OPEN ACCESS Journal

International

Of Modern Engineering Research (IJMER)

High Voltage Cables Fault Detection Using Partial Discharge – A Simulation Approach

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ABSTRACT :*Partial discharges (PD) can be used to measure the insulation corrosion and its lifespan. It is defined as a localized electrical discharge that partially bridges the insulation between conductors and which may or may not occur adjacent to a conductor. The purpose of this study is to investigate partial discharge signal generated by faults in high voltage cables and to enhance the detection of partial discharge using wavelet de-noising analysis. In this study a partial discharge model circuit was constructed physically and accordingly the PD model circuit was simulated using MATLAB Simulink considering the characteristics of the void in the insulation material. The results were recorded from both the physical circuit and the simulated circuit. Then the recorded data of the partial discharge signal was analyzed using wavelet de-noising analysis. From the results, it is found that there is a pattern between the input voltage and the amplitude of partial discharge signal. It is concluded that the size of void effects the production of the partial discharge, although there is no pattern between them.*
KEYWORDS:*Cable faults, High voltage cables, HV Cable maintenance, Partial discharge detection, PD Generation, PD Signal pattern, Void size and effect, Wavelet de-noising analysis.*

Date of Submission: 18-04-2018 Date of acceptance: 03-05-2018

I INTRODUCTION

The attention to fault detection and failure diagnose systems is increasing worldwide. The reason for this attention is the increasing interest and the rising demand for the best performance, increasing reliability, and the efficiency of the industrial systems. Failure diagnoses systems and fault detection methods are considered to be very important when considering the safety in industries. For example, automobiles industries, construction industries, chemical plants and power plants are types of industries that consider safety to be very important. Any fault or failure in the system of these industries is considered to be very costly. Therefore, when failure or fault is detected or diagnosed; maintenance should be done to the failed part of the system. This is one of the reasons for conducting this study on “High Voltage Cables Fault Detection Using Partial Discharge”. Maintenance is off three main types: preventive maintenance also called schedule maintenance, predictive maintenance, and condition based maintenance.

The preventive maintenance is also called scheduled maintenance. This type of maintenance is widely used in maintaining the electrical equipment. A wide-range test practices are conducted on the equipment while they are offline. Usually, the data collected from the conducted tests are mostly about the insulation resistance, its power factor, and standardized setting points. These data are then used to evaluate the existing state of the equipments of the system in the industry. When equipment is found to need maintenance it is again scheduled to execute maintenance. The major drawback in the preventive maintenance is that it is a costly maintenance method. That is because to do the maintenance the equipment have to be offline and it will only payback if there was failure that was avoided just before occurring.

Predictive maintenance is another type of maintenance where failures are predicted from the analysis of the tests’ results conducted on the equipments. Predictive maintenance is different test is done for each equipment to predict if it has a fault or not. Important values are observed and measured by the maintenance team and compare them to the standard values of the equipment. From the measured values engineers can predict the problem in the equipment, schedule the equipment to retest it and repair it. This type of maintenance is cost effective since the equipment is only offline when a problem is predicted, unlike preventive maintenance where the equipments are forced to be offline to do the check up procedures.

The third type of maintenance is condition based maintenance also known as CBM. Condition based maintenance is similar to predictive maintenance where data is collected from the equipments while they are online and compared to the standard and normal data that are accepted in the normal working conditions. The CBM is more thorough compared to predictive maintenance because it analyzes the collected data when the equipments are online and offline. When a test results in CBM indicates that the equipment is in an excellent or a good condition, it may skip the next scheduled maintenance. On the other hand, if the test results showed some deviation from the standard values, the equipment is scheduled from the next maintenance. Moreover, if the deviation in the results was found to be severe, the equipment removed from the system, retested and get repaired or replaced. This type of maintenance is very effective compared to other types because the numbers of equipments that need maintenance are reduced from the one maintenance period to the other. Since, only the equipments that are found to have problems are scheduled for the next maintenance period. CBM requires a computerized data base to collect, analyze, store test data, and compare it with the next scheduled maintenance period (Dileo, M., et. al., 1999) [3].

CBM method is usually used to monitor the partial discharge occurring in high voltage cables. PD is frequently observed in high voltage equipments such as transformers, transmission cables, etc. It is defined as an electrical discharge which is localized at a point in the insulation material. This discharge to some extent bridges the insulation between conductors. Partial discharges are usually a result of localized electrical stress whether inside the insulation material or in the surface of the insulation material. These types of discharges usually appear as impulses, which are pulses having duration of much less than 1μs. Partial discharge normally occurs in high voltage cables because of the voids which are air impurities bubbles created in the insulation layers of the cables. The dielectric constant of the void is less than the rest of the surroundings. Therefore, the void is responsible for partial discharge by weakening the insulation region near the void. A small discharge will only downgrade the performance. When partial discharge continues to take place, a major failure will occur in the insulation system (Sabat and Karmakar, 2011) [12].

Partial discharge can be detected using electric or non electric methods. Optical detection method, acoustic detection method, chemical detection method, and electrical detection method are one of the main detection methods used to detect partial discharge in high voltage cables.

When using the electrical detection method the voltage and current signals are measured and analyzed in time domain and frequency domain.

II REVIEW OF LITERATURE

The purpose of this study was to detect high voltage cables faults using partial discharge. This section reflects some of the most recent research and studies related to the variables in this study.

Muhr Schwarz (2006) [10] conducted a paper on ‘Partial Discharge Measurement as a Diagnostic Tool for HV-Equipments’. The purpose of the paper was to give an overview of different techniques and methods for partial discharge measurements. According to them the partial discharge measurement is a fixed method in industrial applications as a non destructive high voltage test so that it gives an early warning about the condition of the insulation system of the high voltage equipment. The authors defined partial discharge as small electrical pulsation from the electrical fail in a cavity or in an extremely stressed electric field of the insulation. Furthermore, the authors explained a number of detection methods such as Conventional Measurement of Partial Discharges, UHF Measurement of Partial Discharges, HF Measurement of Partial Discharges, Acoustic Measurement of Partial Discharges, Chemical Verification of Partial Discharges, and Optical Partial Discharge Detection.

Sabat and Karmakar (2011) [12] conducted a study to investigate the simulation of Partial Discharge (PD) activity due to presence of a small cylindrical void inside the solid insulation material of high voltage power equipment using the MATLAB Simulink platform. According to the authors, a variety of solid, gaseous, liquid and combination of these materials are used as insulation in high voltage power equipment. The quality of such insulation plays an important role on HV power equipment in view of quality assessment. However, the insulation of power equipments are gradually degrades due to the cumulative effects of electrical, chemical and mechanical stresses caused by the partial discharges (PDs). The authors stated that PD phenomenon usually commences within the void, cracks, in bubbles within liquid dielectrics or inclusion within the solid insulating medium. In addition, PDs also occur at the boundaries between the different insulating materials, contamination, poor conductor profiles and floating metal-work in the HV equipment. The main purpose of the study was to investigate the maximum PD magnitude, number of PDs and number of other PD related parameters like PD distribution, frequency content of obtained PD pulse by using phase resolves partial discharge (PRPD) measurement technique. The schematic diagram for detection of partial discharge inside the solid insulation consists of high voltage transformer (Vs), filter unit (Z), high voltage measuring capacitor (Cm), coupling capacitor (Ck), void model of solid insulation called as test object (Ct), detector circuit for measurement of partial discharge (Zm) and the measurement instrument (MI). The detector circuit for measurement of PD is a parallel combination of the resistor, inductor and the capacitor. The cylindrical void model (test object) of the insulating material is represented as 'abc' diagrams. It is observed that the apparent charge is also a function of volume geometry of the cylindrical void model. It is also observed that, the volume is directly related to apparent charge. It is also observed from simulation result that the relation between void volume and apparent charge curve is a linear one. The authors concluded that Partial discharges are a major source of insulation failure in high voltage power system which needs to be monitor continuously to avoid the incipient failure in the power system network. It is also concluded that the PD activity inside the solid insulation is highly depends on the entire geometry of the void presence inside the solid insulation model. In addition, PD is increases with the increase of applied voltage inside the solid insulation.

Danikas and Karlis (2011) [2] conducted a paper on Partial discharge diagnostics in wind turbine insulation. The purpose of this paper was to review work undertaken on partial discharges and their influence on the insulation of wind turbines. Although in general, large PD causes insulation failure in machines, attention has to be paid also to small PD. PD phenomena tend to become even more serious when they are combined with stresses of other types (e.g., thermal, mechanical), some of which have a cumulative effect on the insulation. The problem of PD in machine insulation is to be considered with the more general problem of combined stressing on electrical equipment. Wind generators are subjected to a number of stresses, which may be simultaneous. A factor to bear in mind is the salinity of the sea, especially for wind generators functioning off shore. This paper concentrates mainly on the deteriorating effects of PD no matter where they come from. No special consideration has been given to the problems arising from pulse-width modulation (PWM) converters directly connected to the rotor winding. The authors in this paper provided a review on PD was given regarding wind turbine insulation. The general approach concerning this insulation is not that different from the diagnostic techniques in other types of machine insulation. The peculiarity of wind turbines is that they have frequent starts and, in this way, they may stress even more their insulating parts. This peculiarity may mechanically stress the generator, given the different coefficients of expansion of the insulation, and copper and iron parts within it. Such frequent starts may also induce magnetic forces by the flow of large magnitudes of starting currents and large accelerating torque values, which in turn may add to the mechanical stress. According to the authors, wind turbine insulation is a good example of insulation subjected to a multitude of stresses.

A study conducted by Stenzel and Chenen (2008) [11], investigated the fault location approach for EHV overhead line combined with underground power cable. They developed an accurate fault location method considering the special characteristics of combined transmission lines with power cables which can locate the fault position with high precision in 40 ms after the fault has happened. The fault location system with the new method has been modeled and tested with the field conditions. Connection of the location device in CO type EHV combined line system is shown below:

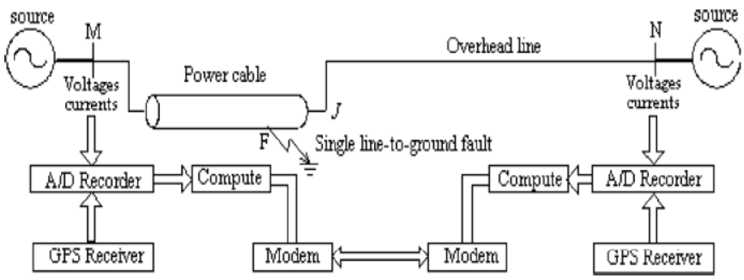


Figure 1: Connection of the location device in CO type EHV combined line system

Their analysis reveals that the negative sequence voltages at the fault point and at the junction have different characteristics when the fault occurs in the overhead line or in the power cable, which can be used to discriminate the faulted section. The analysis` also shows that the fault resistance and unsynchronized data do not have influence on the fault location precision. According to the authors the new method can be used with high precision under different conditions both in CO and OCO combined line systems.

Badrzadehand Shahrtash (n.d.) [1] conducted a study describing application of two digital signal-processing techniques (Linear prediction and Discrete Wavelet Transform) to partial discharge site location. These techniques have been used for both on-line and off-line PD location. According the authors, the distribution of power in industrial complexes often relies in medium voltage shielded power cable systems.

Power outages due to failure of cables or their accessories during operation could cause the forced interruption of critical processes. It is therefore important to know the state of health of the cable network (as one of the asset) in an electricity supply system. Although, various methods of noise reduction have been developed and proven successful in on-line and offline PD measurements such as correlation, adaptive filtering, the researchers in this study used the Open-loop noise reduction techniques such as wavelets to measure the noise prior to a measurement (Closed-loop noise reduction) thus computational time increasing dramatically. The main focus of the study was on two digital filters: Linear Prediction (LPC) and Discrete Wavelet Transform (DWT). The authors presented two methods for PD location in cable networks. In off-line PD location, PDs are located by TDR principle (One end measurement) and noise suppressed by LPC and DWT. The Results revealed the effectiveness of both algorithms. While in on-line PD location, PDs are located by arrival time (Two end measurement) method and results show the effectiveness of DWT noise suppression (LPC doesn't show an effective performance in on-line PD location). The results also show the effectiveness of these algorithms when applying them to the acquired signal and one can obtain almost the true shape of PD signal under noisy conditions.

Liu, et al. (n.d.) [5] developed a study on the propagation of PD pulses in a HV Cable. The authors examined the effect of PD pulse propagation in high voltage cables. The study mentioned that PDs are generated because of voids overstress. In the experiment conducted by the authors a capacitive sensor was used to measure the pulse transmission with the use of high frequency response. The authors compared the theoretical results with the experimental results and found that they significantly agree with each other. In this study it was found that there were some errors occur in locating the PD. The error of location is primarily produced by the high frequency attenuation which is not only linked with pulse itself but also its propagation characteristics. Moreover, the experimental and analytical results found in this study showed that when faults takes place near the measurement point, more high frequency components can be discovered. The authors concluded that proper design of high frequency couplers to find out the mentioned high frequency components could be another method of monitoring PDs in HV cables.

Valatka, Sučila, and Daukšys (2003) [14] investigated the voltage influence on partial discharge characteristic parameters in solid insulation. They pointed out that partial discharges are different from other electric discharges by its character, and it is unipolar process. According to the authors partial discharge can occur at the weakest insulation and from a strong electric field near the sharp electrode edges too. In addition, most dangerous partial discharges occur in liquid or solid insulation voids and gaseous micro-layer junctions and cracks, where the discharge processes occur at much weaker than the electric fields in liquid or solid insulation whole paragraph.

The figure below illustrates the simulation results of partial discharges current pulses in the model for one period. During the investigations of spherical defects, the authors found out that initial partial discharge (10 pc) begins when the defect size reaches 0.5 mm, while, for the solid insulation the initial permissible level of partial discharge (50 pC) is when defect size reaches 1.8 mm. However, the critical partial discharge capacity (1000 pC) is achieved when the defect is 4 mm. The authors noted that at this size of defect in the insulation begins intensive insulation dielectric breakdown processes.

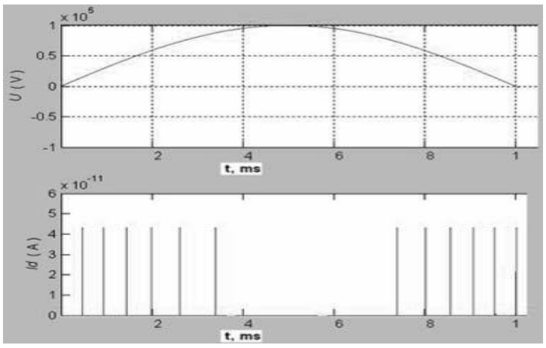


Figure 2: The simulation results of partial discharges current pulses in the model for one period

When the authors conducted an investigation of equal volume and equal linear sizes, but of different structural shapes of defects in the insulation, it appeared that the form of the defect has no significant impact on the amount of partial discharge characterizing apparent charge, but it was noted brief influence on partial discharges energy.

The authors concluded that for the spherical defect case initial partial discharge (10 pC) starts when the defect size reaches 0.5 mm. They also noted that initial permissible level of partial discharges (50 pC) starts when defect size reaches 1.08 mm, while the critical partial discharges capacity (1000 pC) is achieved when the defect is 4.5 mm.

Yonghong, et.al. (2003) [14] conducted a study on the Partial Discharge Characteristics of the XLPE Insulation Samples during Electrical Treeing Ageing. The condition of electrical tree initiation is well established under ac stress. Specimens using point-plane electrode geometries in XLPE insulated samples have been investigated. The authors pointed out that the characteristics of UWB partial discharge signals have a change observably in the time-domain and frequency-domain during electrical treeing. The high energy density area of the partial discharge signals of the XLPE insulation specimens moves to the higher frequency during electrical treeing. Therefore, the status of XLPE insulation can he evaluated by detecting the partial discharge signals occurring in them. It is important of this research for evaluating the status of XLPE power cables in service.

Two kinds of partial discharge detecting method, TE571 partial discharge detector and UWB partial discharge detecting system are used to study the ageing characteristic of XLPE insulation in this paper. These methods could detect discharge signals well and there was a definite homologous relationship between them. The statistical parameters detected by TE57 1 varied obviously during the electrical treeing of the XLPE insulation specimens. Especially, the skewness of the phase-position quantities changes from positive to negative when the XLPE specimens were aged. The UWB discharge characteristics also changed. The amplitude of discharge waveform in time-domain increased greatly (from 2mV to 17mV) during ageing. Furthermore, the characteristic peaks of discharge are moving to higher frequency with ageing time adding. Before aging, the high energy density area of the discharge signals located up to 15MHz. It located in the range from 2MHz to 30MHz after ageing for 20 hours. And after ageing for 50 hours, the range of discharge in the spectrum is from 0 to 5OMHz and from 125MHz to 200MHz. So the skewness of statistical parameters of partial discharge and the characteristic peaks of UWB discharge can be used to new feature parameters for XLPE detecting.

The TE571 PD detector was applied to detect the discharge signals in XLPE insulation specimens during electrical ageing. From the frequency-domain waveforms illustrated below, it appears that the discharge frequency locates on a wide range. The results indicated that before ageing, the discharge energy locates on the low frequency domain. On the other hand, when the time of ageing is longer, the discharge frequency moves to high frequency domain.

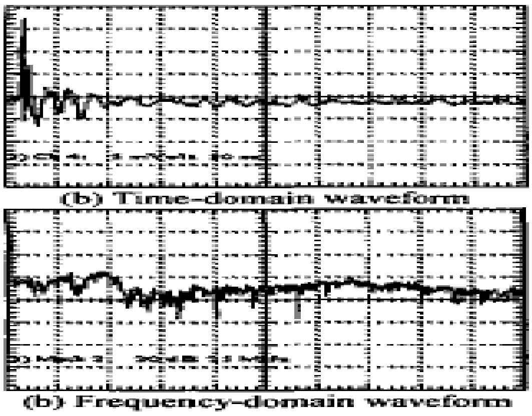


Figure 3: The frequency-domain waveforms

The authors found that the characteristic peaks of discharge are moving to higher frequency with ageing time adding. So, the insulation status can be evaluated by the characteristics of UWB partial discharges.

Ljumba (2008) [6] conducted a study investigating the factors and design considerations in the High voltage cable insulation systems. The author claims that partial discharges occur in voids or at protrusions that occur in the insulation due to manufacturing systems flaws and contamination. Voids can also occur due to expansion and contraction of the insulation, caused by changes in the loading cycles of the cable. The gas in the void has a lower permittivity and dielectric strength compared to the surrounding solid insulation. As illustrated in the figure below, the electric stress in the void is enhanced by a factor equal to the relative permittivity of the insulation and this could cause a discharge if the breakdown strength of the gas in the void is exceeded.

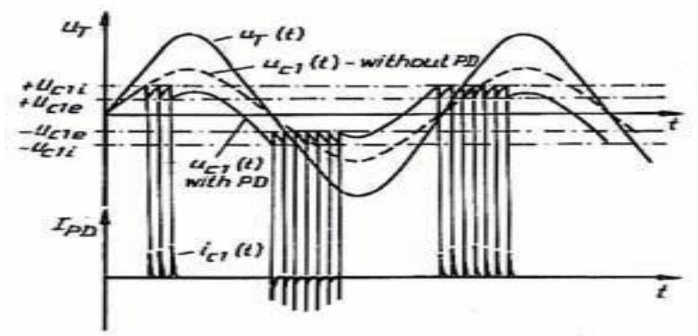


Figure 4: The electric stress in the void is enhanced by a factor equal to the relative permittivity of the insulation

The study shows that the operating electric stresses of cables are in the range of 3-11 kV/mm, which is much lower than the withstand capacity of insulating materials used. According to Ljumba (2008) [6], the electric stress in practical cables is reduced by the following factors:
• Increased operating temperatures
• Length of operation
• Length and thickness of insulation (high probability flawed insulation)
Test data in this study show that electric stress has a big influence on the ageing rate (see figure below).

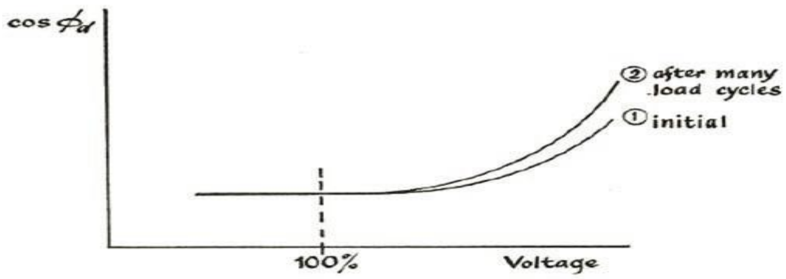


Figure 5: The influence of electric stress on the ageing rate

The allowance made for ageing has an influence on the eventual size of the cable. The author identified a number of design considerations such as:
• Semi-conducting cylinders in polymer cables for stress control.
• Filling voids with oil in oil filled cables.
• Increasing of pressure of gas in voids in pressurized cables Condition monitoring.
Ljumba concluded that the condition of the cable insulation is usually monitored through two main methods:
• Loss tangent measurements in which the variation of tan δ with temperature and voltage is measured periodically. In a good material, tan δ should be small and constant over the operating voltage range. A different characteristic is an indication of faulty insulation.
• Partial discharge measurements in which the health of the insulation is indicated by the patterns of the pulses recorded. Accordingly, partial discharge measurements require specially shielded laboratory facilities and equipment to ensure that the results are not affected by of any external interference.

Vedral, and Kriz (2010, pp. 55-64) [15] conducted a paper comparing between the traditional and modern ways in measuring and diagnosing the condition of the high voltage insulation system. The authors examined four measurement methods, two were analog based methods and two were digital based methods. The analog based methods are the traditional methods. The first on was a signal chain with a circuit that detects the peak with a slow ADC, while the second analog method was a signal chain with logarithmic amplifier and the same peak detection circuit and ADC. The digital based methods were a digitalized wideband PD signal chain and a digitalized narrowband PD signal chain. The authors compared all the four diagnosing ways and found that all the four signal chains can benefit the measurement of PD signal by saving time and resources if used for online diagnostic measurement.

In the literature review all the authors agreed on that the insulation failure is mostly because of partial discharge. Most of the authors gave the same definition to partial discharge and explained its causes. The majority of the literature reviewed mentioned different types of PD detection using different types of sensors. All the authors agreed on PD detection and measurement is necessary to predict the insulation lifespan for HV power equipments and cables. Moreover, they highlighted the fact that PD detection can assure high quality of insulation in HV cables and equipment. Furthermore, there was a consistency in using the electrical PD detection method more than the other detection methods.

III. THEORETICAL BACKGROUND

1.1 High Voltage Cables (HV Cables)

Normally cables can be defined and characterized as low voltage, medium voltage, and high voltage cables. Therefore, the requirements such as maintenance strategies, testing, and locating the faults, differ between the cable types and they are defined according to the cable type.

However electricity power is transmitted in terms of high voltage. Therefore, HV cables are used to do the transmission of the power. Furthermore, these power cables are classified by the type of their insulation system, so, basically there are four types of cables. They are the low density polyethylene (LDPE), high density polyethylene (HDPE), cross linked polyethylene (XLPE), and ethylene propylene rubber (EPR) (Ljumba, 2008) [6].

Figure 6: Single core, XLPE insulated (Ing. Tobias Neier, 2009)

The insulation systems in these cables should be characterized with a high dielectric strength to survive the regular and standard operating and impulse voltages. Therefore, when the operating and impulse voltage fluctuates beyond the normal tolerance of the cables insulation system; there will be a high chance of defects occurring in the insulation system, resulting in faulty cables.

1.2 Types of Faults in the Cables

The faults in cables are like any other defects that affect the performance of the cables by causing inconsistency, non-homogeneity current flow, or weakness in the cables.
Cables can be subjected to a number of defects and faults, for example, electrical trees coupled with water trees, de-lamination, and another fault or defect is the physical damage produced by violent handling.

- Electrical trees

Electrical trees are a phenomenon when there is an electrical pre-breakdown in solid insulation. It is known as a damaging process that develops through a stressed dielectric insulation material in a path similar to the branches of the trees. The figure below shows how an electrical tree looks like.

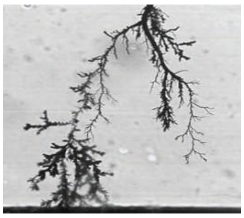


Figure 7: Electrical trees

It occurs when a dielectric material is subjected in an extended period of time to a deviating and high electrical field stress; it has been observed that the electrical treeing starts from some of the cable manufactured defects such as gas voids and impurities, or such as mechanical defects. These defects cause in a small dielectric region an extreme electrical field stress (William and Thue, 1997) [16].

- De-lamination

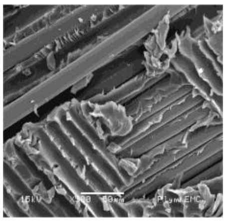


Figure 8: De-lamination

The de-lamination is a type of fault that occurs in composite materials, such as, insulation material. De-lamination occurs when the composite material layers starts to separate or breaks down into layers. The cause of de-lamination is the weakened bonds that hold the layers of the material together. This type of fault causes an unexpected breakdown, since it happens inside the material and it does not necessarily show any signs of wear. Moreover, there are a number of factors that boost the speed of de-lamination, for example, the rapid rise or fall in the temperature and pressure. Generally speaking, the process of de-lamination is extremely developed when wear signs are shown outward (McGee, 2012) [8].

1.3 Generation of Partial Discharge Signals

The starting points for partial discharge to generate are normally the voids, impurities in the dielectric material, or cracks. These points are usually between the conductor and dielectric material. The starting points of partial discharge differ according to the type of the dielectric material. For example, bubbles in liquid dielectrics and gas voids or cracks in solid dielectrics. The occurring discharges are limited to a small portion of the insulation material; therefore, they partially link the space between the electrodes.

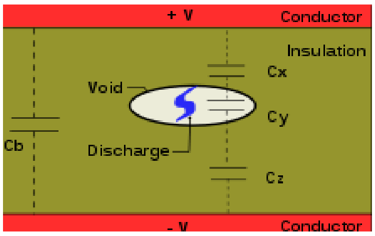


Figure 9: Void inside a cable represented by a capacitor

When considering a solid dielectric material, the partial discharge will initiate from a gas filled voids. The reason for that is deference between the dielectric constant of the void and the surrounding dielectric – insulation- material, where the dielectric constant of the void is significantly less compared to the surrounding dielectric material, while the void has a much higher electric field across it compared to the equivalent distance of dielectric. As a result to the deference in the dielectric constant and the electric field, the partial discharge activity will start in the void when a voltage stress increases across the void to be above the halo foundation voltage for gas in the void. Furthermore, partial discharge can occur in another place of the insulation material of the cable, that is, it can cause a breakdown along the insulation surface by occurring along the surface of the solid insulation only if the surface was at a tangent with a high enough electric field.

1.4 Parameters of Partial Discharge Signals

In general, the partial discharge (PD) signal has a certain parameters that characterize it. There are three main parameters, the first one is the rise time (Tr) which is the time needed for the signal to rise from 10% to 90% of the peak pulse value. The second parameter is the decay time (Td) which is the time needed for the signal to decay from 90% to 10%of the peak pulse value. While the third parameter is the pulse width (Tw) which is the time period between the 50% of the peak pulse value on both sides of the peak. The following figure illustrates the parameters of the partial discharge signal.

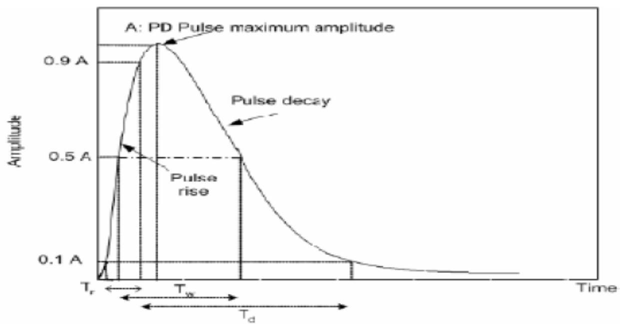


Figure 10: Parameters of the partial discharge signal

IV. METHODOLOGY

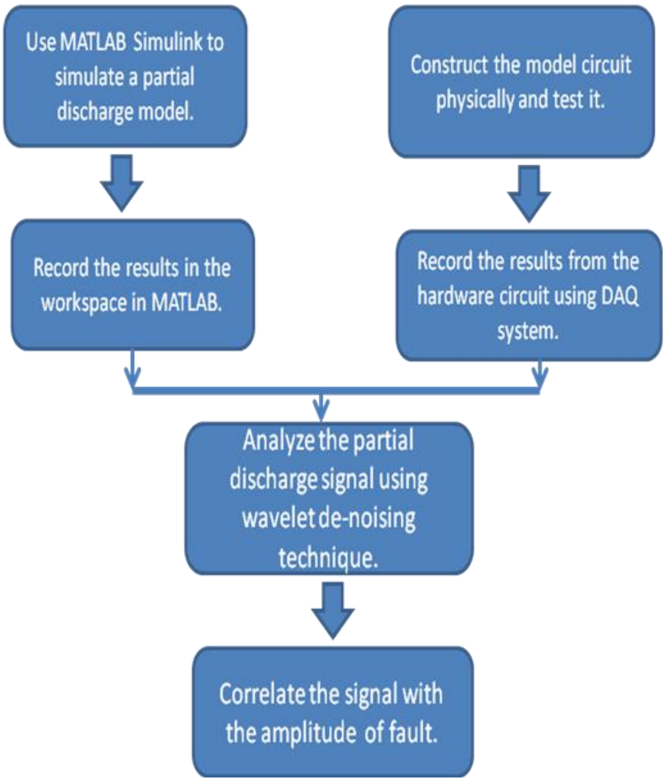


Figure 11: The methodology flowchart

This study was conducted to investigate partial discharge signal generated by faults in high voltage cables. In order to study the partial discharge signal generated by a faulty high voltage cable, two methods were used to acquire the partial discharge signal. One method was using MATLAB software to simulate the circuit that will generate the PD signal from a faulty cable using Simulink application. This method started from learning about Simulink application, then designing the circuit to be simulated using SimPower Systems toolbox. After that the required data analysis was done.

The second method used to acquire the PD signal generated by a faulty cable was using a hardware circuit. The circuit was constructed, soldered, and tested to get the results from it. Moreover, to do the data analysis on the hardware circuit results, a Data Acquisition Card (DAQ system) from National Instruments was used to capture the PD signal from the circuit.
The results from the two methods were analyzed using wavelet de-noising analysis and compared to each other.

1.5 The Software Circuit

A small and simple equivalent circuit well-known as the capacitance model represents the behavior of the partial discharge signal in cavities, voids, and defects in the dielectric material. The circuit below shows the capacitance model that demonstrates a void inside a dielectric material.

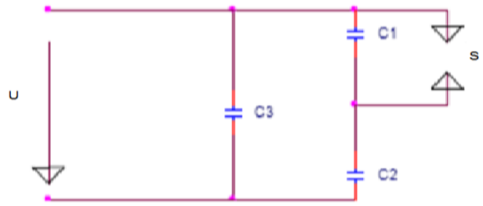


Figure 12: Capacitance model

In the figure above it can be seen that the applied voltage is given as (U), the cavity is represented by the capacitor (C1), the insulation material around the cavity is represented by the capacitor (C2), while the remaining insulation material is represented by the capacitor (C3). The figure also shows (S) as the spark gap that represents the discharge of the capacitor (C1).
The capacitance model had to be improved because it does not give an accurately correct result, since, it does not consider the parameters of the cavity or void. There are a number of modified models of partial discharge circuits based on the characteristics of the dielectric material, whether it is a solid dielectric or a liquid dielectric. Otherwise, the model would be modified based on void characteristics and dimensions. The different models for the same circuit will generate the partial discharge (PD) with different characteristics in different conditions.

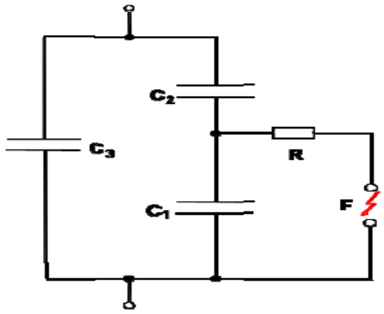


Figure 13: A modified capacitance model

The above figure shows a modified capacitance model having a current limiting resistor.The final extended circuit used in this study looks like the circuit in figure below. This circuit has a capacitor which represents the local charge growth.

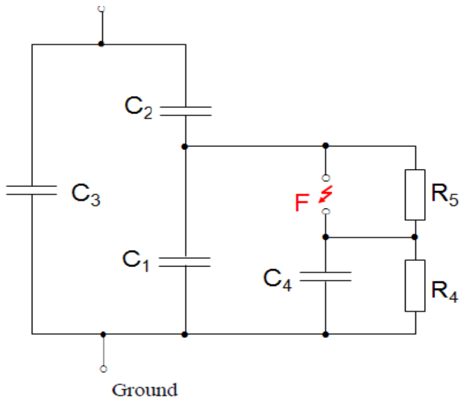


Figure 14: The final extended circuit

The circuit was then built in Simulink in MATLAB to be simulated and get the partial discharge signal. To implement the circuit properly, the spark gap was replaced by a circuit breaker. The circuit breaker was set to a defined timing (Taufik, 2009) [13] to signify the time where the PD signal will occur.

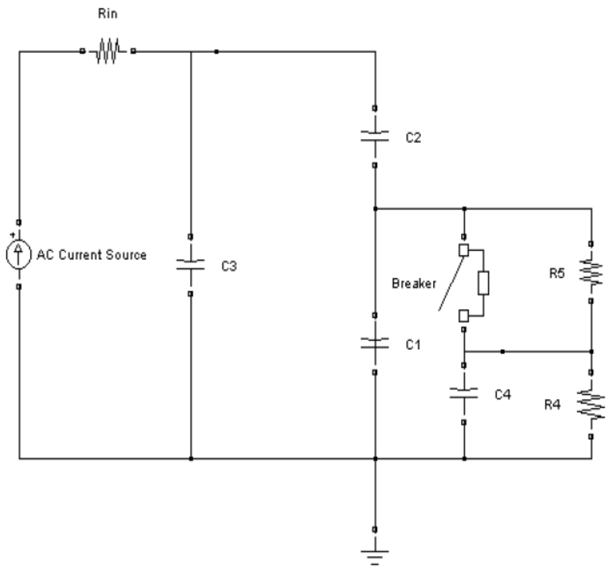


Figure 15:The circuit simulated in MATLAB Simulink

The model used in this study was based on the characteristics of the void in the dielectric insulation material.

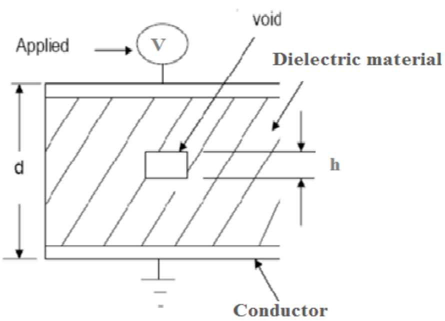


Figure 16: The void inside thedielectric material

The required factors to get the suitable values for the designed PD circuit are the parameters of the void, such as the height, the diameter, and the area of the void and the permittivity of free space (ξo) parameter.

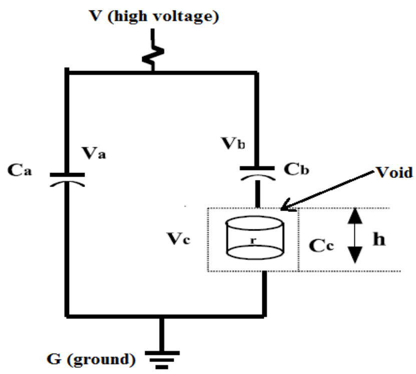


Figure 17: The relation between the void and the capacitance model

The above circuit shows the relation between the void and the capacitance model, where it shows that the capacitor (Cc) represents the void inside the solid dielectric insulation in the shape of cylinder. Usually Cc

has the lest capacitance since normally Ca>>Cb>>Cc. Also, Cc is the responsible for the incidence of break down.
A void of a cylindrical shape having a height of 0.002m and a diameter of 0.01m was considered to get the value of Cc. letting the void to be sited at the center of the sampled insulation material, the capacitor Cc is calculated using the following equation,

$$C_C = \frac{\varepsilon_o \times A}{h}$$

Where A is the area of the void, h is the height, ξo is the permittivity of free space.
The values of the component parameters are shown in the following table:

Table 1 : The parameter sittings

Parameter	Value	
Input AC	50 Hz, 10KV	
Rs	5KΩ	
Ca = C3	4.83 pF	
Cb = C2	3.89 pF	
Cc= C1	2.77 pF	
Cd= C4	1pF	
R1	5KΩ	
R2	10KΩ	
Breaker Timing	Open	1/60
	Close	1/55
White Noise	Noise Power	0.9
	Sample Time	0.0005
	Seed	23341

The above sittings were done to the circuit model as below. Also, scopes were embedded to get the readings of the output. Moreover, the solver used for this simulation was ordinary differential equations solver ODEs. It is normally used to solve unbendable problems but in low accuracy. The solver type was ode23tb.

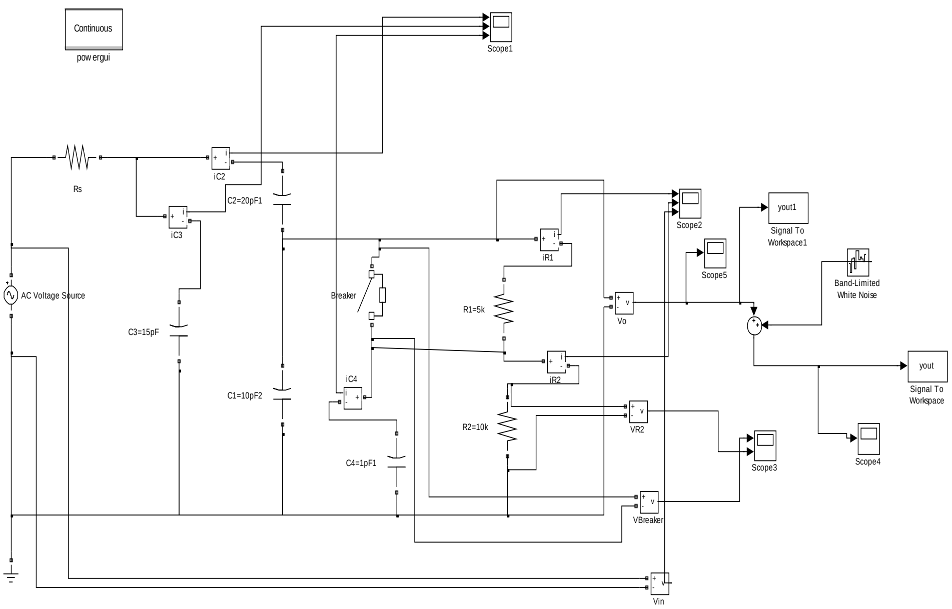


Figure 18: The simulated circuit with the scops connected

1.6 The Hardware Circuit

A first order high pass filter (HPF) was used in this study because it generates a signal that has similar characteristics as the characteristics of partial discharge signal. HPF only generates this signal when a pulse waveform is applied to it using a non-inverting amplifier. The figure below illustrates the circuit diagram.

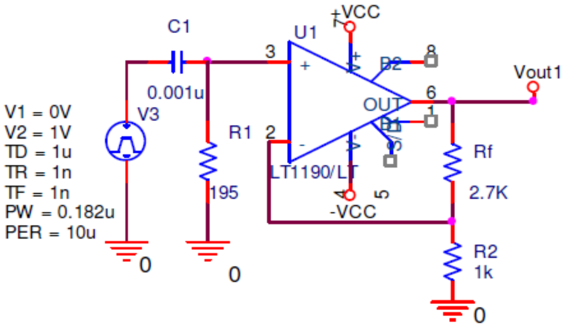


Figure 19: HPF circuit diagram

According to Mothiki, 2007 [9] the design steps of the above circuit are as follows:
The pulse wave input is,

V0= 0 (zero)
V1= 3Volts

The high pass filter (HPF):

The lower cutoff frequency fL= 813.3KHz

Using the HPF formula,

$$f_L = \frac{1}{2\pi \times R_1 \times C_1}$$

Taking C1 = 0.001uF, then R1 will be calculated as 195.69Ω.
The next step is to find R2 and Rf from the equation of the non-inverting amplifier which is as follows,

$$Gain = 1 + \frac{R_f}{R_2}$$

Equating the gain to 3.7 and taking Rf as 2.7KΩ, R2 is found to be 1KΩ.
The circuit was then built on a copper board and soldered to carry out the tests and record the reading to do the analysis on them. The circuit is shown in the figure below.

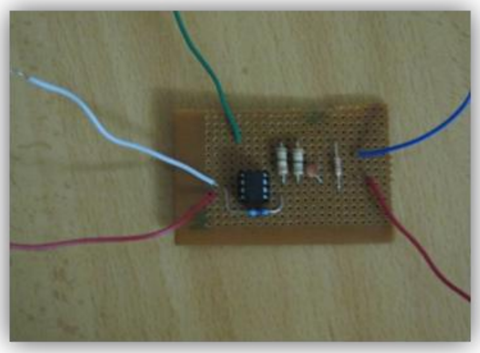


Figure 20: Soldered circuit

The following figure illustrates the experimental setup; where the circuit was connected to the Data Acquisition Card (DAC) system and the DAC system transfer the output to the computer using Lab View software.

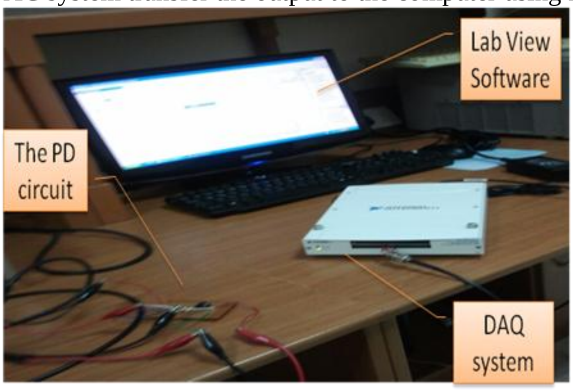


Figure 21: Experimental setup

1.7 Wavelet De-noising Analysis

Since the original signal captured has noise associated with it; it is very essential to apply a de-noising analysis to the signal in order to get and find the characteristics and features of the wanted signal. There are a number of analysis methods and techniques used in condition based monitoring or maintenance (CBM), for example, Fast Fourier Transform (FFT) analysis, Time Domain analysis, and Wavelet Transform analysis. In this study Wavelet Transform analysis was used instead of FFT or Time Domain analysis because FFT and Time Domain consider two dimensions only the amplitude verses the frequency and the amplitude verses the time correspondingly, whereas the Wavelet Transform consider 3 dimensions the amplitude, frequency, and the time. As a result, this will give a better understanding to the features and characteristics of the signal. When using Wavelet Transform analysis there are a number of wavelet shapes to select from. The selection of the wavelet is based on the signal nature and the needed information from the signal. For example, here Morlet wavelet was chosen because the nature of the partial discharge signal and the required data to be extracted from it are similar to the Morlet wavelet. The Morlet wavelet is shown in the following figure.

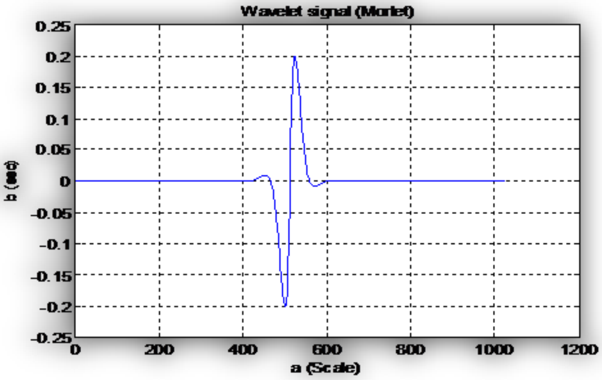


Figure 22: Mortet wavelet

In order to perform the Wavelet De-noising analysis, there are three stages the wavelet transform, the threshold, and the inverse wavelet transform. In the wavelet transform there will be wavelet coefficients which are functions of scale and position. In this process convolution is done to get the wavelet coefficients. The similarity between the signal and wavelet function is represented by the magnitude of the wavelet transform. After the wavelet transform threshold is done for its coefficients. The next and last stage is the inverse wavelet transform to get the original signal with the noise eliminated from it.

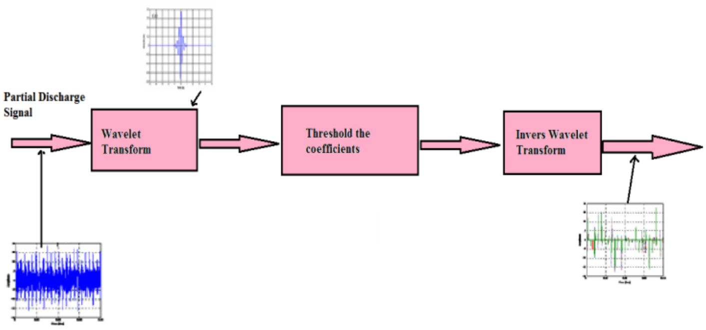


Figure23: Stages of wavelet de-noising analysis

V. RESULTS AND DISCUSSION

In this chapter the results of the software and the hardware will be displayed and discussed.

1.8 Software Results

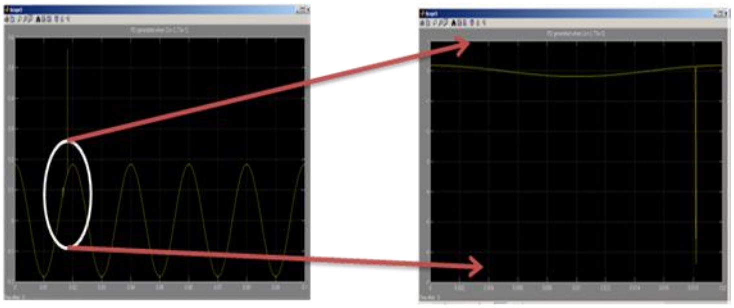


Figure 24: Output of the simulated circuit

The above figure illustrates the output of the simulated circuit taking the void height as 0.002m and its diameter as 0.01m. On the other hand, for the same sittings a noise was added to the output and the wavelet de-noising analysis was applied to get the original back. This is illustrated in the following figure.

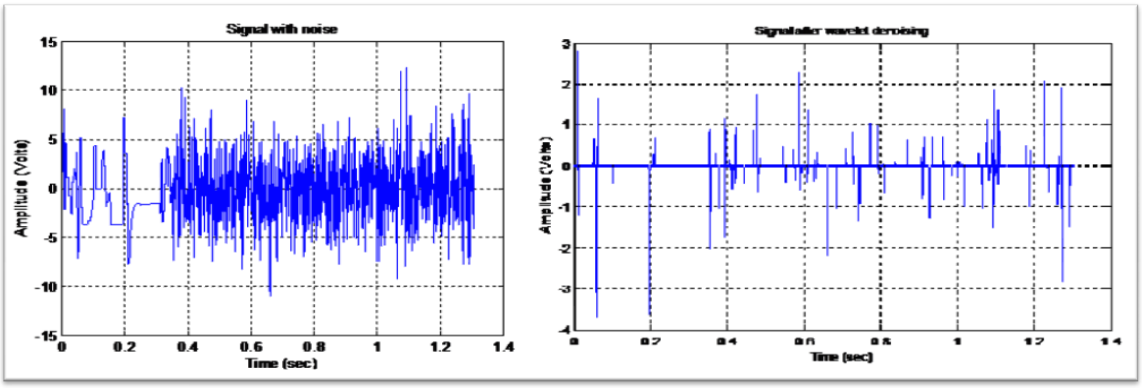


Figure 25: Output of the simulated circuit with wavelet de-noising

The results proved the efficiency of the wavelet de-noising analysis as shown in figure above.

1.9 Hardware Results

In this section the experiment was done with different input voltages to study the affect of the input voltage on the partial discharge signal.

For 2 volts input the results were as follows:

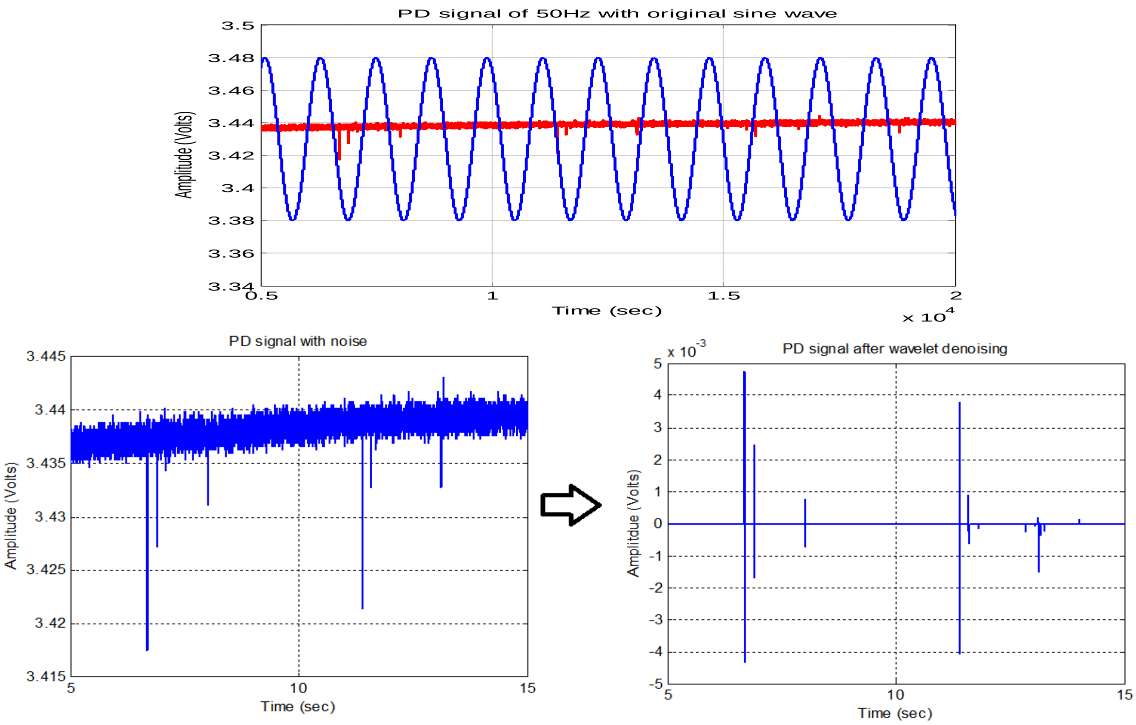


Figure 26: 50Hz and 2 volts PD signal

For 3 volts input the results were as follows:

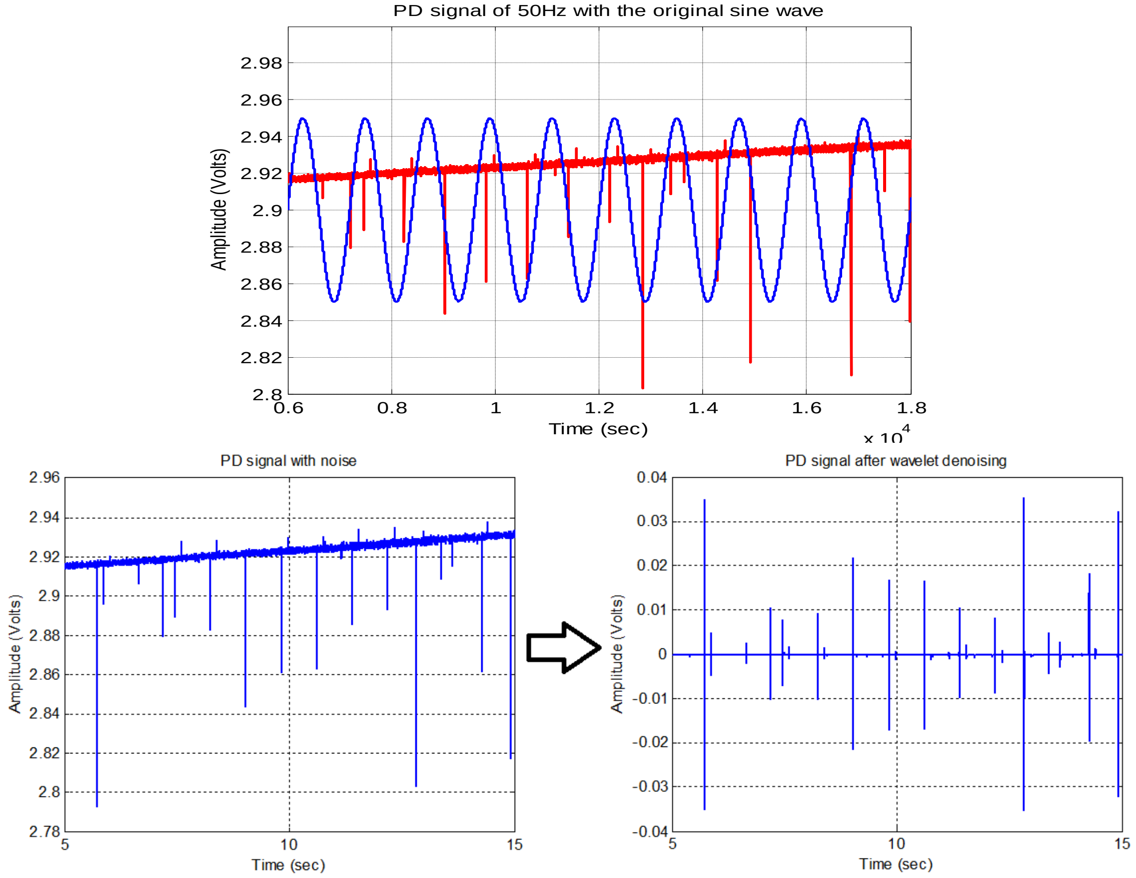
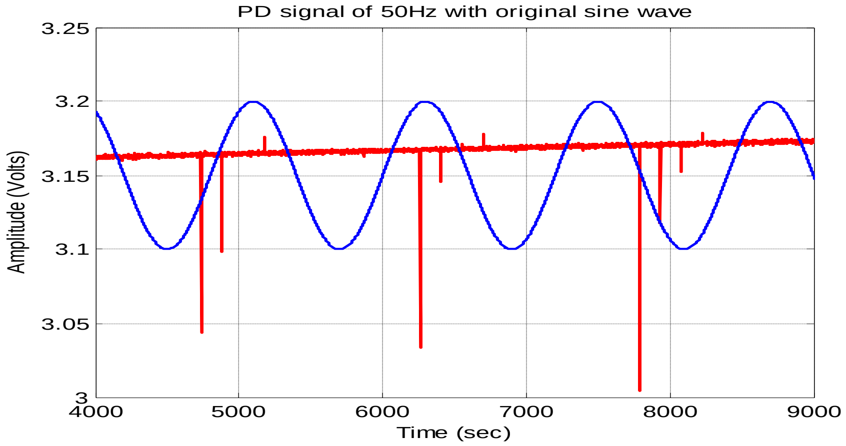


Figure 27: 50Hz and 3volts PD signal

For 4 volts the results were as follows:



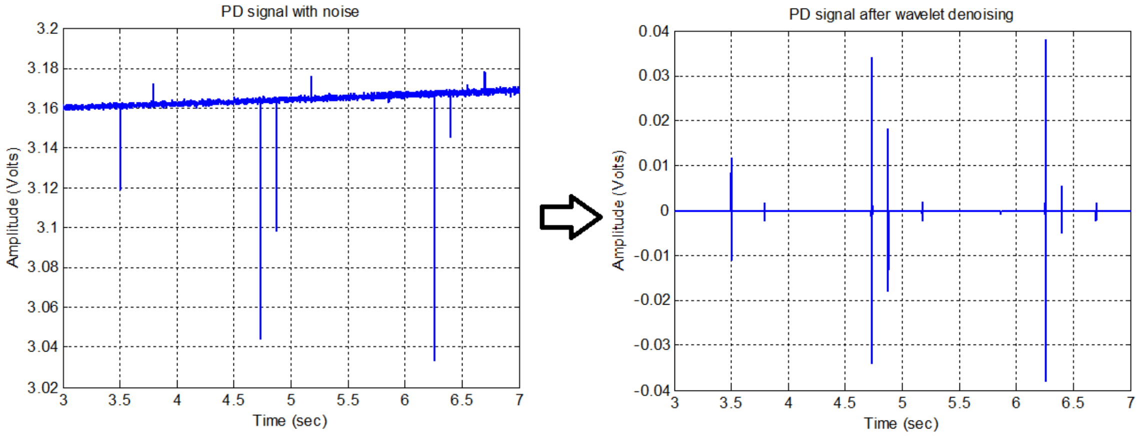


Figure 28: 50Hz and 4 volts PD signal

For 5 volts the results were as follows:

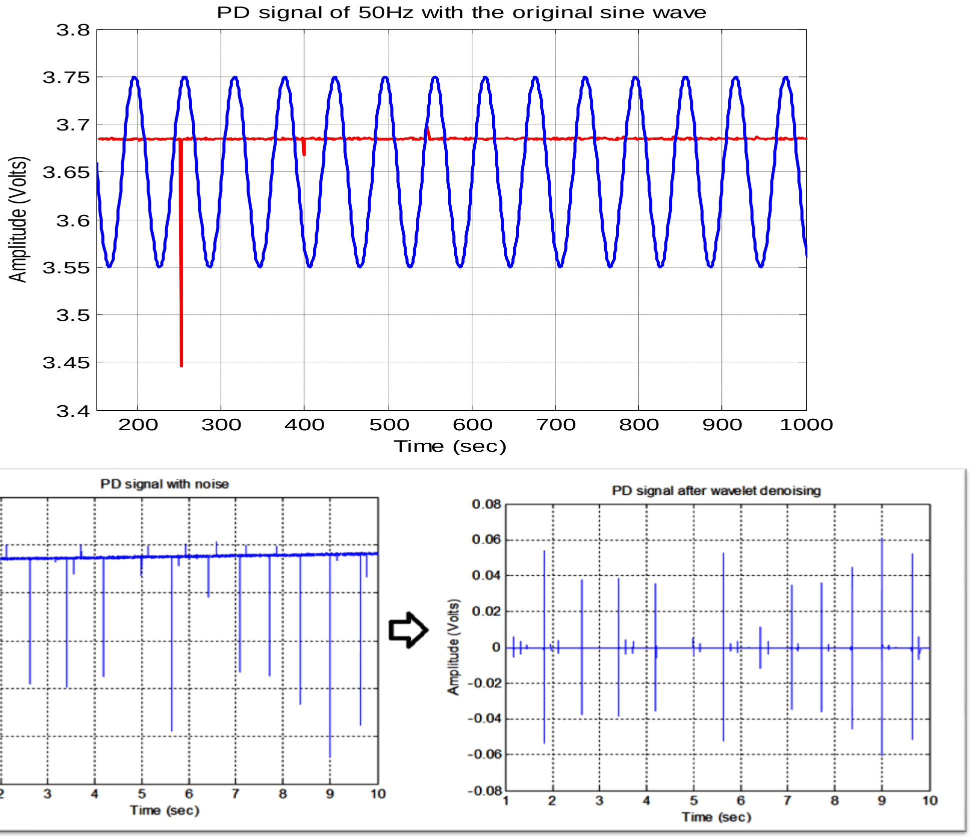


Figure 29: 50Hz and 5 volts PD signal

The results of the hardware throughout the range of applied input voltage showed that the maximum peak of partial discharge signal occurs when the original sine wave is either at its maximum positive peak, or at its maximum negative peak. Moreover, from the different readings wavelet de-noising was efficient and gave the original PD signal after removing the noise.

The following table indicates the amplitudes of the maximum peak of partial discharge signals throughout the input voltage range.

Table 2: The Amplitude of PD Signal throughout an Input Voltage Range.

Input voltage	PD amplitude
2 volts	0.04
3 volts	0.13
4 volts	0.14
5 volts	0.16

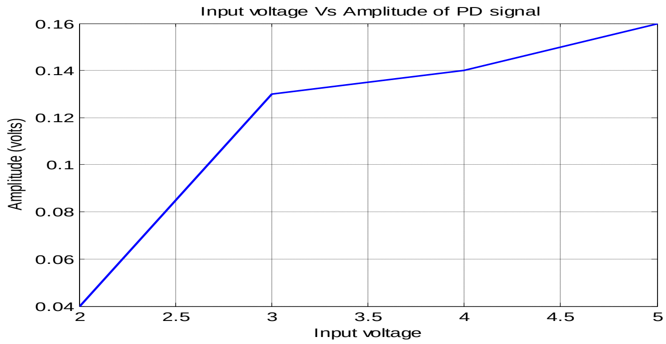


Figure 30: The relationship between the input voltage and the amplitude of PD signal

The above figure shows that there is a patter between the input voltage and the amplitude of PD signal. This means that when the input voltage increases the amplitude of the PD signal also increases. In other words there is a linear relationship between these two parameters.

2. FIGURES AND TABLES (11 BOLD)

To ensure a high-quality product, diagrams and lettering MUST be either computer-drafted or drawn using India ink. (10)

Figure captions appear below the figure, are flush left, and are in lower case letters. When referring to a figure in the body of the text, the abbreviation "Fig." is used. Figures should be numbered in the order they appear in the text. (10)

Table captions appear centered above the table in upper and lower case letters. When referring to a table in the text, no abbreviation is used and "Table" is capitalized. (10)

VI. CONCLUSION AND FUTURE WORK

It is concluded that PD detection and measurement is very important and necessary to predict the insulation lifespan for HV power equipments and cables. Also, it is understood that PD detection can be used to assure a high quality of HV cables and equipment. In addition, it is concluded that the electrical PD detection method is widely used in detecting PD in HV cables more than the other detection methods.

Furthermore, it is found that there is a linear pattern between the input voltage and the amplitude of partial discharge signal. It is concluded that the size of the void affects the production and the amplitude of the generated partial discharge.Much work has to be done in order to understand and describe the nature of (PD) process. Future work can be done with the use of PD sensor to collect and analyze the real electrical signals with different fault condition. Also, further investigation can be done with the use of different de-noising techniques such as adaptive filters and compare with the wavelet de-noising. Moreover, another research can be done to find a pattern between the sizes of void and the partial discharge amplitude.

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