# Partial discharge detection device using ultrasonic sensor on medium voltage XLPE cable

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**ABSTRACT**

There are many methods that have been studied by earlier researchers in order to detect the acoustic properties of Partial Discharge (PD) emitted by PD sources. One of the methods known as ultrasonic sensing on medium voltage Cross-Linked Polyethylene (XLPE) cable was adopted to detect partial discharges on commercial applications, usually by using Acoustic Emission (AE) sensors. This paper presents the processes of designing a PD sensor to detect the acoustic properties of the partial discharges on medium voltage XLPE cable. This PD sensor method works by detecting the partial discharges occurred at the joint of the cable which can act as an early warning device to help minimize the repair and maintenance costs of degrading cable. Result of the experiment shows the complete design of the prototype device, the device after fabrication and the functionality of the device. This design of the prototype can be beneficial for future uses in designing cost efficient and smaller sized PD detection devices. By positioning the sensor in horizontal position directly to the source of PD on the cable, the sensor will be able to detect acoustic properties of PD, by picking up the frequencies beyond 40 kHz. By varying the voltage applied values, a design of experiment (DOE) is carried out accordingly. Result of the experiment shows that the prototype device is functioning as expected, and hence this finding will be very useful to the consumers of power industries as the sensor device can serve as an alternative device to the commercialized PD sensing devices which are bulky and expensive.



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## 1. INTRODUCTION

Power cable makes up the majority of important assets in the field of electrical power system. Mostly used for transmission of electrical power, power cables are also used under variety of electrical, mechanical and environmental conditions [1]. Partial discharge (PD) analysis is important to assess and evaluate the insulation state of high voltage equipment under service in order to determine the severity of degradation [2-5]. PD is a phenomenon where a breakdown process of a small area of an insulation, which is subjected to high voltage occurs. PD is an electrical discharge that do not completely or partially bridge the insulation between conductors and which can or cannot occur adjacent to a conductor [6, 7]. It can be due to faulty design, material defects and aging assets. These factors will eventually lead to the production of various PD sources [8, 9]. Void discharge is a type of internal PD and it normally happens in the medium voltage cables with defects in the joints[10, 11].

Nevertheless, numerous studies have confirmed that PD drastically promotes long term degradation which eventually leads to failure of electrical insulation. Majority of electrical equipment produce a broad range of sound and the most basic electrical problems produce distinct ultrasound waves which can be detected through ultrasonic testing. Furthermore, there are many kinds of sensors and methods that have been developed to assess the ultrasonic testing [12-16]. Ultrasonic measurement is one of the most powerful on a comparative basis and will significantly increase the reliability of correct detection of PD when used with other online PD testing technologies. On the other hand, with the advancement of technology especially in the development of Integrated Circuits (IC), the term operational amplifiers or op amp comes into the limelight. The concept of op amp is used as a basis in this research to design the custom Partial Discharge Detection (PDD) device. Hence, This paper presents the design process of the custom PDD device, and the functionality of the device to detect PD on medium voltage XLPE cable have been studied and presented.

## 2. METHODOLOGY

In this study, the customized PDD device is developed to detect the PD source, which comprises an ultrasonic sensor as a sensing element to detect the acoustic sound waves of a range of 40 kHz and above. Thus, it is of utmost importance to adhere to the meticulous design process. The first design process is to create a receiver circuit, where the receiver itself is of an ultrasonic device. This receiver circuit should function in a three-step process. The first functional process is to detect the ultrasonic signal from the PD source and goes through the differential amplifier, in order for the receiver to differentiate and amplify the collected signal that varies with a gain. The second functional process is for the amplified signal to pass through a high pass filter in order to remove lower unwanted frequencies or noises. The final functional process is for the filtered signal to be analyzed by an oscilloscope. Speaking of operational amplifiers, an op amp is a device containing a circuit that consists of transistors, resistors, capacitors and diodes. It typically requires connection of bipolar power supplies which are both +Vs and –Vs with respect to ground [17]. This custom PDD device focuses on using differential amplifiers and high pass filter. An ideal differential amplifier provides an output voltage with respect to ground, that is some gain times the difference between two input voltages. The formula is expressed as following:

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

A is the differential gain and both $V_a$ and $V_b$ are voltages with respect to ground. LT Spice was used to construct the circuit design of the differential amplifier, and it is as shown in Figure 1.

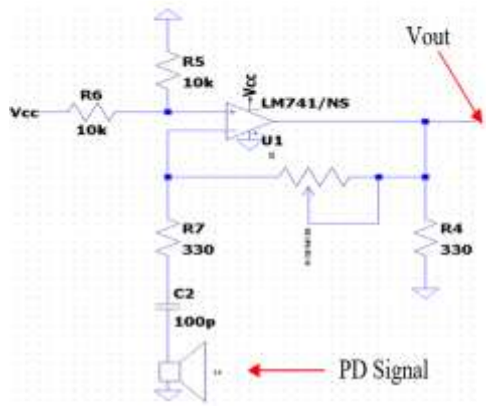



Figure 1. Circuit diagram of a differential amplifier designed using LT Spice, which is used in the prototype device.

The differential amplifier consists of two 10 kΩ resistors, two 330 Ω resistors, one 5 kΩ variable resistor with adjustable gain, a 100 pF capacitor, a buzzer and a 741 operational amplifier. The whole circuit design functions as a differential amplifier. The common formula for the differential amplifier in order to get the $V_{out}$ is as the following:

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

The second functional process consists of a high pass filter. A high pass filter is a filter that only allows high frequency signals to pass through, and in the same time, removing the lower frequency signals. This helps to classify the collected PD signal better since it only allows a frequency of 40 kHz and above to pass through. The circuit design of the high pass filter used in this project is shown in Figure 2.

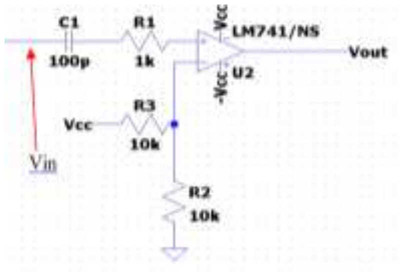



Figure 2. Circuit diagram of a high pass filter designed using LT Spice, which is used in the prototype device

The circuit diagram consists of a 1 kΩ resistor, two 10 kΩ resistors, a 741 operational amplifier, and a 100 pF capacitor. The $V_{out}$ is the filtered PD signal, and the next step is the analysis process done using an oscilloscope. Combining the two circuits together, a functional PD detection device circuit will be obtained. Figure 3 shows the combined circuits with additional components such as voltage sources:

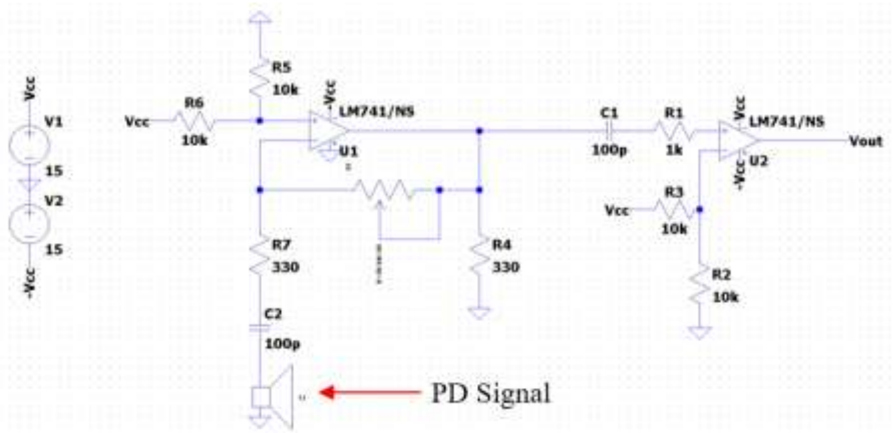



Figure 3. Combined circuit diagram of differential amplifier and high pass filter designed using LT Spice, which is used in the prototype device. External 5V voltage sources to power up the device is abbreviated as $V_{cc}$.

With a completed design using LT Spice of the prototype device, the design can now be transferred to Autodesk EAGLE in order to construct the design of the Printed Circuit Board (PCB). In Autodesk EAGLE, a schematic diagram must be created first. Only then can the schematic diagram be converted into a PCB diagram. The LT Spice schematic diagram can be converted into Autodesk EAGLE schematic diagram format.

With the completed schematic diagram, now the design can be converted directly into a PCB diagram. The converted design is not in an orderly manner, therefore, modifications need to be done in order to get the final design. Ratsnest was clicked in order to get the shortest possible connections between the elements automatically. The Ratsnest action tab redefined the wires' connections and it created the shortest route, for the best possible design. Only one layer is used for the PCB design. Next step is to define the boundary of the PCB design in order to make sure the components fits in nicely onto the PCB, according to the components respective positions. Finally, the finished product of the custom PDD sensor will be fabricated based on the final design of the PCB diagram. Note that the design can still be modified if further improvements of the prototype device is to be amended. The device was fabricated and components were soldered at a fabrication company.

Figure 4 shows the fabricated prototype device which is ready to be tested for its functionality.

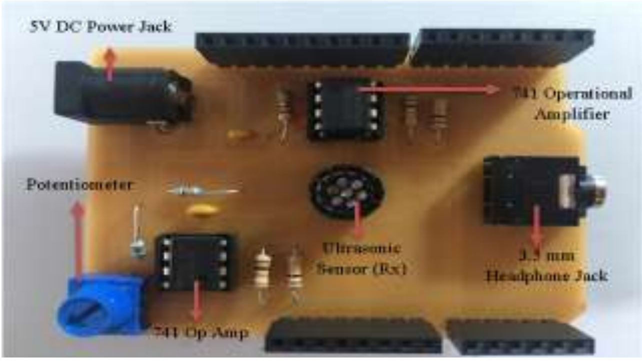



Figure 4. The fabricated prototype device known as PDD device that is ready to be tested for its functionality

## 3. EXPERIMENTAL MEASUREMENT

This section explains the details of the artificial PD source and also the setup of the experiment used in investigating the acoustic properties of PD signal measured from HFCT and the ultrasonic sensor or custom PDD sensor accordingly. The measured PD signals by the HFCT connected to the earth braid of cable joint are used for further analysis to compare the performance of the sensor. An experimental setup has been designed and constructed in the TNB Research Sdn. Bhd Laboratory to simulate void discharge inside a cable. Void discharge that has 1.15mm depth and 2.93mm width was generated artificially in the laboratory which then was used to locate near to insulation screen of XLPE cable as input data. Void discharge is a common type of discharge activity that occurs within a power line cable. Void discharges are common due to defects known as cavities that appears inside an electrical insulation [18]. The defects inside a cable tend to appear due to poor manufacturing errors or improper transportation of the cable. When subsequent amount of voltage equaling to the minimum inception voltage is applied, void discharges start to occur within the power cable and PD signals travel within the cable from the source location via the HFCT to the ground. A Teledyne Lecroy digital oscilloscope with a sampling rate set to 2.5 GSs-1 and a bandwidth of 500 MHz respectively is then used for real time waveform analysis and data recording. The Channel 1 of the oscilloscope is connected to the HFCT sensor unit while the ultrasonic sensor was connected to Channel 2. The trigger on the oscilloscope was set in phase to the applied voltage. The data obtained from the HFCT sensor was then used for comparison purposes with the data obtained from the ultrasonic sensor.

## 4. PARTIAL DISCHARGE EXTRACTION

In this section, a converter was used to convert the stored data into Matlab files format (.mat) for further analyses and this is known as the initial pre-processing stage. To allow for further processing, the DC offset needs to be removed from the raw data. This is because a DC offset was produced in the measured signals due to the operation of the pulse generation hardware. This was done by subtracting the mean amplitude of the entire cycle from one of each individual sample in order to ensure that it exhibits a zero mean. For background noises, it is of utmost importance to remove the noise in order to extract PD pulses. This is because background noises affects the measurement of the PD pulses. The experimentations were carried out in a controlled laboratory condition which have a low noise level, and in order to de-noise the raw signal and extract the PD pulses, a method known as hard-thresholding [19] was used. The process of extraction was done using a well-known algorithm known as a peak detection technique. The technique is implemented onto the raw data, transferring each pulse into a new variable matrix, replacing the removed pulse with a zero vector [20, 21]. To ensure the peak magnitude of the remaining pulses within the raw data is smaller than a pre-defined threshold value, this process was repeated several times. With this, the significant PD pulses can be isolated from background noise. Identifying the value of background noise via the signal plot of raw data which clearly show the noise level is very important before carefully setting a threshold value. If the threshold value was set too high, possibility of loss of PD pulse information will be immense. On the other hand, if the threshold value was set too low, PD events might be interpreted from noise pulses [22, 23]. For some cases, according to particular conditions, the threshold value can be differed. Figure 5 proves that the value of the threshold was set to 1.5 mV for both HFCT and ultrasonic sensor.

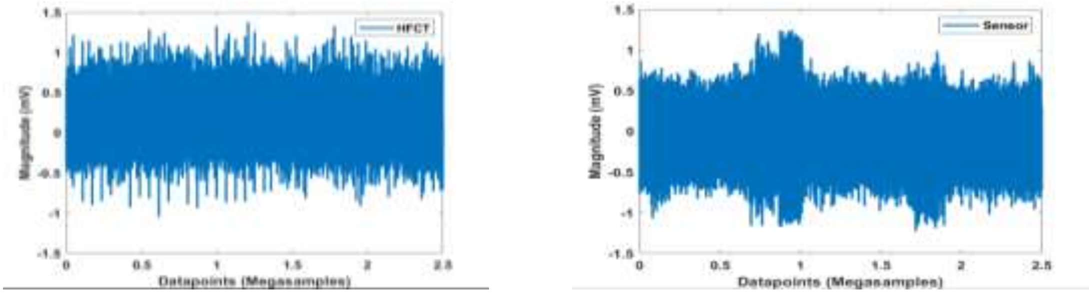
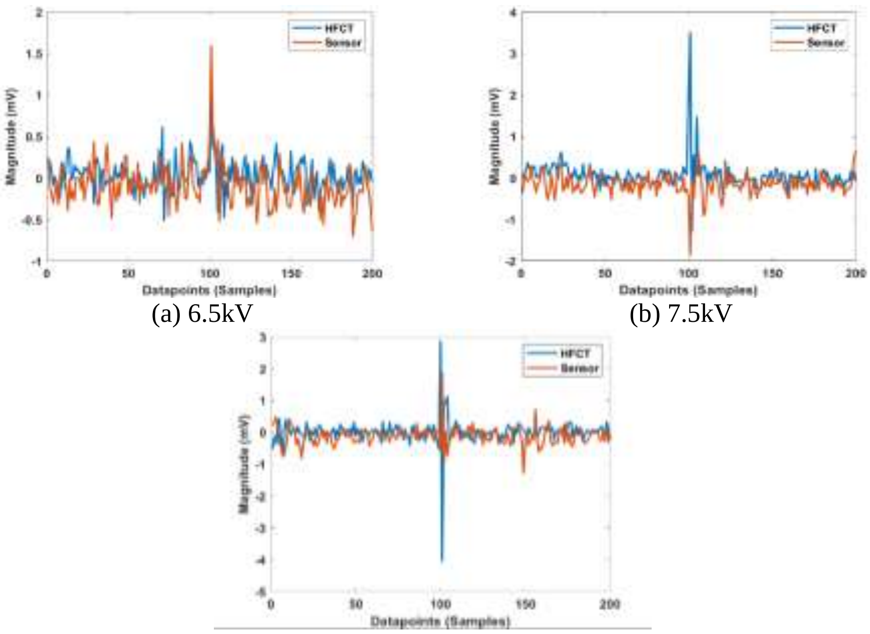



Figure 5. Threshold value was set to 1.5 mV for both HFCT and ultrasonic sensor

The background noise and the DC offset was then removed, and the pure signal from the HFCT and PDD devices is assumed to only contain PD pulses of interest [22]. The task of noise suppression within the PD data obtained can be carried out with various de-noising techniques. The techniques are known as Fast Fourier Transform (FFT) based de-noising, wavelet de-noising and low pass filtering [24-27].

## 5. RESULTS AND ANALYSIS

In this section, before a comparison can be made, the process of finding and matching the pairs of PD pulses from the HFCT and ultrasonic sensor was carried out by using the pulse pairing process which is based on a reasonable time of flight duration. In investigating the performance of the ultrasonic sensor, a main analysis was done by comparing in time domain of measured PD pulses from both measurement techniques. Figure 6 shows the correlation of individually measured PD pulses from the two measurement techniques under an applied voltage of 6.5kV, 7.5kV and 8.5kV respectively.




(a) 6.5kV (b) 7.5kV

(c) 8.5kV

Figure 6. Individual comparison of measured PD pulses from both measurement techniques under different values of applied voltage

Figure 6 shows that the sensor can detect most of the PD pulses detected by HFCT. However, the magnitude of measured PD signals from the HFCT is sententiously greater compared to the magnitude of pulses measured from the ultrasonic sensor. This is due to the nature of acoustic emission sensing method, which is affected by signal attenuation and extraneous noise while HFCT is not affected. Therefore, the waveform of the PD detected by ultrasonic sensor is affected, hence, the difference in magnitude. The values of PD captured are depending on the voltage applied during the experiment. Table 1 shows the maximum average magnitude of PD pulses captured by the sensor for each voltage applied. It is found that the higher the voltage injection into the cable, the higher the maximum average magnitude of the PD pulses detected by the sensor.

Even though the sensor is not able to capture the PD pulses as accurate as the HFCT sensor, ultimately the custom PDD sensor is still able to achieve the main objective of this research project, and that is being able to detect PD pulses in Medium Voltage XLPE cable due to void discharges. Further improvements of the ultrasonic sensor device will be amended in the near future if applicable. These are the advantages of the PDD sensor:

a) The value to assemble the Custom PDD sensor costs much less compared to purchasing a whole set of HFCT. This shows that the custom sensor has a large advantage of being very affordable and easy to maintain.
b) The custom PDD sensor is really easy to be installed and used as it only needs to be positioned horizontally and very near to a PD source. Unlike HFCT which needs to be positioned at the ground braided cable of the Medium Voltage XLPE cable, the Custom PDD sensor does not have to.
c) The customized PDD Sensor is much smaller in size compared to a HFCT sensor. This is due to the design of it’s Printed Circuit Board which emphasizes on functionally without having to sacrifice portability. Meanwhile, the HFCT is bulky and is quite a hassle to be installed on the Medium Voltage XLPE Cable.
d) The Custom PDD sensor is opened to a wide range of customization. Installing an artificial intelligence controlled by a microcontroller on the device is the next future step in making the sensor a SMART sensor, fulfilling the IOT aspects of futuristic design. This cannot be done on the HFCT sensor.
e) The custom PDD sensor can provide real time monitoring of PD. By using artificial intelligence, PD can be monitored in real time without having to turn off the power source of the PD. In laymen’s term, the custom PDD sensor can be used for online testing of PD, while HFCT cannot. Image classification of waveforms of PD can be amended into the future AI and this can help the sensor to better detect PD intelligently.

Table 1. Maximum Average Magnitude of PD Pulses Captured by the Sensor for Each Voltage Applied

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

## 6. CONCLUSION

This paper presents an insight on the design process of the PD Detection Device prototype. The objectives of this study which are to design a functional PCB diagram and to test the functionality of the PD Detection Device have been achieved. Studies also show that by using ultrasonic sensor to detect PD, the significant magnitude values can be obtained in order to predict PD severity value with reasonable accuracy. Results of the experiment infers that the PD Detection Device is functioning as expected and that the values of PD achieved are acceptable, and the waveform obtained is a PD waveform which almost equivalent to the waveform detected by the HFCT sensor. With regards to the finished fabrication of the device, some future improvements can be done unto the device if necessary. The future improvements are installing another ultrasonic sensor on the device to improve detection range and accuracy, and embedding Artificial Intelligence into a microcontroller that can be installed onto the device, so that the device is able to carry out Image Characterization of waveforms, in order to better detect PD waveform spikes.

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