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Development process and testing of partial discharge detection device on medium voltage XLPE cable

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ABSTRACT

High voltage assets play a vital role in providing uninterrupted power to the consumers and any slight problems experienced by the assets may cause losses in millions of dollars to businesses. Therefore it is of utmost importance to monitor the health of high voltage assets. This research presents the development process of a Partial Discharge (PD) device that is able to detect PD acoustic waves for monitoring high voltage assets purposes. Medium voltage Cross-Linked Polyethylene (XLPE) cable was used which was introduced with spherical void defects at the joints of the cable that functioned to produce PD acoustic waves. Outcome of the development processes provides the finished design of the PD sensing device, known as Partial Discharge Detection (PDD) device. The functionality of the PDD device was also assessed through controlled experimentations, and they proved to be successful. Pure PD waveform captured by the ultrasonic sensor was similar when compared to a HFCT sensor's pure PD waveform. The PDD device is a small and affordable, and is opened to various improvements such as integrating Artificial Intelligence (AI) unto the device, and one day may replace most existing bulky and expensive PD sensing devices that are readily available in the market.

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1. INTRODUCTION

Power cables are considered to be an important asset. Power cables are not just being utilized in electrical power transmission but are also used under various environmental and mechanical conditions [1]. Under all these utilization fields of power cables, 'Degradation' occurs in power cables. Normally, PD is the main culprit for the degradation in power cables. PD is a natural breakdown phenomenon of a minute area of insulation which is subjected to high voltage [2]. In a detailed perspective, PD occurs adjacent to a conductor when the insulation between conductors do not completely bridge each other [3]. Aging assets, faulty design, and material defects are usually the main causes which can eventually lead to the production of various sources of PD [4, 5]. In this paper, internal partial discharge in the form of void discharge will be of the main focus in which the air voids are located near to the insulation screen of the XLPE cable. Void discharge is a common type of internal PD which commonly occurs in medium voltage XLPE cables that have joint defects [6, 7].

The development of high rated voltage for XLPE cable systems is commonly used in meeting the increasing demand of high power transmission fields [8, 9]. Since delivering efficient power to consumers revolves heavily around the XLPE cables' health, continuous observation of their health is crucial. PD damages the health of XLPE cables through the degradation of insulation materials, thus a PD monitoring device should be developed. PD monitoring devices are already available in the market, however, these devices are expensive and bulky [10, 11]. Most electrical equipment produce a broad range of sound, this includes ultrasound waves which can be easily detected through basic ultrasonic testing procedures. Various methods and sensors have been developed in order to assess the ultrasonic testing [12-16]. This paper will be using ultrasonic measurement as a means of detecting internal PD due to void discharge, it is considered to be one of the best acoustic emission testing method. A High Frequency Current Transformer (HFCT) will also be used in this research for comparative purposes.The completed PDD device prototype should be able to detect internal PD in medium voltage XLPE cable. Future major accomplishment of the PDD device is that the device would be able to pose as a better option when compared to PD sensors that are already mass produced such as HFCT sensors and Acoustic Emission (AE) sensors [17-19]. Therefore, this paper's main focuses are the elaboration of the design details of a working PDD prototype and the functionality tests of the device based on controlled PD experimentations which have been studied and presented.

The rest of the paper is organized as follows: Section 2 presents the methodology of the paper, which is divided into smaller sections, whereby Section 2.1 explains the Mechanism Flowchart of PDD device, while Section 2.2, Section 2.3, and Section 2.4, explains the List of elements needed, Designing the PDD device using LT Spice and Designing the PDD device using Autodesk EAGLE respectively. Section 3 explains the Design of Experiment while Section 4 shows the extraction of pure PD waveform using MATLAB. Finally, Section 5 displays the Results and Discussions of this research paper and Section 6 presents the conclusive findings for this research paper.

2. METHODOLOGY

In designing the PDD device, certain necessary steps have to be taken. The steps to be followed are pre-design process, defining the mechanism flowchart of PDD device, listing the required elements in designing the PDD device, designing the PDD device using LT Spice and designing the PDD device using Autodesk EAGLE.

2.1. Mechanism Flowchart of PDD device

A mechanism flowchart was prepared in order to fully explain the process flow of the functionality of the PDD device, and only from there can the list of electronic elements be provided.The PDD device will be positioned near a designated high voltage asset which consists of PD sources. The ultrasonic sensor on the device then detects the acoustic PD waves and captures the PD waveforms manually through the use of a digital oscilloscope. The captured PD waveforms will then be processed using MATLAB for further analyzation in order to obtain pure PD waveforms. The mechanism is based on an infinite loop process in order for the device to continuously collect raw PD waveforms and will serve as a base guideline for the whole functionality process of the PDD device. Figure 1 shows the mechanism flowchart of the PDD device.

2.2. List of required electronic elements needed in designing the PDD device

In designing the PDD device, the fundamental characteristics of the major electronic elements or components that are to be used must be taken into primary consideration. This is to ensure a smooth assembly process of the device is achieved in the form of a Printed Circuit Board (PCB). The list of components that were used in this research were ceramic capacitors 101 (C3 and C2 with values of 100 pF each), 2mm 5kV DC Barrel Jack, resistors (R8, R7, R5 and R4 with value of 10 kΩ, R2 with value of 1 kΩ and R1 and R6 with value of 330 Ω), 3.5mm Stereo Jack with two switches (KYCON STX3100), ultrasonic sensor (C1) with frequency of 40 kHz and sensitivity of -63 dB typ. (0dB= 10V/Pa), trimmer potentiometer (R3) with value of 5 kΩ and integrated circuit µA741CP (IC4 and IC3). These components will be orderly assembled into a PCB form, where the design parameters and specifications of the PDD device can easily be entered using Autodesk EAGLE software.

2.3. Designing the PDD device using LT Spice

The PDD device comprises of an ultrasonic sensor, which enables itself to detect acoustic sound waves. This device is designed only for the sole purpose of having to detect a real PD waveform produced by the void discharge in the medium voltage XLPE cable. For the first process, a receiver circuit is created, which serves the purpose of consisting of an ultrasonic sensor. In this step it is important to detect the ultrasonic signal emitted by the PD source, so that the captured signal will go through a differential amplifier. The function of the differential amplifier is to roughly differentiate and amplify the captured signal with respect to a varied gain. The PDD device mainly revolves around the utilization of a high pass filter and a differential amplifier. In laymen's term, an ideal differential amplifier will normally provide an output voltage with respect to ground, which is commonly some gain times the two input voltage's differences. The above statement is explained based on the following basic formula which importantly serves as a main basis for the first pre-design process:

$$V_{out} = A(V_a - V_b) \tag{1}$$

As shown in (1) shows that A is defined as the differential gain and both V_a and V_b are voltages with respect to ground. A software known as LT Spice was wholly used throughout the first pre-design process in order to construct the circuit design of the differential amplifier. The Differential Amplifier helps to differentiate which signal is of ultrasonic range and which is not due to the void discharge from the PD source. The differential amplifier circuit consists of two 330 Ω resistors, two 10 kΩ resistors, one 100 pF capacitor, a 5 kΩ variable resistor with adjustable gain, one 741 operational amplifier and a buzzer. The basic formula for a functional differential in obtaining the value of V_{out} is as shown below:

$$V_{out} = \left(\frac{R_2}{R_1}\right)(V_2 - V_1) \tag{2}$$

As shown in (2) shows that A from in (1) is expressed as (R_2/R_1) while V_a and V_b from in (1) are expressed as V_2 and V_1 as shown in (2). For the second functional process, a high pass filter circuit must be created. By definition, a high pass filter is a filter that allows only high frequency signals to be able to pass through. With this, unwanted signals such as lower frequency signals can be easily removed, which ease the classification process of the captured raw PD signal. The High Pass Filter only allows high frequency signals to pass through, inevitably removing unwanted lower frequency signals. The High Pass Filter circuit diagram consists of two 10 kΩ resistors, a 1 kΩ resistor, a 100 pF capacitor, and a 741 operational amplifier. The V_{out} is the filtered raw PD signal, which is later to be processed and analyzed using MATLAB. These two finished circuit designs has to be combined in order to finally form the completed PDD device circuit diagram. The circuit designs can be viewed in a previous research paper [10]. With this completed final circuit design of the PDD device, this exact design can be exported into Autodesk EAGLE software. This is to ensure that the same circuit design can be converted into a Printed Circuit Board (PCB) format. Only with this PCB format can the device be fabricated into a physical form.

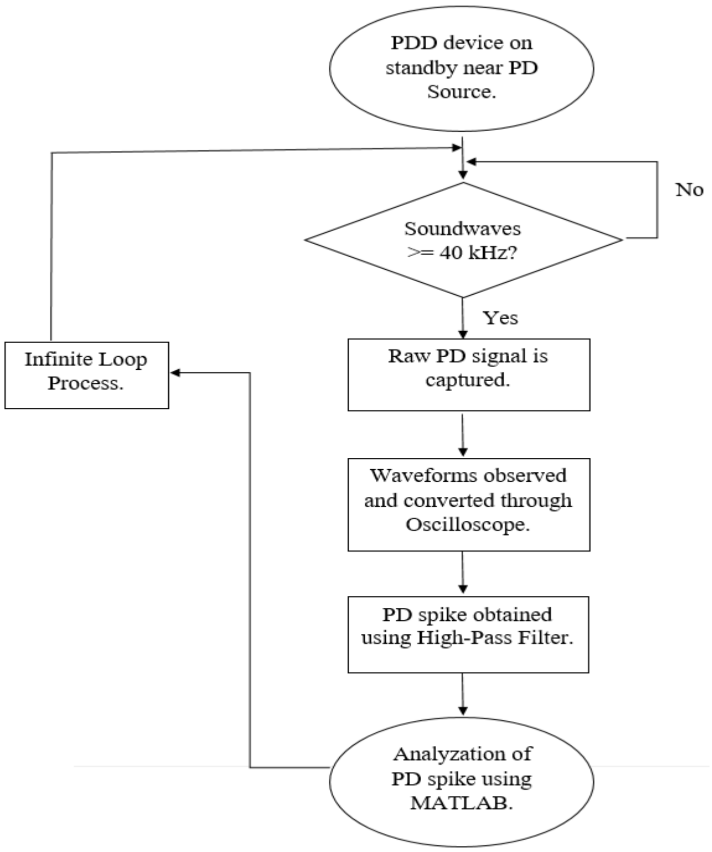


Figure 1. Design flowchart of the PDD device

2.4. Designing the PDD device using Autodesk EAGLE

Exporting the final circuit diagram from LT Spice into Autodesk Eagle enables the diagram to be converted into a schematic diagram. The electronic components were carefully selected and inserted into the workspace provided in Autodesk EAGLE. Arrangement of the chosen electronic components were done in an orderly manner and the 'Net' action tab was used to connect all the electronic components. With that done, the software will automatically connect all the components together in order to establish secure connections between the components. Next, the conversion of the established schematic diagram into a PCB diagram allows the PCB to be designed in the shortest possible route specifically for the 'Via'. A 'Via' functions to establish connections between the bottom and top layer of the PCB. The PDD device uses a simple single layer circuit board, where only one copper layer is visible on the bottom side of the PCB. Air wires that are visible in the PCB diagram are actually guides for the connections of the PDD device's electronic components.

When converting from schematic diagram into PCB diagram some minute arrangements must be done unto the electronic components by dragging them in the desired design specifications. Next, the ground area of the PCB diagram has to be defined. This is actually done to ground the area that has no air wires or connections in order to avoid any unwanted interferences during the experimentation of the PDD device, which ultimately helps in improving the quality of the PD waveforms that are to be captured. For the net class details of the PCB diagram, the suitable values that are to be keyed in the software are 12mm for the width, 20mm for the drill and 10mm for the clearance. To minimize the complexity of the design, the net class values were keyed in using the values provided which enable the design of a single layered PCB with a copper layered bottom for secure electronic connections. By carefully following the procedures in creating the PCB diagram, the end result is that in the form of secured connections of the air wires that are connected together simultaneously with respect to the shortest and simplest available route. The air wire connections are better suited in a more refined light blue color. This allows better indication of the PCB having established successful connections. This finished design will be fabricated by PCB manufacturers and can be viewed in a previous research paper [10].

3. DESIGN OF EXPERIMENT (DOE)

It is time to test the functionality of the device, through controlled experimentations. As stated above in the methodology section, the source of the PD is due to void discharge. To create the void discharge, holes are being introduced at the joints of the medium voltage XLPE cable. These holes serves as air pockets which then allows the cable joints to be considered as 'damaged' or contaminated, in order to allow joint failure. The joint failure will promote PD to occur, which therefore then allows the PDD device to be able to detect and captured the acoustic waves produced by the PD. The specifications of the holes created for the void discharge, are that the depth is 1.15 millimeters, the width is 2.93 millimeters, the shape construct is in spherical form, the permittivity of air which has a value of 1 and lastly, the void discharge is located on the right and left side of the joints of medium voltage XLPE cable which is very near to the insulation screen. With these specifications, a simulation of electric field strength in order to determine the value of PD emitted due to the void discharge can be done using a software known as Finite Element Method Magnetics (FEMM). This FEMM software aids in constructing a cutout version of the medium voltage XLPE cable used in this research.

Since it is understood that the electric field strength is directly proportional to the magnitude of PD created, it is safe to say based on the simulation done, the void discharge is sufficient enough to produce an abundant magnitude of PD. In theory, the electric field strength and an insulation's current density are known to be the highest when it is near the conductor and becomes significantly weaker when it is further away from the conductor [20, 21]. For the actual experimentation, the PDD device is placed horizontally near to the PD source, which is at the joints of the medium voltage XLPE cable. The device is supplied with a 5V DC voltage supply continuously in order to function and detect acoustic soundwaves. An AC voltage supply is used to inject subsequent amount of voltages into the medium voltage XLPE cable. The AC voltage varies from 2.5 kV until 15 kV. Any higher than 15 kV will propose danger to the safety of the lab's environment. When injecting AC voltage into the cable, the defect in the cable joints causes void discharges to occur and therefore, releasing acoustic waves that can be translated into PD waves. These PD waves is detected by the ultrasonic sensor on the PDD device, and converted into electrical signals. The electrical signals flow to an oscilloscope, and this oscilloscope functions in directly capturing raw PD waveforms. The oscilloscope is that of a Teledyne Lecroy oscilloscope with a bandwidth of 500 MHz, a sampling rate of 2.5 GS respectively and uses a 50 Hz filter. In this experimentation, a commercial PD sensor known as a HFCT is also used to detect the acoustic soundwaves of the PD source. This is purely for comparison purposes in order to justify the functionality of the PDD device. The PD waveforms from the two sensors captured by the oscilloscope will be further analyzed using MATLAB.

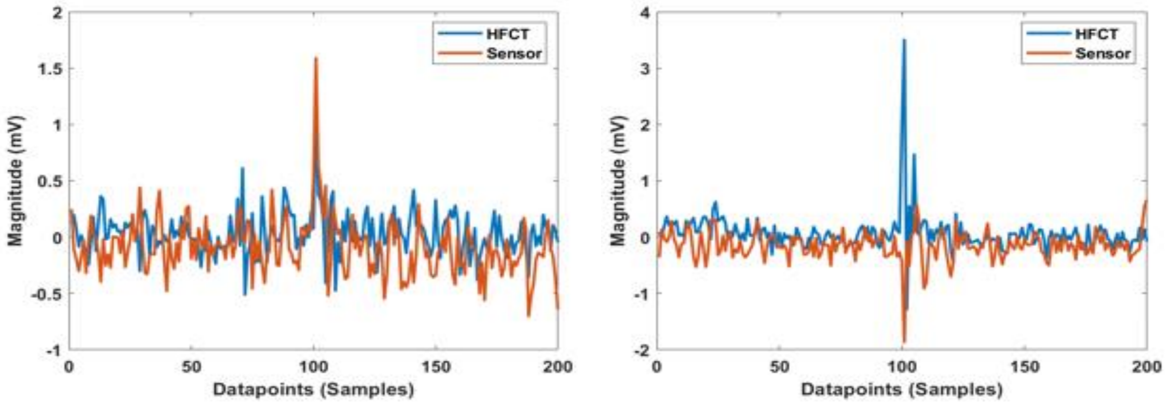
4. PURE PD WAVEFORM EXTRACTION USING MATLAB

Raw PD waveforms contains unwanted signals such as noise, and the extraction process helps to remove the interferences in order to realize the comparison of both sensor's data. The first step process is to convert the raw PD waveforms captured using the digital oscilloscope into excel file type format. These excel version of the waveforms will then be converted again into a new file type format known as MATLAB files format (.mat). This is basically known as the initial pre-processing stage of the extraction process. Next, DC offset from the raw data is removed for further processing. The reason why DC offset is removed from the raw data is because the raw signals that are captured using both sensors already consist of the production of DC offset. The main culprit for the production is due to the operation of the pulse generation hardware during the experimentation. In order to remove the DC offset, the mean amplitude of the entire cycle was subtracted from one of each individual sample. By doing this, each of the individual sample will be able to exhibit a zero mean [22, 23]. Although the experimentations were done in a low noise level controlled laboratory condition, background noises still have to be removed before exerting the extraction process unto the raw PD waveforms. This process is known as de-noising which can be used to comply the task of noise suppression, and such techniques are known as Fast Fourier Transform (FFT) based de-noising and low pass filtering. A method known as hard-thresholding was carried out to pre-extract the PD pulses after de-noising process. The value that was set for hard-thresholding is set to 1.5 mV. For the actual extraction process, a famous algorithm called peak detection technique is used. The technique was executed unto the raw data, transferring each pulse into a new variable matrix. This new variable matrix replaces the removed pulses with a zero vector [22, 23].

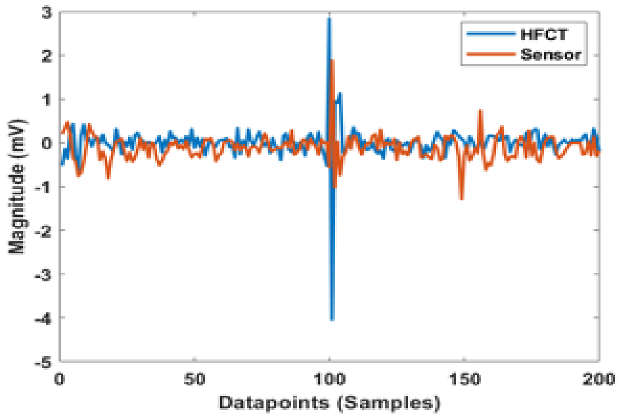
The peak detection technique process was done several more times in order to ensure that the peak magnitude of the remaining pulses in the raw data is much smaller than the pre-defined threshold value. Then only can the PD pulses be isolated from unwanted background noises. The threshold value however cannot be set too high, as a large possibility of information loss in PD pulses may likely to occur during the process. On the contrary, if the threshold value is set too low, PD pulses might be mistakenly interpreted from unwanted noise pulses [24-26]. The final step process is the Pulse Pairing Process. This process is carried out when the peak magnitude of a PD pulse is much smaller than the stated pre-defined threshold value. This process is also done based on a reasonable time of flight duration of the PD pulses. In the end, these pure PD pulses that are obtained from both PDD device and HFCT are then measured and compared based on their time domain.

5. RESULTS AND DISCUSSIONS

The results that were obtained after going through all the stated process in obtaining pure PD pulses are as expected. The pulse pairing process of the PD pulses from both sensors can be seen in Figure 2. Note that the voltage chosen for the display of results are picked from the best amongst the pairs that are obtained. It can be simply seen that the PD pulses detected by the PDD device are similar to that of the PD pulses detected by the HFCT sensor. This proves that the PDD device is working perfectly as expected and that the functionality of the device is justified by comparing it to the HFCT. There is without a doubt that the PDD device functions just as how the HFCT would in terms of detecting PD pulses. Figure 2 displays the orange color to be the PDD device's PD pulse while the blue color is stated to be the HFCT's PD pulse.



(a) 6.5 kV (b) 7.5 kV



(c) 8.5 kV

Figure 2. Pulse pairing process of PD pulses captured using both PDD device and HFCT sensor

From Figure 2, it can be justified that the PDD device does detect pure PD pulses much like the HFCT sensor did. However, it can also be observed that the magnitude of the PD pulses detected by the PDD device is quite smaller as compared to the HFCT sensor. This is naturally due to the nature of acoustic emission sensing method by using an ultrasonic sensor itself, whereby the method is abruptly affected by extraneous noise and signal attenuation tends to happen frequently. HFCT sensor is not affected by these factors so to say, hence the difference in the magnitude of electric field strength.

As for the FEMM simulation of the spherical void defect, the magnitude of the electric field strength from the simulation is found out to be approximately 3 MV/m. This value is indeed a high value for production of PD. Since electric field strength is directly proportional to the magnitude of PD, it can be stated that the artificial void discharge caused by the spherical void defect is more than enough to provide abundant PD which then leads to high production of acoustic soundwaves. This in return helps ease both the sensors to detect easily the soundwaves and capture abundant PD waveforms using the digital oscilloscope. The electric field strength decreases as it is further away from the spherical void defect. The magnitude values of PD pulses captured by the PDD device are very much dependent on the magnitude of AC voltage applied during the experimentation. The higher the magnitude of the injected AC voltage, the higher the magnitude of the PD pulses. Table 1 shows the maximum average magnitude of the PD pulses obtained by the PDD device for each different voltage applied.

Table 1. PD pulses maximum average magnitude captured by PDD device

Voltage Applied (kV)	Maximum Average Magnitude (mV)
6.5	0.1017
7.5	0.4024
8.5	0.6981

Although the PDD device falls behind the HFCT sensor in terms of the accuracy of capturing PD pulses, ultimately, the device is still able to achieve the main objective of this research and that is to detect PD pulses in medium voltage XLPE cable due to internal void discharges. Advantages of the PDD device compared to the HFCT sensor are such as costing a lot less as compared to buying one whole set of HFCT sensor, smaller and much easier to be used and opened to a wide variety of upgrades such as implementing Artificial Intelligence (Ai) which are quite hard to implement unto the HFCT sensor.

6. CONCLUSION

In this research paper, an intuitive insight on the meticulous design process of the PDD device is presented properly. The main objectives of this research which are to design a functional PDD device that can detect PD due to void discharge in medium voltage XLPE cable, and to assess the functionality of the PDD device through controlled experimentations have been realized and achieved successfully. Results obtained throughout the experimentations strongly infers that the PDD device is positively functioning as expected, and that the values of the magnitude of PD obtained are in the acceptable range. Furthermore, the pure PD waveform captured by the PDD device very much resembles the pure PD waveform captured by the HFCT sensor. PD monitoring is very crucial in maintaining the health of high voltage assets in reducing the repair and maintenance costs, and this PDD device helps proficiently in this particular field. All in all, this research much likely aids in opening new pathways for the PDD device to blossom into a more sophisticated and technology driven sensing tool.

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Mohamad Izmir Farhan Mohamad Radzi has successfully completed his Bachelor Degree in Electrical Power Engineering (First Class Honour), from Universiti Tenaga Nasional (UNITEN) in December 2019 fully sponsored by Yayasan Tenaga Nasional (YTN). He successfully obtained 6 semesters of Dean's List. He started his degree in Virginia Polytechnic Institute and State University in the United States of America back in 2014. He completed an industrial training program in TNB Research Sdn. Bhd and is currently working on a life assessment project for Medium Voltage Underground Cable (MVUG) under professional supervision of Assoc. Prof. Dr. Ir. Azrul bin Mohd Ariffin in conjunction with TNB Research for his Master's Degree. He previously worked as a Research Officer under the same project and supervisor. Currently, he is officially working for TNB's Distribution Network under Stakeholder Management department whilst pursuing his Master's Degree in Electrical Engineering in UNITEN.

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