [5]. Therefore, many of the available standards recommend applying electrical methods in diagnosing PDs in the equipment of power systems. Two different offline and online modes can be considered in the detection of the PDs in power equipment. In the online mode different parameters such as currents, voltages, or temperatures can be monitored, so fault detection can be performed more accurately and quickly. Compared with the online mode, using the offline mode measurements are gathered in discrete intervals and PDs may occur between the intervals. This can be translated to an inability of the condition monitoring system in diagnosing the PD signals and therefore the probability of insulation failure occurring is increased [6].

In power systems, different noises such as radio waves, power electronic firing pulses, coronas, and switching waves exist. These noises affect the PDs and, in online monitoring, it is difficult to detect the PD signals from among them. In this regard, signal processing methods must be applied for removing the noises from PD signals. So far, a lot of research has been conducted in the area of denoising the PDs in XLPE cables. In [7], maximum likelihood estimation and deconvolution were utilized for noise reduction in measurements of shielded cables. In [8], analog/digital notch filters were used with the minimum target of an AM broadcast noise removing process, and an adaptive digital filtering scheme that incorporates a cable transfer function was used for more accuracy.

In [9–11], analog to digital conversion schemes and open/close loop noise reduction techniques were investigated as two methods in the context of PD detection. In [12], digital filtering, frequency spectrum analysis, PD waveform miscorrelation, and wavelet transforms were applied for denoising of polluted PD signals. In [13,14] an adaptive filter was used for PD signal detection in noisy environments. Instead of a software method, the directional coupling sensors and electro-optic modulators were used as 2 hardware methods in [15,16] for denoising of PD signals. In [17], time domain features were used, known as short-time energy and short-time zero-crossing counts, for PD detection in XLPE cables. The wavelet transform is widely used for denoising of PD signals in XLPE cables [18–20].

Complementing past works, this paper proposes a new scheme based on the Bhattacharyya distance approach with the main goal of detecting PD signals in XLPE cables. The proposed method, as a preprocessing tool, is used for detection of PD signals in a noisy environment. The simplicity and the accuracy of the Bhattacharyya distance approach were the 2 main advantages that grabbed the attention of the authors in introducing this technique for detection of the PD signals in different high-voltage power devices. In order to remove the noises between intervals of the PD signal measurement, other simple signal processing techniques should be used as a postprocessing tool. Detection of PD signals in a noisy environment, i.e. finding the times of PD occurrence, is the most important and difficult stage in online PD signal monitoring. The Bhattacharyya distance method is a simple approach that can be used for detection of short duration time signals, such as PDs.

The remaining sections of this paper are organized as follows. The measurement circuit and related sensors that are used for detection of the signals in XLPE cables are explained in the second section. The proposed method for detection of the PD signals is introduced in the third section. In the fourth section, the proposed technique is implemented on several PD signals occurring in XLPE cables and the effectiveness of the approach is investigated. Finally, the paper's conclusion is given in the last section.

2. PD detection circuit

For online detection of PD signals occurring in XLPE cables, the circuit in Figure 1 is suggested. The circuit consists of a high frequency current transformer (HFCT), coaxial cable, oscilloscope, and computer. Because of the high frequency content of PD signals, the sampling frequency of the test circuit is considered to be 100 mega samples per second and so the applied apparatus must operate with good accuracy at these frequency ranges.

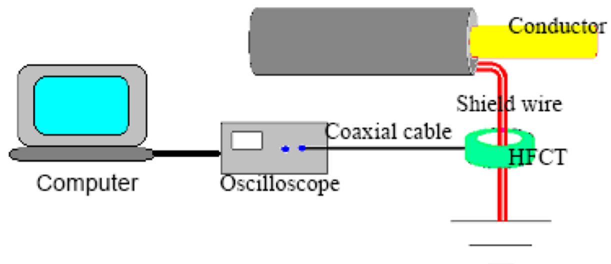

Figure 1. Online PD signal detector circuit of an XLPE cable.

In a substation, the cable shields are connected to the ground through the ground wire. As can be seen in the measurement circuit, the ground wire is passed through the HFCT and then connected to the ground. When PD occurs in the cable, it travels to the ground through the shield and the ground wire. Based on Ampere's law, the PD currents generate a magnetic field in the outside area, i.e. in the HFCT, and induce a current proportional to the PD magnitude in the secondary winding of the HFCT. This induced current is transferred to the oscilloscope using a coaxial cable. The PD signals that are shown on the oscilloscope screen incorporate noises. The noisy PD signals are recorded and transferred to a computer for detection and denoising.

The waveforms associated with the 4 different types of PDs are presented in Figures 2–5. They are respectively related to the corona discharge, PD occurring in the cylindrical cavities, PD arising from the fixed metallic particle, and surface discharge. As can be seen in these figures, the duration times of PD signals are very short. Therefore, an efficient method needs to be applied, aimed at detecting and denoising these PD signals. In this paper, the Bhattacharyya distance method has been proposed to reach this important target.

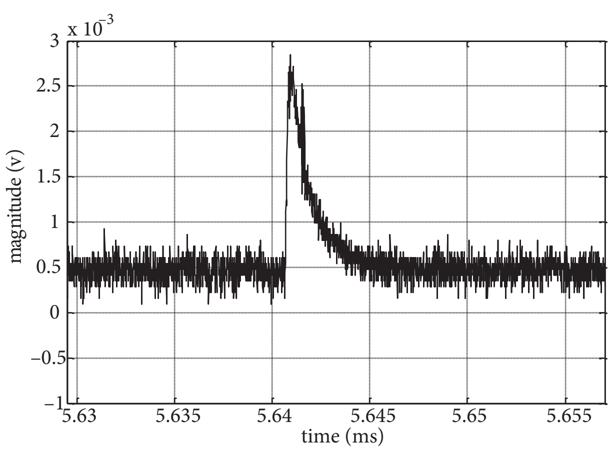

Figure 2. The waveform of corona discharge.

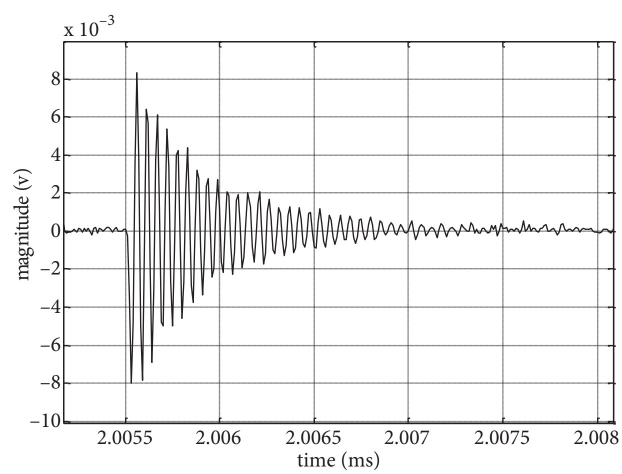

Figure 3. The waveform of PD signal occurring in the cylindrical cavity.

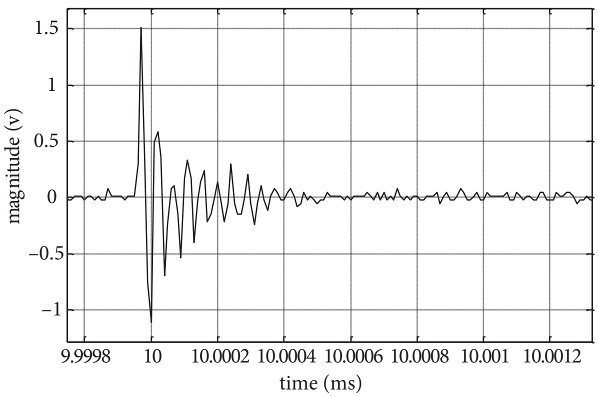

Figure 4. The waveform of PD signal arising from a single metallic particle.

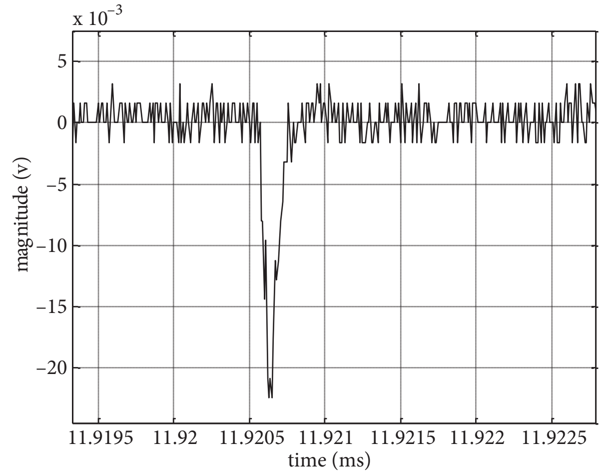

Figure 5. The waveform of surface discharge.

3. Bhattacharyya distance method

This section first discusses a mathematical model of the PD signals, then briefly introduces the main principles associated with the Bhattacharyya distance technique and presents the implementation procedure of this method suggested for denoising and detection of PD signals.

3.1. Statistical and mathematical model of PD signals

A mathematical model of the PD signals can be presented as follows:

$$x_{pd}\left(t\right) = h\left(t\right) * s\left(t\right) = \Sigma_k a_k s\left(t - t_k\right) \tag{1}$$

where:

$$h\left(t\right) = \Sigma_k a_k \delta(t - t_k) \tag{2}$$

In Eq. (1), the signal $s(t)$ refers to the PD signal, which depends on the occurrence time of the PDs. This signal has a finite period time T. In other words:

$$s\left(t\right) = 0, t \notin [0, T] \tag{3}$$

The PD signals are impulse signals occurring at time t_k with a magnitude of a_k. The difference time between t_k and t_j, is considered to be long enough so that no overlapping can be seen between $s\left(t - t_k\right)$ and $s\left(t - t_j\right)$. The other assumption is that the PD signal $\left(x_{pd}\right)$ at most times is 0 and only in a short duration interval (after t_k) is it not 0, i.e. $s(t)$ has nonzero value.

The mathematical model of the noisy PD signal $\left(y_{pd}\right)$ can be presented as shown in Eq. (4):

$$y_{pd}\left(t\right) = x_{pd}\left(t\right) + n\left(t\right) = \Sigma_k a_k s\left(t - t_k\right) + n(t) \tag{4}$$

where $n(t)$ is an additive noise.

Based on inherent features of the PD signals, it can be concluded that for noisy PD signals$\left(y_{pd}\right)$:

- At time t, when the PD signals ($s(t)$) are zero, only the noises are available.
- At time t, when the PD signals ($s(t)$) are nonzero, PDs with the noises ($n(t)$) are available.

On the other hand, the mathematical form of a PD signal can be presented as:

$$y_{pd}(t) = \begin{cases} a_k s(t - t_k) + n(t) \, \exists k, & t \in [t_k, t_k + T] \\ n(t) \, \forall k, & t \notin [t_k, t_k + T] \end{cases} \tag{5}$$

Modeling the PDs as the signal shown in Eq. (5) calls for a proper statistical distance. In this regard, it is first required to obtain the probability distribution function (pdf) of the noisy signal ($y_{pd}(t)$). To reach this function, it is assumed that the noise $n(t)$ is independent of the PD signals and also that the PD signal is deterministic. Taking into consideration these two assumptions, the pdf of noisy signals can be considered as shown in Eq. (6):

$$p_y(y_{pd}) = \begin{cases} p_n\left(y_{pd} = a_k s(t - t_k) + n(t)\right) \exists k, & t \in [t_k, t_k + T] \\ p_n(n(t)) \, \forall k, & t \notin [t_k, t_k + T] \end{cases} \tag{6}$$

where $p_n(n(t))$ is the pdf of the noise $n(t)$.

Since most types of available noises in the power substations can be modeled by a Gaussian pdf, it is considered that the noise also follows the Gaussian distribution with zero mean and σ^2 variance, $N\left(0,\sigma^2\right)$. Taking into account this assumption, the probability mass function (pmf) of the noisy signal would be as presented in Eq. (7):

$$p_y(y_{pd}) = \begin{cases} N\left(a_k s(t - t_k), \sigma^2\right) \exists k, & t \in [t_k, t_k + T] \\ N\left(0, \sigma^2\right) \forall k, & t \notin [t_k, t_k + T] \end{cases} \tag{7}$$

The pdf of PD and that of noise signals has different mean values. Consequently, this parameter, i.e. mean values of the signals, can be utilized with the main goal of detecting the PD signals from the Gaussian noises. However, only the mean value of the PD signal is dependent on the PD signal, which is not available. In this stage, PD signal recognition is required, and for this purpose the statistical distance between the 2 distributions should be obtained.

3.2. Bhattacharyya distance

The Bhattacharyya distance technique has been applied for epileptic seizure detection and phone clustering [21,22]. This method has proved its abilities in extracting the main features of signals with short duration time in noisy signals. The Bhattacharyya distance is the theoretical distance between 2 Gaussian distributions and is equivalent to the upper limit of the classified error. For 2 distributions, $p(x)$ and $q(x)$, the Bhattacharyya distance is defined as follows:

$$D_B(p,q) = \frac{1}{8}(m_1 - m_2)^T P^{-1}(m_1 - m_2) + \frac{1}{2}\ln\left(\frac{\det(P)}{\sqrt{\det(P_1)\det(P_2)}}\right) \tag{8}$$

where m_i and P_i are the mean value and covariance matrix of the distribution, respectively, and $P = \frac{P_1 + P_2}{2}$.

The first term in Eq. (8) is the difference between distribution mean values (separation), and the second term is the decomposition of the 2 distributions due to the difference in their covariance matrix. The classification error between 2 classes is calculated as shown in Eq. (9):

$$\epsilon \leq \sqrt{p_{w_1} p_{w_2}} \exp\left(-D_B\right) \tag{9}$$

where p_{w_1} and p_{w_2} are the probability of the occurrence of the classes, w_1 and w_2, respectively.

3.3. Proposed algorithm for detection and denoising of PD signals

The main idea for the detection and denoising of a noisy signal is the statistical similarity measurement between the 2 as investigated in Eq. (7). To employ the Bhattacharyya distance with the goal of denoising the PD signals, the pdfs of $p(x)$ and $q(x)$ should be defined as follows.

$p(x)$ represents the states only having noises. Therefore, this pdf can be modeled as $p(x) = N(0,\sigma^2)$. In other words, $m_1 = 0$, $P_1 = \sigma^2$. The Gaussian distribution is considered for the noises and σ^2 is estimated using Eq. (10) [23]:

$$\hat{\sigma} = \frac{median(|W_1^D|)}{0.6745} \tag{10}$$

where W_1^D is detail coefficients associated with the first scale of wavelet transform. Considering the assumption of the stationary characteristic for the statistical distribution of the noises at all times, the parameter of $p(x)$ for each signal is adjusted for one time and is fixed for the other remaining times.

$q(x)$ is related to the state with PD signals involved with noises. The signal $z(t)$ is defined as in Eqs. (11) and (12) to estimate parameters, m_2 and P_2 at arbitrary time t_0.

$$z\left(t\right) = y_{pd}\left(t\right) \Pi\left(\frac{t - t_0}{T_w}\right) \tag{11}$$

$$\Pi\left(\frac{t}{T_w}\right) = \begin{cases} 1 & |t| \leq \frac{T_w}{2} \\ 0 & |t| > \frac{T_w}{2} \end{cases} \tag{12}$$

It is considered that the signals are ergodic and parameters m_2 and P_2 are estimated as in Eqs. (13) and (14), respectively.

$$\hat{m}_2 = \frac{1}{T_w} \int_{-T_w/2}^{T_w/2} z\left(t\right) dt \tag{13}$$

$$\hat{P}_2 = \frac{1}{T_w} \int_{-T_w/2}^{T_w/2} \left(z\left(t\right) - \hat{m}_2\right)^2 dt \tag{14}$$

For detection of PD signals, based on the Bhattacharyya distance, the following algorithm is proposed. The sampling rate of the PD signal is considered to be f_s. In this paper 100 MHz is considered for the sampling frequency of the PD signals.

Initialization

$$\mathbf{T_w} = \frac{\mathbf{N_w}}{\mathbf{f_s}} \mathbf{m_1} = \mathbf{0}, \mathbf{P_1} = \left(\frac{\mathbf{median}\left(|\mathbf{W_1^D}|\right)}{\mathbf{0.6745}}\right)^{\mathbf{2}},$$

$$\text{For } \mathbf{k} = \mathbf{1} : \mathbf{N}(\text{Length of } PD \text{ signal})$$

$$\mathbf{z_k(nT_s) = y_{pd}\,(nT_s)\,\Pi\left(\frac{nT_s{-}kT_s}{nT_s}\right)}$$

$$\mathbf{m_2{=}\ 1/N_w \sum_n z_k(nT_s)}$$

$$\mathbf{P_2{=}\ 1/N_w \sum_n \left(z_k\,(nT_s)\,{-}m_2\right)^2}$$

$$\mathbf{Dist\,(k)\,{=}D_B\,(p,q) = D_B(m_1P_1m_2P_2)}$$

$$\mathbf{Dist = Dist - E[Dist]}$$

$$\mathbf{Dist = abs(Dist)}$$

$$DI = \text{ Dist, Detection Index } (DI)$$

Using the proposed technique, by inserting a simple threshold into the detection index, the trend of PD signals (the times that the PDs occurred) can be detected. For a noisy signal, in which the PDs do not exist, the detection index is very small. In contrast, as long as the PDs are available in the signal under study, the value of the detection index would be increased. Based on this fact, detection of the PD signals can be performed as presented in Eq. (15).

$$x_{dn}\,(t) = DI(t){*}y_{pd}\,(t) \tag{15}$$

In this method, along with reducing the noises around PD signals, the PD signals can successfully be detected. In fact, this technique cannot recognize the PDs at times when both noises and the PDs are available. In order to extract the PD signal with high quality and without any noises, other typical denoising techniques can be used on $y_{pd}\,(t)$ only in the intervals where $DI(t)$ has significant value. The proposed technique is simple and can successfully detect the different types of PD signals. Implementation of the method for detection of the different PD signals is given in the next section.

4. Case studies

In this section, the proposed technique is implemented on different PD signals occurring in the XLPE cables and the ability of the method to extract different types of PD signals is investigated.

4.1. PD signals occurring in 11 kV XLPE cable

In these studies, voltages up to 25 kV are applied to the 11 kV XLPE cable conductor. In this condition, the PD occurs and the resulting PD signals are recorded. Using MATLAB software, different Gaussian noises (with low and high amplitude) are added to the PD signals. Then the proposed method is implemented on the noisy signals and, after a denoising process, the original PD pulses are extracted. The results are presented in Figures 6 and 7. In each figure, the first, second, third, and fourth diagrams, respectively, represent the original PD signals, the noisy signal (i.e. the PDs accompanied with the noises), the extracted PD signals, and the associated Bhattacharyya distance. Based on results illustrated in the figures, the Bhattacharyya distance approach can successfully remove the noises with low and high amplitude from the PD pulses. Moreover, the original PDs are extracted with good accuracy.

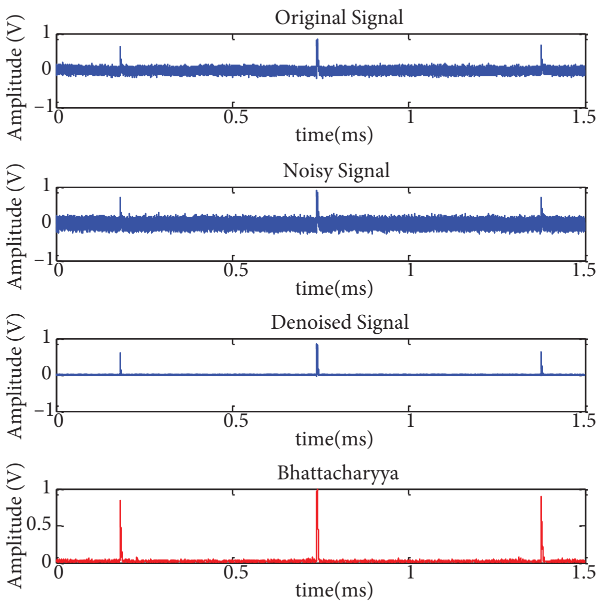

Figure 6. Denoising of PD in the 11 kV XLPE cable (low noise addition).

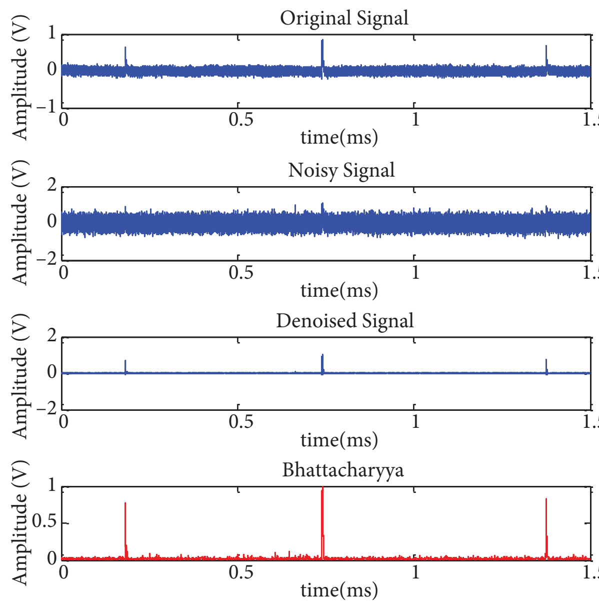

Figure 7. Denoising of PD in the 11 kV XLPE cable (high noise addition).

To more practically scrutinize the abilities of the proposed method, Gaussian noises with various signal to noise ratios (SNRs) were added to the generated PD signals. For each case, detected PD signals were extracted, associated SNRs were calculated, and the results are presented in Figure 8. As shown in the figure, the proposed technique can effectively perform the denoising procedure as long as the SNR values are low; however, at high SNR values, because of the original signal noises, the SNR does not increase. As can be seen in Figures 6 and 7, the original PD signals contain noises with low amplitude and, after the denoising process, because the original noises may be removed by the proposed method, the extracted PDs are available without the original noises and so the detected signal may be different from the original signal. Although the detection process is done successfully, in this condition the SNR value is negative.

4.2. PD detection due to cylindrical voids in XLPE materials

In aiming to examine the abilities of the proposed technique in detecting PD signals arising from cylindrical voids, several cylindrical voids were deliberately made in the XLPE materials. Once the high voltage source was applied to the XLPE cable, the PDs occurred. High amplitude Gaussian noises were added to the recorded PD signals, and the proposed method was then applied and the PD signals were extracted. These signals are presented in Figure 9. It is deduced from the figure that the proposed technique can successfully detect the PD signals arising from the cylindrical voids in XLPE materials.

4.3. PD detection due to fixed particle in XLPE materials

In this stage, a fixed metallic particle was extruded with the XLPE materials. Applying the high voltage, PD signals occurred. Then high amplitude Gaussian noises were added to the recorded signals. The proposed method was applied, and the denoised PD signals were extracted and are presented in Figure 10. From the figure it can be concluded that the proposed technique can successfully denoise the PD signals arising from fixed metallic particles in XLPE materials.

4.4. PD detection due to single voids in XLPE materials

In this test, only one void was made in the XLPE material. Once the high voltage source was applied to the XLPE cable, PDs occurred. High amplitude Gaussians noises were added to these signals. Using the proposed method, the denoised PD signals were extracted and are presented in Figure 11. It is deduced from the figure that the proposed technique can successfully denoise the PD signals arising from a single void in XLPE materials.

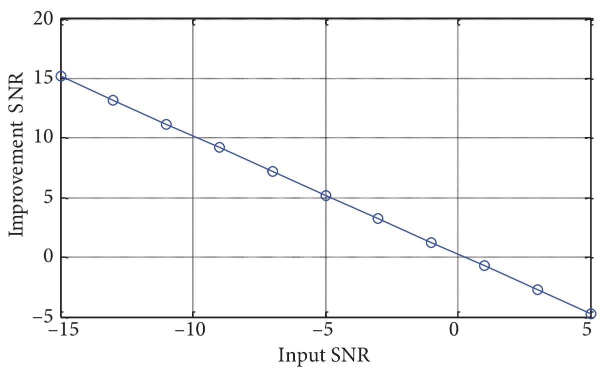

Figure 8. Improvement of SNR versus SNR of original signal.

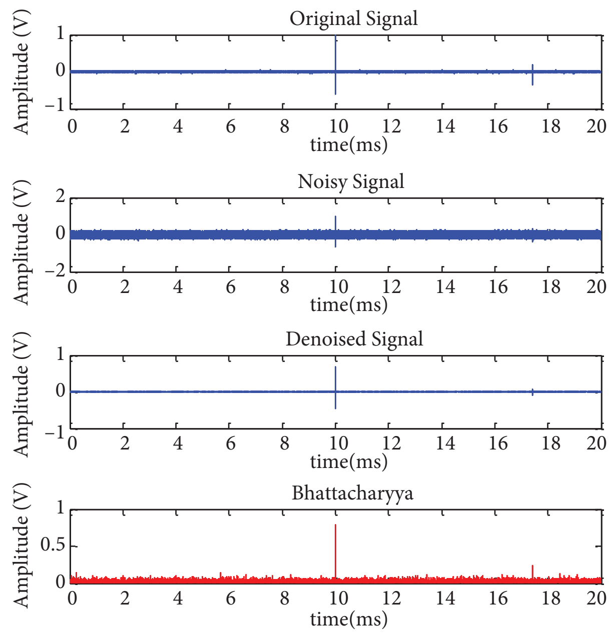

Figure 9. Denoising of PD in the cylindrical void (high noise addition).

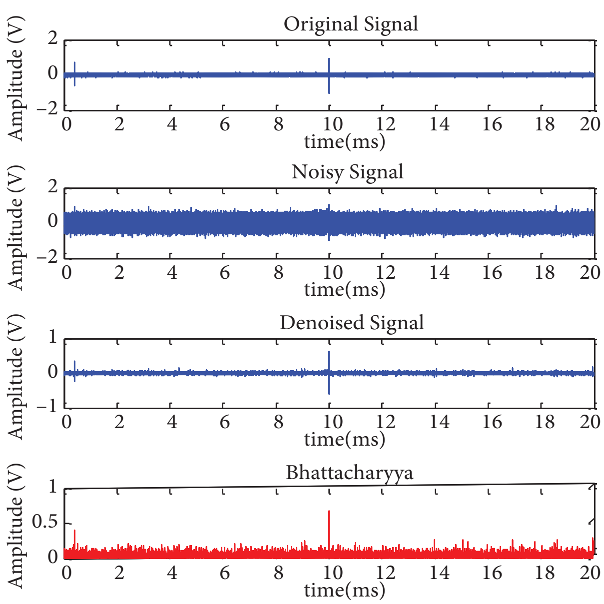

Figure 10. Denoising of PD arising from fixed metallic particles.

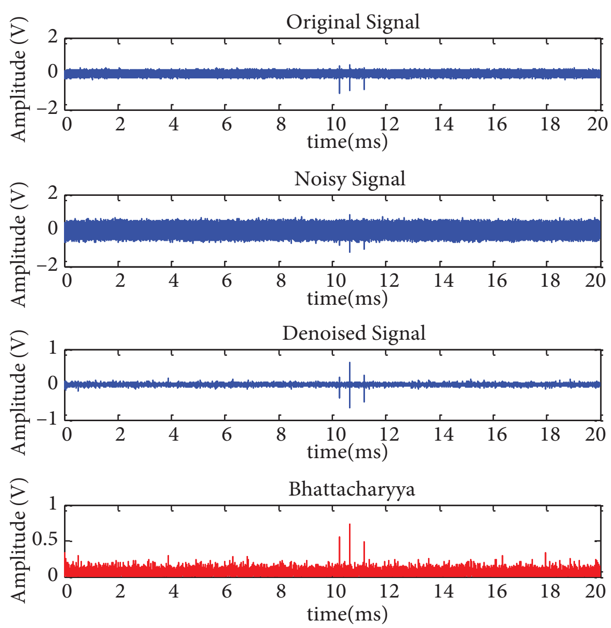

Figure 11. Denoising of PD arising from a single void in the XLPE materials.

4.5. PD detection due to multiple voids in XLPE materials

As in the other test, multiple voids were made in the XLPE material. On applying high voltage, PD signals occurred and were recorded. Gaussian noises were added to these signals. Following the proposed method, the denoised PD signals were extracted and are presented in Figure 12. It is deduced from the figure that the proposed technique can successfully denoise the PD signals arising from multiple voids in XLPE materials.

4.6. Surface discharge

In this stage, the surface discharge signals that occurred as a result of contamination of the insulation surface were recorded. Gaussian noises were added to the surface discharge signals. Then the proposed technique was applied and denoised signals were extracted. These signals are presented in Figure 13. It is deduced from the figure that the proposed technique can successfully denoise the discharge signals.

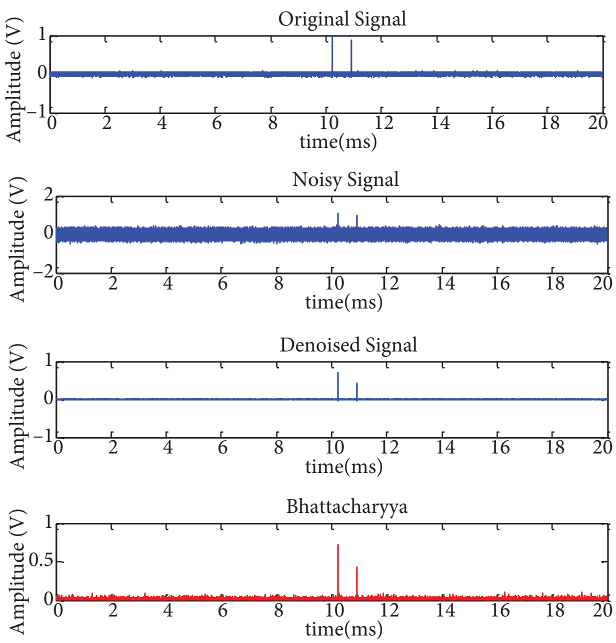

Figure 12. Denoising of PD arising from multiple voids in the XLPE materials.

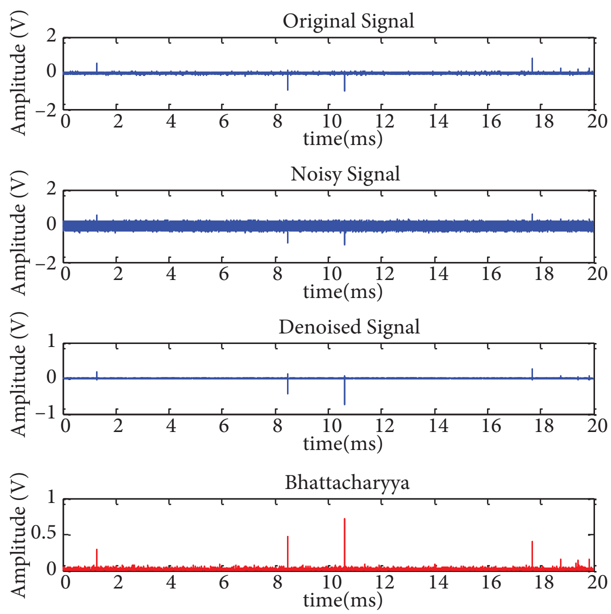

Figure 13. Denoising of surface discharge signals.

4.7. Corona discharge arising from needle

Corona discharges may occur when a cable is connected to another cable or device, such as at joints, cable endings, etc. Here a high voltage source was applied to a needle and a corona discharge occurred in the air around the top of the needle. The corona discharge signals were recorded and high amplitude Gaussian noises were added. Then, using the proposed technique, denoising was performed and the corona discharge signals were extracted. These signals are presented in Figure 14. From the figure, it can be concluded that the proposed technique can successfully denoise corona signals.

5. Conclusion

In this paper a new method based on the Bhattacharyya distance was proposed to detect PD signals and remove different noises from the PD signals in high voltage XLPE cables. The simplicity of the proposed method and

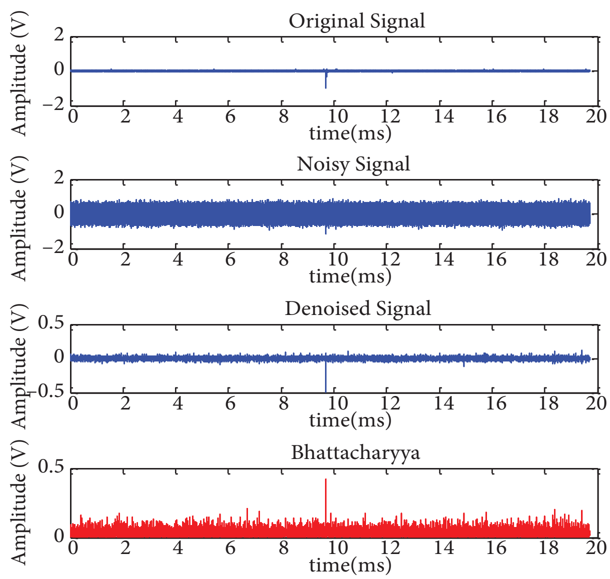

Figure 14. Denoising of corona discharge signals.

its accuracy were the 2 main advantages that made it attractive for PD signal detection of a high voltage apparatus. The mathematical model of the PD signals was described and then the Bhattacharyya distance algorithm applied for detection of these short duration signals was introduced. Then the proposed method, as a preprocessing technique, was applied to different discharge signals, including PD in 11 kV XLPE cables, PD in cylindrical voids, PD arising from fixed metallic particles, PD arising from a single void, PD arising from multiple voids, surface discharge, and corona discharge in the air. It was concluded from the results that this technique can successfully be used for detection of different types of PD signals originating from different sources.

As mentioned in this paper, the method can be used for denoising of signals with very short duration and it is not dependent on the shape of the signals. Although the noises in the region outside of the PD signals can be removed simply, this method cannot remove the other remaining noises, i.e. the noises that occur near the PDs. Besides, the non-Gaussian noises, i.e. random and impulse noises that are similar to PDs, cannot be removed with the proposed method. Thus, a postprocessing technique must be implemented on the resulted output signals, i.e. signals after Bhattacharyya distance application, and the PDs with high quality can be extracted. In future works, using a trained classifier or pattern recognition can remove the impulse noises and distinguish them from the PD pulses, and also a simple signal processing technique must be applied for removing the noises near the PD signals.

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