Partial discharge detection and identification at low air pressure in noisy environment

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Abstract
Increasing demand for electric power in more electric aircraft requires a higher operating voltage for the power system that leads to higher electric stress on the insulation system. Operating at high altitudes where the electrical strength of air is weakened exposes the insulation system to even higher levels of electrical stress. As such, the probability of partial discharges (PD), which result in insulation degradation and failure, is higher. The presence of switching circuits in the power distribution system of the more electric aircraft is capable of producing high levels of noise. This noise in combination with the background noise and parasitic impedances will cause high amplitude ringing in the measured partial discharge signal waveform. Here, a method based on the combination of the wavelet and energy techniques is employed to detect PD pulses in a noisy environment under the low air pressure condition. To verify the technique, a laboratory setup consisting of two separate PD sources mounted in low air pressure (33 kPa) chamber is developed where sine and square waveforms are used as the applied voltage. The obtained results demonstrate that the proposed approach offers low computational complexity, high performance in PD phase localization, and robustness in a noisy environment.

1 | INTRODUCTION

The ever-increasing electrification of the more electric aircraft has led to the replacement of heavy mechanical, hydraulic, and pneumatic-based systems with electrical systems to reduce the weight of the aircraft [1–4]. Since increasing the ampacity of the conductors is not a viable approach, the only option to meet the increased demand for more electric power is to increase the operating voltage [5]. However, the increased operating voltage imposes higher stress on the electrical insulation which increases the chances of failure [3, 6]. Furthermore, electrical insulation of minimum thickness is employed to enable aircraft manufacturers to ensure low-cost and compact design [7, 8]. Vibration, thermal ageing, humidity, pollution, and internal discharges are environmental factors that may cause insulation degradation during an aircraft operation. This kind of degradation causes insulation cracks and abrasion that leads to flashover between wires or surrounding metals [7, 9, 10].

The detection of insulation defects is primarily performed by visual inspection during maintenance. The reliability of manual inspection is not satisfactory as it may cause further damages to the insulation system. Therefore, a technique other than visual inspection is required to detect defects in the insulation system [7, 11]. The insulation defects reduce dielectric strength and lead to partial discharges (PD). Partial discharge is the formation of an electrical discharge that partially bridges the gap between two conductors. Occurrence of PDs will eventually result in insulation failure [6].

It is well known from Paschen's law that the dielectric strength of air is pressure dependent. An aircraft experiences a wide range of air pressure from ground level to the cruising altitude [12]. Compared to the ground level atmospheric pressure (101 kPa), the pressure at cruising altitudes is as low as 30% of the pressure at ground level. The dielectric strength of air decreases with altitude and this further increases the risk of partial discharges [13, 14].

The PD measurement, which is a widely-used diagnostic tool in electric power systems, can be used for monitoring the insulation condition; however, there are challenges associated with PD detection at low air pressure that are mainly due to the
frequency content of PD pulses at low air pressure and lower inception voltage [15]. Frequency content of low-pressure PD is in a lower range than that of ground-level pressure PD. For example, according to IEC 60,270 [16], in wide-band PD measurement, the lower cut-off frequency is between 30 and 100 kHz. However, the frequency content of PD pulses at low pressure may require that the bandwidth of the sensors and filters be adapted for PD measurement in low air pressure [6]. Also, the corona PD amplitude at low air pressure is very small when compared to the PDs at ground level condition [17]. Since the total number of PDs and PD pulse magnitude depends on the applied voltage amplitude, a lower PD inception voltage at low air pressure implies that PD pulses with a smaller magnitude might be active in the insulation system [18]. As a result, lower PD magnitude in conjunction with background switching noises has an impact on PD detection when traditional methods are used.

The use of multi-level voltage source inverters allows improvement in speed control of the induction motors by controlling the voltage level of PWM [6, 19]. An overvoltage is created during the switching operation of inverters. Partial discharges may occur during such repetitive overvoltage whose detection can be helpful in evaluating the insulation system [20].

At atmospheric pressure, the discharge pulse has a risetime of a few nanoseconds. However, under sub-atmospheric pressures, the PD pulse risetime is much longer, up to hundreds of nanoseconds [21, 22]. The risetime of a PD pulse is defined as the time required for a PD pulse signal to rise from 10% to 90% of its peak value. The frequency contents of a pulse depend on its risetime. Pulses with longer risetime have lower frequency content. At low air pressure, the frequency content of a PD pulse signal may be as low as the switching noises. Commercial filters are not able to detect and identify PD pulse sources at low air pressure. This is because the frequency content of PD pulses at low air pressure falls in the range of switching frequency.

In order to localise and detect PDs accurately, proper time domain filtering and signal processing techniques are necessary to be employed for the development of a PD source identification system. In [23], continuous wavelet transform (CWT) of the measured noisy corona PD signal has been calculated to highlight the arrival time of corona discharges. PD pulses have been extracted by removing the average of the measured signal to obtain non-stationary PD pulses [24]. In the presence of commutation noise due to the power electronic switches, PD identification has been performed by using the standard deviation of the measured PD signal to separate commutation noises from the PD pulses as the standard deviation of PD pulses has larger values at any instant of time [25]. However, simultaneous active PD sources and the effect of air pressure on PD source identification have not been taken into account. Using wavelet transform techniques and digital filtering to remove noises is inefficient as these techniques attenuate the discharge signals significantly. Also, traditional PD measurement is carried out at a single frequency of 50/60 Hz in the atmospheric pressure which cannot give information about PD characteristics at a higher frequency in a low air pressure environment [26–29].

This paper employs a technique based on the combination of wavelet transform and energy technique that can overcome the challenges of PD detection in low air pressure in a noisy environment. In this work, it is used for the detection of PD in two, simultaneously-active sources of PD in a noisy environment under low air pressure and at various frequencies for both sinusoidal and square-wave applied voltage. The outcome of this work shows promising results and a potential for online detection of PD pulses. The advantage of this technique over existing PD detection methods is that the technique can give the phase-resolved partial discharge (PRPD) pattern for PD detection under low air pressure and in excessively noisy environment.

The effect of frequency and air pressure are discussed in the next section, followed by details of the methodology and experimental setup in Sections 3 and 4. The results and discussions are in Section 5 where the key contribution of the paper are presented.

2 | EFFECT OF FREQUENCY AND AIR PRESSURE ON PARTIAL DISCHARGE CHARACTERISTICS

The density of gas molecules decreases as the gas pressure is reduced. As a result, the probability of an electron collision with other gas particles decreases as it travels. Because of lower number of electron collisions, the dissipation of energy caused by the collision reduces and, thereby, a lower applied electric field intensity or a lower applied voltage is needed to supply electrons with kinetic energy necessary for ionisation via collision to initiate electron avalanches. Therefore, the breakdown voltage of a gaseous medium at low pressure is less than that at sea level condition. This has been demonstrated experimentally and is known as Paschen’s law, as shown in Figure 1 where the breakdown voltage of air versus air pressure is plotted [12].

Air pressure also impacts the PD waveform. Figure 2 shows a typical corona PD pulse waveform for a needle-plane electrode under atmospheric pressure. As shown in Figure 2, the risetime of a PD pulse is defined as the time required for a PD pulse signal to rise from 10% to 90% of its peak value. The fall time (FT) is defined as the time required for a pulse waveform to drop from 90% to 10% of its maximum point. Also, pulse width (PW) is defined as the elapsed time between two points with 50% of the pulse peak value. Slew rate (SR) is measured as a voltage change in the risetime duration. Air pressure has a significant effect on the PD pulse’s characteristics. When the air pressure drops, the magnitude of corona PD pulses decreases. As a result, the PD pulses may be overlapped with the background noises, which makes PD detection challenging. In addition, risetime, FT and pulse width increase as the air pressure drops.

To explain the effect of air pressure on PD pulse waveform characteristics, letus assume a positive voltage is applied to a needle-plane electrode while the plane electrode has been grounded effectively. When the voltage magnitude exceeds the partial discharge inception voltage (PDIV), the kinetic energy of the gas particles goes up and this results in electron
In the time duration of risetime (RT), the densities of electron as well as other charged particles rapidly grow in the air gap. As a result, the PD pulse amplitude reaches the maximum point. The role of electrons becomes dominant during the risetime period because of the higher drift velocity of electrons compared to the ions. Upon lowering the air pressure, less free electrons exist in the air gap for the development of electron avalanches. Therefore, the risetime of the corona PD pulse increases as the air pressure drops.

The accumulation of positive ions around the needle tip curvature creates an internal electric field between the needle tip and the positive ions. As a result, the total electric field near the needle tip drops below the PDIV which ceases the formation of electron avalanches. During FT, the amplitude of PD pulses starts to decrease and this time period is mostly governed by the movement of positive ions. If the ratio of applied voltage to PDIV is same for the experiments at low and high pressure, the gas particles at ground-level pressures drift with higher velocity [30]. Since the pulse width of PD signals is in the range of several microseconds, PD pulse characteristics are not significantly affected as long as the frequency of the applied voltage is in the kHz range [31]. However, the applied frequency significantly affects the PDIV and increases PD activity which can result in insulation failure [28, 32, 33].

The existing methods have been designed to detect the PD pulse activity under atmospheric pressure and at a frequency of
The sensitivity of these methods is impacted by the frequency and air pressure because these two parameters alter the PD pulse’s characteristics as discussed above. Another corollary of using existing methods is that PD activity cannot be detected in a noisy environment because of low PD pulse magnitude. If a PD detection method cannot identify PD activity in the insulation system before the onset of an insulation breakdown, the withstand strength of the insulation system might be compromised and this can cause catastrophic failures in the HV equipment due to the increased stress on the insulation system.

This paper proposes an effective approach to detect and identify the PD pulses under low air pressure and in a wide range of frequencies. This technique utilises the time-domain properties of the recorded PD signal to generate the phase resolved partial discharge (PRPD) pattern and also demonstrates robustness against noise. The proposed technique, which is based on the combination of the wavelet and differential energy, uses a sliding time window to compute the differential energy of the PD signal. In this work, this technique was implemented in software in the post-processing stage. However, the results of this paper provide proof of the concept and show the potential of this technique to detect PD pulses under a noisy environment. Another salient feature of this method is its sensitivity to detect the simultaneously activated PD sources, which can be useful for the inspection of the insulation system.

### METHODOLOGY

In the online PD measurement, the captured PD signal is weak due to the environmental noises and parasitic impedance. In addition, the amplitude of PD discharge decreases at low air pressures and PD pulses can be masked by the noise. Therefore, a technique is needed to identify the PD pulses in the noisy measurement environment for further investigation.

Figure 3 presents the proposed PD detection method under low air pressure for a high-frequency applied voltage. The processing technique involves de-noising measured signals using wavelet-based technique, detecting PD pulses using energy-based technique, and identifying PD discharge pulses based on the phase resolved PD pattern.

A wavelet-based technique, which has been found to be a powerful filtering algorithm [36, 37], is used to attenuate the continuous background noises and low-frequency voltage ripple of the measured voltage signals. The wavelet transform of signals gives the coefficients which are derived by splitting the signal spectrum into a low-pass and a high-pass part. The low-pass part of the signal spectrum contains information pertinent to PD and switching noise, whereas the high-pass region of the spectrum is related to background noise. The process of low-pass and high-pass filtering is repeated to generate a two-band filter bank. The output of low-pass and high-pass filters at each level creates approximation coefficients and detail coefficients, respectively.

![Diagram](image_url)

**Figure 3** Proposed algorithm for PD detection. CDMDE, Cumulative Distribution of MDE; DE, differential energy; MDE, mean of differential energy; PD, partial discharge; PRPD, phase-resolved partial discharge.
These coefficients contain the signal’s characteristics which can be utilised to rebuild the signal in the reconstruction process [38, 39].

The wavelet transform was implemented through the Symlet wavelet filters. In order to find the Symlet filter orders, the Fast Fourier Transform (FFT) technique was used. FFT can give the frequency characteristics of the captured signals. By comparing the results of before and after PD occurrence, it was seen that the frequency contents of PD is between 50 kHz and 1.6 MHz. Because of this, the Symlet filter of order 9 and 13 were used to remove noises from the signal. In order to attenuate background noises that have frequency contents of more than 2 MHz, a Symlet filter of order 9 was used in the wavelet algorithm. On the other hand, low-frequency voltage ripples have frequency contents of less than 100 kHz which can be obtained using a Symlet filter of order 13. In order to remove both the background noise and voltage ripple, the output signal of a Symlet filter of order 9 was subtracted from the output of a Symlet filter of order 13. The output of this step gives PD pulses generated by the sources of PD, twisted-pair of magnet wires, corona discharge pulses, and switching interference as described in Section (4). The switching noises are symmetric and can be removed by using energy-based technique as discussed below.

Data is recorded for $M$ cycles of the applied voltage and each cycle of the acquired data is divided into $N$ equal sub-windows. In our experiments, we used $N = 200$ and $M = 20$. An energy-based technique is now used to identify sub-windows with PD pulses and separates them from the noisy sub-windows [19].

The energy sum in the $j$th sub-window and $w$th cycle, $E_{w}^j$, is calculated using [19].

$$E_{w}^j = \sum_{i=1}^{P_{w}} k_{i} x_{i}^{2}$$

where $x_{i}$ represents the recorded signal that is located in the $j$th sub-window of $w$th cycle and $P_{w}$ is the number of data points in this sub-window. The coefficient $k_{i}$ is defined as

$$k_{i} = \begin{cases} +1, & \text{if } x_{i} \geq 0 \\ -1, & \text{if } x_{i} < 0 \end{cases}$$

In (1), $E_{w}^j$ is called the differential energy of signal in $j$th sub-window. Due to symmetrical characteristics of low-frequency switching signals in a sub-window with only switching signals, $E_{w}^j$ will be very small in magnitude ($E_{w}^j \cong 0$). On the other hand, the magnitude of $E_{w}^j$ in the $j$th sub-window with a PD signal will be high enough to reveal the PD signal’s phase location.

The length of the phase angle of each sub-window is equal to $2\pi/N$. Within each $2\pi/N$-wide phase angle window, there are $M$ different values where $M$ is the number cycles recorded ($M = 20$). The mean of the $M$ values is calculated for each of the $2\pi/N$-wide phase angle windows that creates a distribution of $N$ values in a $2\pi$ phase angle window as given by

$$E_{w} = \frac{\sum_{j=1}^{M} E_{w}^j}{M}, \quad w = 1, \ldots, N$$

In (3), $E_{w}$ is the mean of differential energies (MDE) in the corresponding phase window ($w$). These $N$ values are assigned as MDE in reference to the phase angle.

The cumulative sum of all data values as phase windows progress provides the cumulative distribution (CD) of the MDE (CDMDE) over a $2\pi$ phase angle window as shown in

$$CD_n = \sum_{w=1}^{n} E_{w}, \quad n \leq N$$

where $n$ is the phase window number. The CDMDE starts to rise/fall where PD pulses occur. On the other hand, the value of CDMDE is constant where there is no PD pulse. In other words, the gradient of CDMDE shows the occurrence phase angle of PDs. The following describes the test setup that was developed to acquire PD pulse data and the implementation of the methodology discussed above.

## Measurement Test Setup

The test setup shown in Figure 4 was utilised to generate and detect PD pulses at low air pressure. The experiments were conducted on artificial defects in a high voltage laboratory. Two different artificial defects were developed to generate PD pulse signals. Each defect was implemented in a low-pressure test cell. The test cells were connected electrically and parallelly to enable simultaneous measurement of PDs generated by two sources. The test setup (see Figure 4) consists of a power source for energising the test cells, a coupling capacitor ($C_{k} = 1 \text{nF}$) for sensing partial discharges, a measuring impedance (Omicron CPL 542) for converting PD current pulses to voltage signals that can be recorded by an oscilloscope (Keysight DSO9254 A). The power source consists of a linear high-voltage power amplifier and a signal generator. The signal generator is used to generate a signal of desired waveshape and frequency. The high-voltage power amplifier (Trek PD05034) was connected in series with the output channel of the signal generator used to step up the voltage magnitude. The high-voltage amplifier can generate square waveform voltages with risetime of longer than 5 $\mu$s. The measurement procedure and system calibration were performed according to IEC 60,270 standard [16]. A wide-band PD measuring system in frequency range of 50 to 500 kHz was used.

### Test Cells

Two specific types of insulation defect were simulated. They generate corona partial discharge and partial discharge that occurs in an air gap between motor winding turns. They are considered to be representatives of two common sources of PD in aerospace applications [14]. The corona discharge may
occur in the non-uniform high electric field around a sharp edge, loose wire strand or transmission conductor in the power distribution system [40, 41]. The type of stator winding structure used in PWM fed actuator is a random-wound stator. The insulated copper conductors used for random-wound stators are magnet wires. The magnet wire insulation can be degraded by partial discharges because the insulation is organic and not resistant to PD. The presence of an air gap between winding turns as well as the difference in the permittivity of air and insulation material of the wires can lead to partial discharges in the air pocket [42].

To model corona discharge and the air gap between winding turns, a needle-plane electrode and a twisted pair of magnet wires were established in small-scale test cells as shown.
in Figure 4. The test cells were designed to be able to tolerate low-air pressure condition. The needle used for needle-plane electrode is made of tungsten with a tip diameter of 20 μm. The magnet wires comprise 24 AWG copper wires with a jacket diameter of 0.58 mm and a temperature rating of 200°C. The insulation of magnet wires (NEMA MW 35-C) is made of a heavy polyester layer coated with a layer of polyamide to obviate the problem of PD occurrence on the insulation surface. The procedure for the preparation of a twisted pair sample was carried out according to the IEC 60,851-5 standard [43]. The magnet wires consist of 3 turns over a distance of 3 cm.

4.2 Test procedure

The PD measurements were carried out on each of the test cells to determine their PDIV. Sine and square wave voltages at different frequencies were applied to the test cells. These are the waveforms that represent the voltage waveforms that exist in an aircraft power system [40]. The risetime of applied square wave voltage with a duty cycle of 50% was set to 5 μs. The air pressure inside the test cells was reduced to 33 kPa which is 30% of the ground-level air pressure and corresponds to an altitude of 30,000 feet. The amplitude of the applied voltage was increased to 70% of the expected PDIV value and then slowly raised in steps of 100 V. Each voltage step was maintained for 30 s. The reason for this length of time is that the number of gas molecules and photons reduces with decreasing air pressure and thus the gas needs more time to initiate photon ionisation [32]. Because of the stochastic nature of PD, PDIV values vary. 10 PDIV tests were carried out on each test sample for each test condition. The mean of measured values was determined as the value of PDIV. In our experiment, the applied voltage was raised up to 1.5 kV which is consistent with the 1 kV voltage level that the manufacturers are planning to increase to 1.5 kV which is consistent with the 1 kV voltage level that

FIGURE 5 PDIV as a function of the frequency of applied sinusoidal voltage. Due to the power supply current limitation, the PDIV measurement of the needle-plane setup was done for frequencies up to 2 kHz. PDIV, Partial discharge inception voltage

5 RESULTS AND DISCUSSION

In this section, the PDIV values as a function of frequency are determined and the performance of the proposed discharge detection method is examined. The measurements were carried out at a pressure level of 33 kPa.

Figure 5 shows the PDIV values as a function of the frequency of applied sinusoidal voltage under an air pressure level of 33 kPa. As shown in Figure 5, the PDIV of the twisted-pair of magnet wires is much lower than the needle-plane electrode. Figure 6 shows that the PDIV value under the sine wave applied voltage decreases with increasing frequency [44]. However, the frequency does not have any influences on PDIV if a square-wave voltage is applied. In fact, the parameter of the square-wave voltage that influences the PDIV is the risetime and not its frequency [40]. Under a square-wave voltage, the PDIV of the twisted-pair of magnet wires and needle-plane electrode are 500 and 1300 V, respectively.

The frequency affects the effective discharge time which is the time when PDs are active. When the needle electrode has a negative polarity and the applied voltage is still lower than the inception voltage, the positive ions are accumulated around the tip of the electrode. Increasing the applied voltage frequency causes the positive ions to have less time to dissipate due to lower drift velocity compared to electrons. Because of this the number of positive ions increases. This accumulation of positive ions around the negative electrode enhances the external electric field in the ionisation region which increases with an increase in the frequency. An increase in the external electric field leads to a lower applied voltage or a lower electric field intensity to initiate electron avalanches [33]. Because of this, PDIV decreases with the frequency of the sinusoidal voltage.
The pressure has an effect on the ion mobility of discharges. Ion mobility is defined as the ratio of drift velocity of ions to an applied electric field. The drift velocities of gas particles such as electrons or ions increase significantly under low pressure which leads to the attainment of higher kinetic energy when subjected to an external electric field. In addition, the number of electrons and ions produced during discharge are much higher at low air pressure since the kinetic energy of gas particles is much less dissipated as a consequence of less collisions. It was concluded that PD inception voltage is lower at sub-atmospheric pressures and the number of charged particles increases when the applied voltage is raised [45]. In order to evaluate the performance of the proposed technique, the measurements were carried out at a pressure level of 33 kPa and at frequencies of 1 kHz, 2 kHz, and 5 kHz. Figure 6 shows the measured noisy signal for one cycle of the applied voltage. A bipolar square wave (50% duty cycle) and a sine wave voltage with a frequency of 2 kHz was applied to the test cells. The test cells are a needle-plane electrode and a twisted pair of magnet wires established in small-scale test cells as shown in Figure 4. The measurement was carried out under an air pressure level of 33 kPa in a high voltage laboratory. A background noise level of 5 pC was measured in the laboratory using a commercial PD measurement device (Omicron MPD 600). As shown in Figure 6, the measured signal consists of switching noises, background noises, voltage ripple, PD pulses, and corona discharge pulses. The switching noise is generated by the polarity reversal of square wave voltage and a switching-type power source. The power source is a high voltage amplifier which is the main source of switching noises. It operates based on high frequency switching of electronic devices. The switching frequency results in output voltage ripple and switching noises. The PD pulses come from the twisted-pair of magnet wires that occur during the falling and rising edges of the applied voltage. The corona discharge is a type of partial discharge generated by the needle plane electrode when the polarity of applied voltage is negative. According to Figure 6, the voltage magnitude of corona discharges is very small, which makes corona detection difficult.
The wavelet transform technique explained in Section 3 was applied on the noisy signals. The results of this step for an applied voltage of sine and square waveforms are shown in Figure 7. As shown in this figure, the voltage magnitude of corona discharge pulses is still less than the switching pulses. However, wavelet filtering cannot be employed to remove the switching noise as it also eliminates the PD pulses. To resolve this issue, an energy-based technique was used to attenuate switching noises. In this step, the differential energy (DE), the mean of differential energy (MDE), and the CD of MDE (CDMDE) were calculated, respectively, as explained in Section 3. Figure 8 shows the phase-resolved pattern of partial discharge differential energy for the applied voltage of sine and square waveforms.

The phase-resolved pattern of MDE for both applied voltage of sine and square waveforms are shown in Figure 9.
The MDE signal pattern for the case of sinusoidal voltage is consistent with those shown in [46].

Figure 10 shows the CD of MDE (CDMDE) in reference to the phase angle. Using Figure 10, the value of the gradient of CDMDE with respect to the phase angle at the negative half cycle of the square wave voltage was calculated to be $10/\pi \text{[V}^2\text{s/rad]}$, which confirms the occurrence of corona discharges.

The output results of the proposed technique for measured PD signals under 1 kHz sine wave and 5 kHz square wave voltages are shown in Figure 11 and Figure 12, respectively. Figure 11 shows the phase-resolved patterns of the CDMDE of measured signals under a 1 kHz sine wave voltage. As shown in this figure, the CDMDE magnitude relevant to the twisted-pair of magnet wires suddenly drops to a value of $-0.012$ and then rises to a value slightly more than zero. It can be seen that the starting and ending levels of the CDMDE plot are close to each other. The changes in CDMDE magnitude reveal that PD pulses occur in the positive and negative half-cycle of the applied voltage. The positive and negative PD pulses start at phase angles of 45° and 225°, respectively.

By increasing the applied voltage, the corona discharges that come from the needle-plane electrode appear. As such, the measurement consists of two types of PD pulses that are activated simultaneously. Figure 11 shows that the changes in CDMDE magnitude in the negative half-cycle of the applied voltage is much higher than that in the positive half-cycle. This indicates that the needle-plane corona discharges occur in the negative half-cycle of the applied voltage.

This is due to the fact that the PRPD pattern for the twisted-pair insulated wires is symmetrical, but the PRPD pattern for the needle-plane electrode is asymmetrical.

Figure 12 shows the phase-resolved patterns of CDMDE of the measured signals under a 5 kHz square wave voltage. When there is no PD, the CDMDE magnitude changes very slightly and the change is negligible. These small changes are

**FIGURE 9**  MDEs of signal in reference to phase angle under
(a) bipolar square wave voltage and (b) sine wave voltage. MDE, mean of differential energies

**FIGURE 10**  CDMDE under (a) bipolar square wave voltage and (b) sine wave voltage. CDMDE, cumulative distribution of mean differential energy
caused by switching noises during the polarity reversal of square wave voltage. However, when PD pulses occur during polarity reversal, the CDMDE magnitude abruptly drops to a value of around −90 and then rises to a value close to zero. This was expected as the PD pattern of pulses generated by the twisted-pair insulated wires is symmetrical.

It can be seen in Figure 12 that the PD pattern changes from symmetrical to asymmetrical by increasing the applied voltage to a value higher than 1.5 kV. This is due to corona discharges appearing during the negative half-cycle of the applied voltage that turn symmetrical PD patterns to asymmetrical. The PD phase location can be found by the absolute value of the gradient of the CDMDE. The absolute value of the gradient at phases without any PD pulses will be zero. However, the absolute value of gradient on PD phases will increase from zero to a high value.

**FIGURE 11** Cumulative distribution of mean differential energy in reference to the phase angle of measured signal with partial discharge pulses generated by (a) the twisted-pair magnet wires and (b) both the twisted-pair magnet wires and needle-plane electrode under a 1 kHz sine wave voltage

**FIGURE 12** Cumulative Distribution of mean of differential energy in reference to the phase angle of measured signal without any partial discharge (PD) pulses (a), with PD pulses generated by twisted-pair magnet wires (b), and with PD pulses generated by both the twisted-pair magnet wires and needle-plane electrode (c) under square wave voltage

### 6 | **CONCLUSIONS**

A theoretical-based approach was proposed to detect discharge pulses under low air pressure in an excessively noisy environment. This method is based on the combination of the
wavelet and energy techniques. This method offers high-performance corona discharge detection in an excessively noisy environment. The magnitude of the CD of recorded noisy signals was obtained using the proposed approach. The absolute value of the gradient of the magnitude of CD identifies the phase location at which the PDs were activated in one cycle of the applied voltage. A non-zero value of the gradient shows the phase angle where PDs occur. To verify the performance of the approach, a measurement test setup was developed to acquire partial discharge pulses due to two common sources of partial discharge. The measurements were carried out at a pressure level of 3.3 kPa, and at frequencies of 1, 2, and 5 kHz. A maximum voltage level of 1.5 kV was employed. These voltage level and frequencies should cover future developments in the power system of an aircraft. However, the risetime of modern power electronic components is shorter than what was explored in this work and further investigation is needed. This work presented a proof of the concept that is applicable to faster pulses. The results indicated that the phase-resolved pattern of the calculated CD for PD pulses caused by the twisted-pair of magnet wires is symmetrical. However, when corona discharges occur, the pattern changes from symmetrical to asymmetrical. In this asymmetrical pattern, the CD magnitude increases from a negative value to a positive value much larger than the zero value in the negative half-cycle of the applied voltage. The influence of frequency on partial inception voltage was investigated experimentally. The obtained results indicated that the PDIV of corona discharges and twisted-pair magnet wires decreases with increasing frequency when the applied voltage is sinusoidal. The proposed technique, which allows the detection of PD signals in an excessively noisy environment, can enhance the detection of partial discharges in low air pressure environment.

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