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Detection and Correction of Partial Discharge Faults in Underground Cables: A Comparative Survey

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ABSTRACT

Early detection of fault in underground cables (UC) reduces abnormal degradation. Fault detection is vital to sustain the availability of service to consumers in order to avoid line disruptions or irregularities of supply. This paper presents the methodology of detecting and correcting of aging mechanism known as partial discharge (PD) in underground cables. The methodology of detecting and correcting partial discharge in underground cables necessitates developing a reliable and efficient method of detection when the cable is near failure before resulting to catastrophic failure. For this paper, the Time Domain Reflectometer (TDR) device, offline, online methods were adopted for review, detection and compared by exploring their peculiarities and shortcomings. In conclusion, one method out of the three is chosen after examination and recommended for use to significantly reduce irregularities along the supply line of transmission.

1. INTRODUCTION

Electricity distribution networks are saddled with the task to transmit energy with higher reliability, and this can be achieved by efficient underground cable service (Ahmed, et al., 2001). The demand for energy increases daily both locally and for other industrial purposes. This necessitates proficient energy distribution that must be in place at all times. Underground cables over a long run has been employed in energy distribution networks due to merits associated with its connections (Cynthia. et al., 2019; Mathew, et al., 2019). To this end, this paper discusses the degradation of insulation of cable in underground laid cable and solutions to detections.

Fault is undesirable but unavoidable incidents that temporarily disturb the operation of power system. This fault normally occurs when the insulation of the system fails at any points (Dissado et al., 1992). Faults in laid cables are divided into two general groups permanent and incipient. Incipient fault develops from aging of insulation materials that can be caused by chemical pollution, electrical overstress, severe environmental conditions and mechanical factors and this incipient fault gradually into permanent fault (Hoeskstra, et al., 1974). The demand for reliable service had led to the development of techniques of locating fault when faults occur in transmission lines. A power system must have a protection system that protects users,

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equipment or device. The protection system should detect the fault and be able to isolate the zones that are faulty (Keulanear, Deli 2006). Fast response protection system can prevent damage caused by fault to avoid spread to other system. Fault location is to ensure distribution networks remain reliable as the restoration will be fast so that power outage is minimized. The cost of maintenance will be low if fault is located and corrected promptly. Degradation of the insulating materials is the most common phenomenon on leading to cable failure when the insulation undergoes stress; a gradual deterioration is initiated in parts by voids developed in the insulation. This develops into channels in a tree fashion and propagates through the insulation (Mashikhian, et al., 2000). To this end, this paper opines a comparative method of detection and correction of partial faults in underground cable.

1.1 Deterioration Mechanism in Insulation of Laid Underground Cable

Degradation of cable insulation is a certain phenomenon in underground cables leading to insulation failures. Insulation can be of a variety of materials such as EPR (Ethylene Propylene Rubber, XLPE (Cross Linked Polyethylene), Paper and TRPE (Retardant Polyethylene) compounds whose thickness is a function of cable voltage rating such that the higher the voltage rating, the thicker the insulation. The function of insulation shield is to confine the electric field within the cable (Miri, et al., 1994)

The decline in insulation is caused by single or synergistic action of several declining factors that include thermal, electrical, mechanical, and environmental. Activation of aging mechanisms either change the bulk properties of the insulating materials referred to as intrinsic aging or cause degradation known as extrinsic aging.

The degradation which is as a result of the presence of contaminants, defects, voids and protrusions in the insulation material and their interaction with different declining mechanisms (Mousari, et al.,2002). Under normal conditions, electrical stresses are the prevalent declining factors that may fail cables through partial discharge and tracing mechanisms aggravated by the presence of water. In Cross-Linked Polyethylene (XLPE) cables, the majority of cable failures are related to the treeing activity. Treeing refers to any kind of damages in the insulation medium in which the deterioration path liken the form of a tree. This pre-breakdown phenomenon takes place in the form of either electrical trees or water trees under AC, DC and impulse voltages (Paoletti, et al., 2001). The primary cause of treeing in dry dielectric is partial discharge under high electric stresses and moisture of lower electric stress. Cable can also fail under abnormal conditions through thermally aged insulation breakdown (Nattrass, 1993). Moisture occurs when water penetrates the cable sheath and contacts the conductor; this increases the dielectric losses, so localized heat generation is produced thermally degrades the paper insulation (Kind, and Konig, 1968). The oil paper consists of thin paper strips impregnated with dielectric oil, lapped around the inner conductor (Malik, et al., 1998).

1.2. Overview of Partial Discharge

A partial discharge (PD) is a localized gas discharge in a gas-filled or void on a dielectric surface of a solid or liquid insulation system without bridging the system electrodes (Hussain, et al., 2021) . Partial discharge can occur from the discharge in cavities developed inside the insulation, voids between the semi-conductor and di-electric, tracking discharge along an interface, discharge from electrical or water tree growth. When the electrical field intensity within a cavity or a crack reaches a threshold valve, the gas contained in the detect zone ionizes, producing free electrons which by multiple collisions initiate an avalanche (Chen, 2019). If the size of the void in the direction of the electric field is large enough, the avalanche may eventually initiate a breakdown or discharge across the void. Since the discharge does not affect the entire insulation, it is called partial discharge. To initiates a partial discharge, the cavity size must reach the critical limit for development of a discharge (Metwally, 2004). For XLPE insulation, this critical size is 0.03mm for spherical cavity filled with air at atmospheric pressure partial discharge develop into electrical trees when self-sustaining partial discharge occur at the system operating voltage. Prolong partial discharge activity deteriorate the wall of the cavities physically and chemical that may in turn lead to the initiation of treeing this is evident in **fig.** 1,2, 3 and 4 (.Chen, et al., 2019).

Figure 1: Pictorial view of a faulty underground cable *(https//www.elprocus.com)*

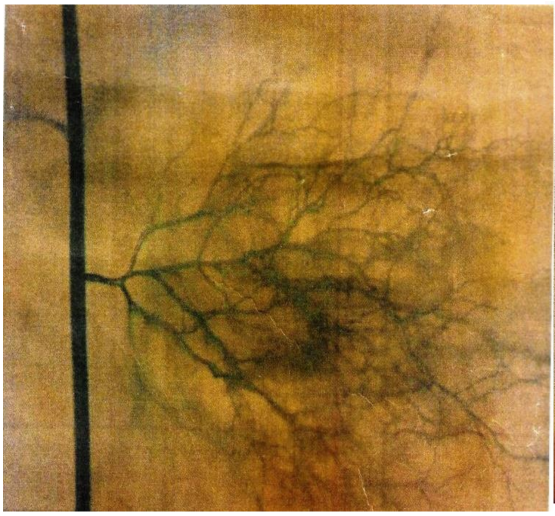


Figure 2: Electrical Tree with visible Aging Contaminants

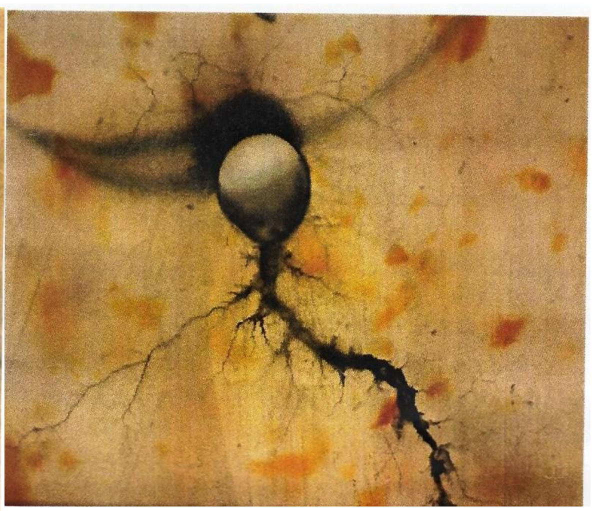
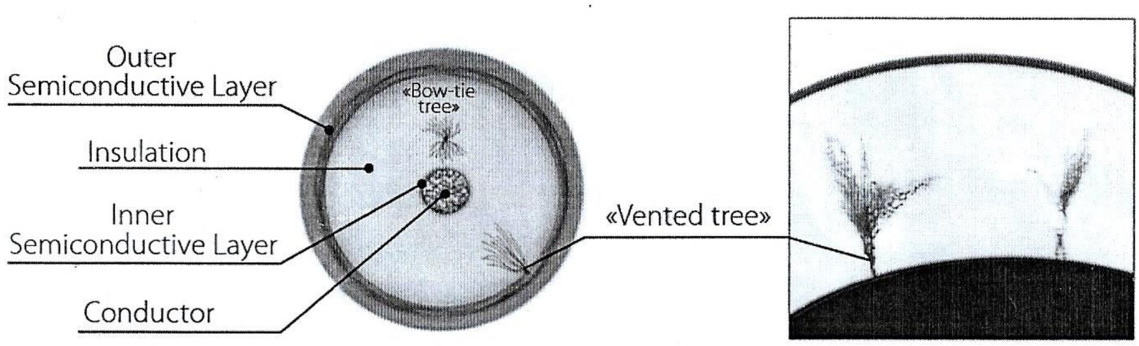


Figure 3: Electric tree breakdown



2. METHODOLOGY

In the context of this study the methodology employed are highlighted as follows;

a) Deep understudy and review of previous research work in this area.
b) Adopt a testing method and evaluate different techniques of partial discharge detection.
c) Compare these methods, exploring their peculiarities, challenges and
d) Then result to a conclusion which of the method best satisfactorily detects partial discharge in underground cables.

2.1. Detection of Partial Discharge Techniques

Partial discharge is a precursor to premature degradation of dielectric materials in a power cable that reveals itself in several ways. The charge displacements are subjected to high frequency radiation emitted by excited particles, heat from particle impact and chemical reactions. The produced high frequency electromagnetic signals travels along the cable and cover a broad frequency range. In solid insulation, this frequency range typically varies from a few hundred KHZ to a few hundred MHZ depending in the location of the PD with respect to the testing points. The partial discharge detection method is based on the measurement of these pulses by high frequency inductive or capacitive sensors (Refaat, and Shams, 2018) The testing methods proceed in three stages.

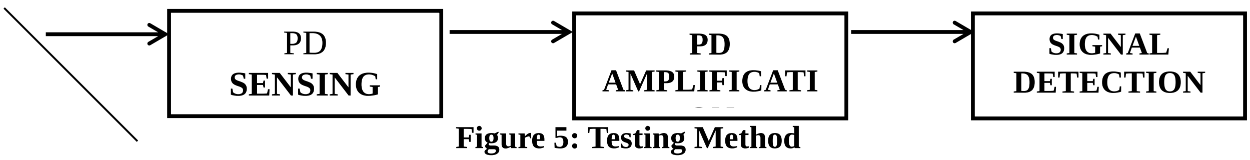


Figure 5: Testing Method

2.1.1 Testing Process

In the first step, Partial Discharge (PD) signals are measured by special sensors such as capacitive couplers, inductive couplers, or antennas. Since the original partial discharge pulses do not possess sufficient magnitude, on amplification procedure is usually followed to enhance the amplified signals are analyzed in frequency and time domain to detect the partial discharge locations. Partial Discharge (PD) measurements can be performed either online or offline and other detection methods (Fruth,1992).

Figure.6 depicts the a pictorial schematics of the partial discharge test circuit

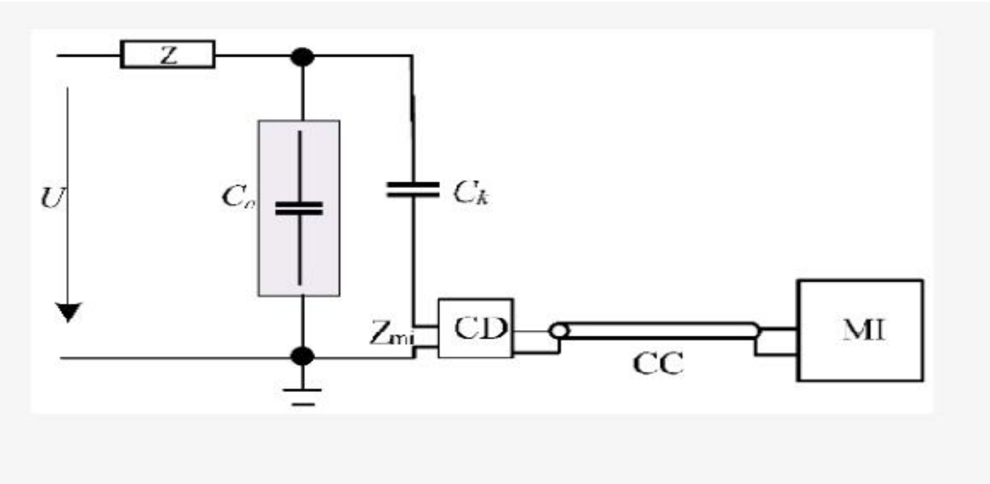


Figure. 6 Schematics of PD test circuit

2.1.2 Offline Method

Offline methods require that the cable be disconnected from the system and elevated voltage applied to generate the diagnosis signals. The de-energized cable system during the offline testing conveys no partial discharge signals. Applying this voltage does not necessarily initiate a discharge because in addition to sufficient excitation voltage, a free electron is required to initiate a discharge. Partial discharge sensing amplification is picked up by sensors, thus to activate the Partial Discharge (PD) sites. The utilized sensors in offline methods involve a high frequency capacitive coupling connected at one end of the cable parallel to the conductor. These conductors' acts as filters, block the 60Hz components and allow the very high frequency pulses associated with partial discharge to be measured. These capacitors must be free of Partial discharge since they are directly connected to the high voltage side and undergo the same test voltage (Seo, et al., 2018). The discharge signals are measured across external impedance which is in series with the capacitor. A resonant circuit is used to amplify the discharge pulses in time domain for a better detection capability. The detection circuit for PD detection is shown in figure 7. Due to the need for a return path, through the cable shield, thus the test method "offline" cannot be applied to unshielded cables, these are highlighted in Table 1.

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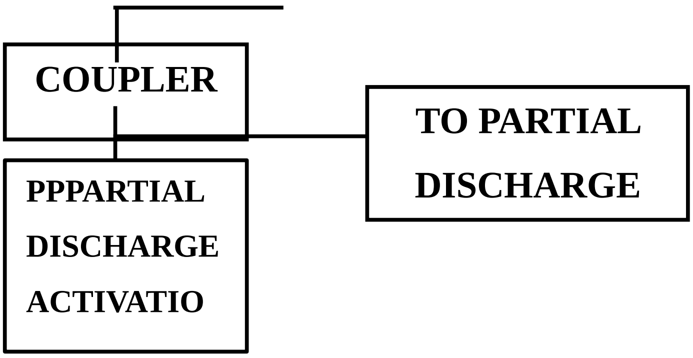


Figure 7: PD Detection Setup

Table.1 Different off-line PD Test

System	Source
AC voltage test	Alternating current voltage with resonant test system
VLF test	Very low frequencies down to 0.01 Hz
Damped AC test	Damped alternating current at frequencies between 20 and 500 Hz

2.1.3 Online Method

In online method of measurement of Partial Discharge (PD), they are conducted without power interruption while the cable is in service. There is no need for heavy and expensive test voltage supply and the coupling capacitors are often replaced with inductive couplers, current transducer place around cables. For these reasons, online Partial Discharge (PD) measurement has a gained much favor over the offline methods (Shima Barakat, 1994).

The general approach to locate PD online is to install the time-synchronized sensors at both ends of the cable section to be monitored and the location of PD can be determined by the arrival time difference at the two installed sensors. Figure 8 depicts a pictorial illustration of sensor location during online testing mode.

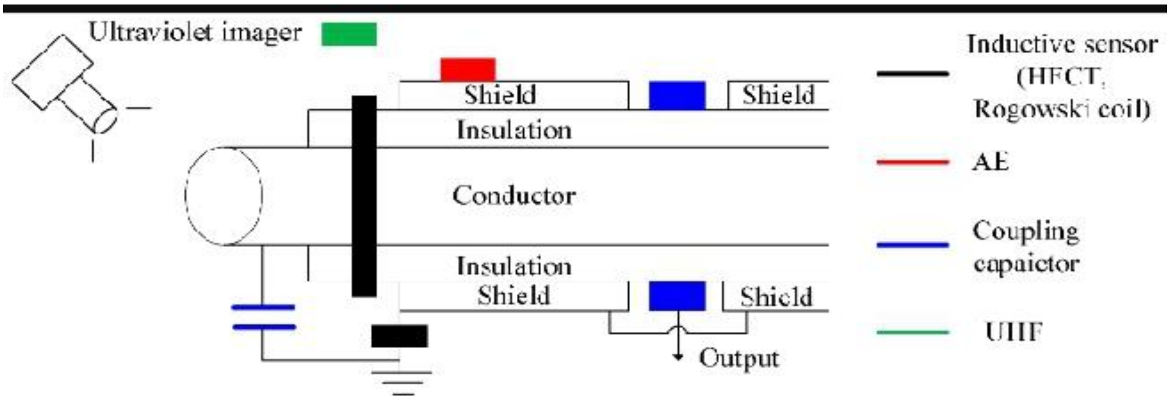


Fig. 8. Pictorial Illustration of Sensor Location during Online Testing Mode

Table.2 PD sensors with merits and demerits

Sensor Type	Merits	Demerits
AE sensors	Immune to electromagnetic noise	High attenuation
HFCT	No intruding installation, wise band width	Material saturation caused by large current at power frequency current loop is needed
Rogowski coil	Light weight, low cost compared to HFCT	Narrow frequency band, current loop is needed
Coupling capacitor	High sensitivity, possible to be integrated in cable	Size and cost of coupling capacitor can become problematic for onsite measurement, problem of installation and safety risk due to galvanic contact.
UHF	Good anti-disturbance performance	Strong attenuation cannot be calibrated, cable shielding effect.
Ultraviolet imager	Easy to use	Can only detect corona discharge at cable termination

2.1.4. Detection Using Time Domain Reflectometry

The Time Domain Reflectometer (TDR) can be used to characterize and locate faults in metallic cables for example twisted pair wire of coaxial cable (Srinivas, and Ahmed, 2003). A TDR is used to determine moisture content in soil and porous modes. The TDR is used to accurately determine the permittivity (di-electric constant) of a material from wave propagation to the strong relationship between the permittivity of a material and its water content, as demonstrated in the pioneering works of (Zhifang, et al., 1997).

The TDR methods require only one partial discharge detection circuit of one end of the cable and the other end of the cable is left open during the measurements. In this method service to the cable must be interrupted to conduct the test. This test uses 100 watts energy signals that do not cause insulation damage, making it possible to locate a faulty section along the cable. It is used to determine the characteristics of electrical lines observing reflected wave forms. It can also be used to locate discontinuities in a connector or electrical path (Madjidi, et al., 2015).

A TDR measures reflections along a conductor in order to measure those reflections. The TDR transmit an incident signal onto the conductor and listen to its reflections. If the conductor is of uniform impedance and is properly terminated, then there will be no reflections and the remaining incident signal will be absorbed at the far end by the terminations. Instead, if there are impedance variations, then some of the incident signal will be reflected back to the sources. If the far end of the cable is shielded, that is terminated with an impedance of zero ohms, and when the rising edge of the pulse is launched down the cable, the cable of the launching point steps up to a given value instantly and the pulse begins propagating in the cable towards the short (Hoof, and Patsch, 1996). When the pulse encounters the short, no energy is absorbed at the far end. Instead, an inverted pulse reflects back from the short towards the launching end, it is only when this reflection finally reaches the launch point that the voltage at this point abruptly drops back to zero, signally the presence of a short at the end of the cable until its emitted pulse can travel in the cable and cable until its emitted pulse can travel in the cable and the echo can return.

If open circuit (terminates into infinite impedance) in this case, though the reflection from the far end is polarized identically with the original pulse and adds to it rather than cancelling it out. So, after a round-up delay, the voltage at the TDR abruptly jumps to twice the originally applied voltage (Lu, et al., 2021).

The benefit of TDR over other testing method is that is a non-destructive method.

1. It can detect resistance in joints, increasing insulation leakage, degrades the cable, and moisture absorption that result to catastrophic failure.
2. It is used for technical surveillance counter measure to determine the existence and location of wire taps. The slight change in the impedance caused by the introduction of a tap or splice will show up on the screen of a TDR when connected to a plane line.
3. It can also determine the Velocity of propagation at which high frequency pulses are travelling a given cable and the speed at which these pulse travel will be influenced by the type of dielectric material and the thickness of the cross-sectional geometry of the cable as shown in figure11.

Figure 9: Diagram of TDR

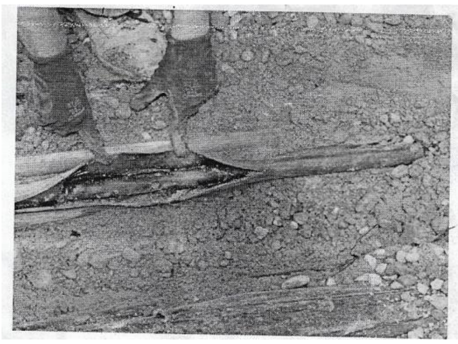


Figure 10: Underground Cable Fault

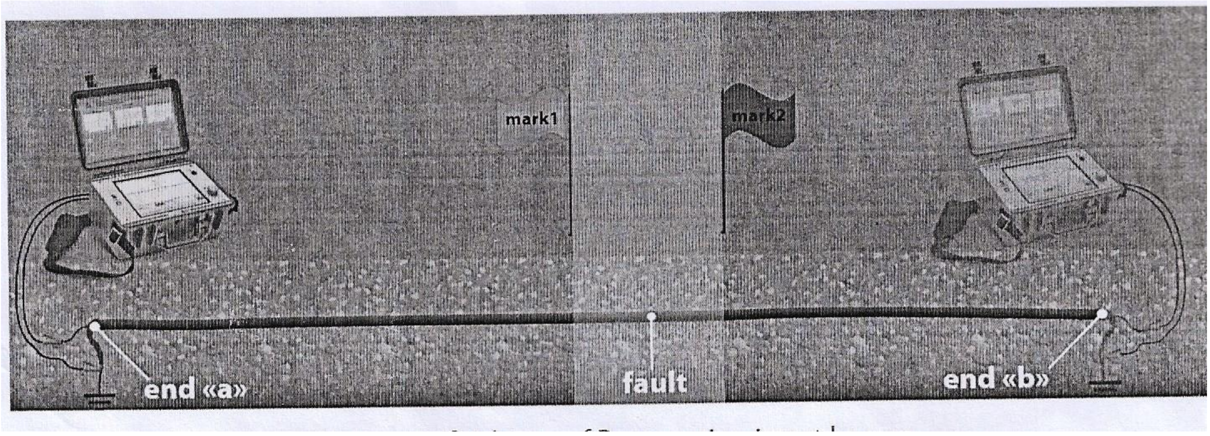


Figure 11: Velocity of Propagation

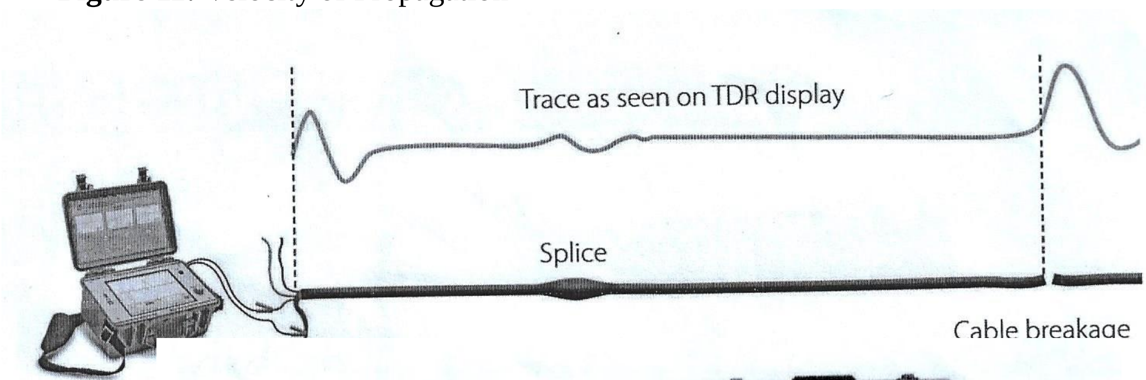
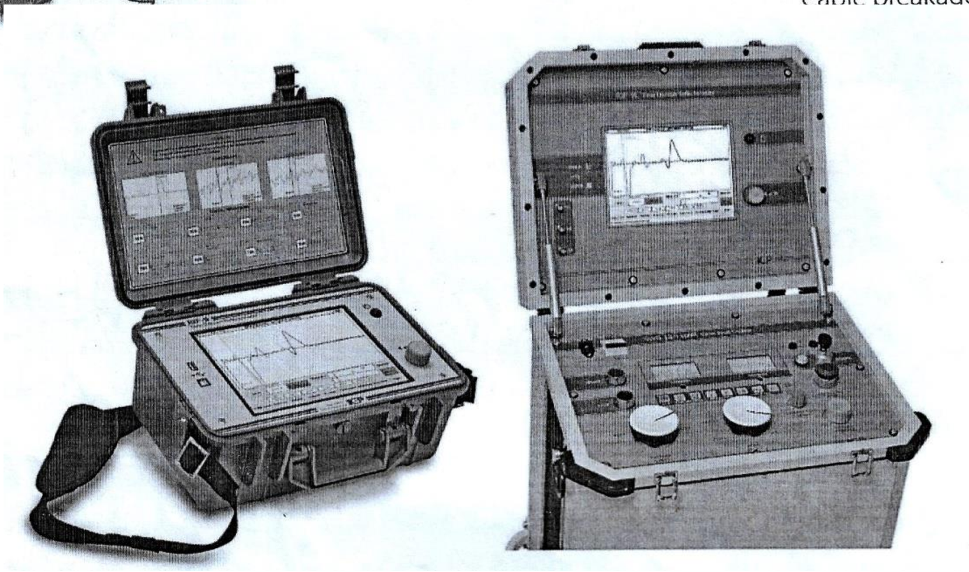


Figure 12: TDR Return Cable End



TDR Cable

Figure 13: Test kit for Fault Location

3. RESULTS AND DİSCUSSİON

In the context of this review, a concise overview of Pulse sequence Analysis was studied and applied. This technique is of two patterns namely Phase-resolved PD (PRPD) and Phase resolved pulse sequence (PRPS) and when applied to the three methods of detection the results is shown in figure 14.

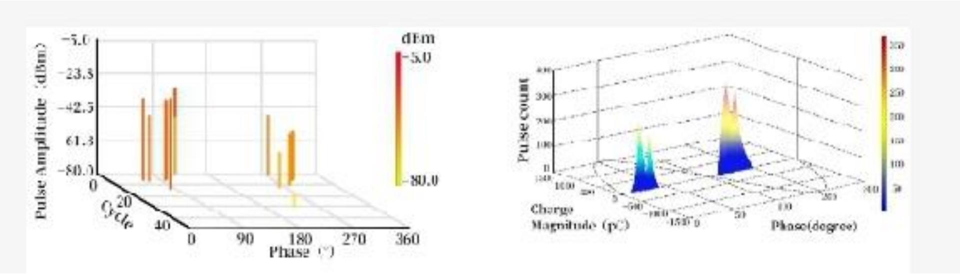


Fig.14 depict PRPS and PRPD results of Pulse sequence analysis of PD

Further, some offline PD test measurements over time has been carried out by various researchers and the results as well as materials used for the examination are detailed in Table 3

Table 3. Off-line PD measurement results

Test object	Result
6 kV plastic insulated cable accessories with realistic internal defects: bad contact between semi-conductor layer and the stress cone and internal cavities	50Hz Ac power frequency and oscillating wave voltage of 1066Hz gave magnitude in the same range without consistent difference.
10Kv Cable sample	Higher PDIV for OWTS than 50HZ
Dielectric cavities embedded in an XLPE sandwich	PDIV values for OWTS significantly exceeded those obtained by sinusoidal waveform
Electric Treeing on an XLPE cable sample	A widespread electric tree for 50Hz while a straight channel for VLF. Thus, number of PD per second for VLF was much lower.
Needle and water tree damage	Oscillating voltages leads to higher electric tree inception than 50 and 0.1Hz tests indicate higher tree ignition than voltage than 50Hz
Three layers of polyethylene	0.1 Hz VLF with sinusoidal waveform, 50 Hz AC and OWTS using frequencies of 200, 500 and 1000 were performed. PDIV increased slightly with frequency.
Full size test setup of 100 m 150 kV XLPE cable with defect created in cable joint	Continuous 50Hz Ac voltage and damped Ac voltage (60Hz, 400Hz) were applied, and similar PD characteristics were observed**.**
Two XLPE cables of 168 and 233m were connected by a defective cable joint. Artificial defects were made to generate internal and surface PD	PDIV at 50Hz is about 80% of 0.1Hz measurement.

Partial discharges are normally subjected to fast transients and non-periodic components which only appear in the high frequency spectrum. Partial discharge detection is some time hindered by noise interface to get correct data. Cable might fail due to the thermally aged insulation breakdown moisture. PD measurement might not indicate the time to failure. If electrical trees develop first, the time to failure is normally short because the initiated electrical tree propagates swiftly through the aged insulation. In order for a PD to progress and cause a failure, self-sustained discharge must be present at the system operating voltage i.e the discharge extinction voltage should not exceed the line voltage. If the partial discharge inception and extinction voltages are both less than the system voltage, there is a good chance of self-sustained discharges (Xiaohua, et al., 2021). Further, when the inception voltage is greater than the system voltage but their extinction voltage is less than the line voltage, for these defects, discharges can initiate due to an abnormal system condition or disturbances. Once initiated, these discharges are well-sustained and visible to detection. Likewise, some defects have the inception and extinction voltage greater than the line voltage, partial discharge dye to these defects can only be ignited by transient's over-voltage and once over stress the partial discharge state is removed, then partial discharge disappears. The detection of partial discharge in cavities highly depends upon the size of the cavity. As the size of the cavity increases, the magnitude of the partial discharge increases, as a result, the detection become easier. Using the online method, the cavity size can be as small as 0.1mm if the cables length being tested is less than any cavity smaller than 0.5mm for shorter cables and 0.7mm for longer cable are not visible to offline methods. They might fail the cable and thus there might not be enough time for early fault detection (Hussain, et al., 2021).

Furthermore, PD forming electrical trees are detectable and can be picked up by both offline and online methods. Electrical tree constitute the final phase of cables degradation. As the tree length increases, the partial discharge magnitude increases ad makes it easier to be sensed by the couplers. The sensitivity of the detection methods need to be high. Finally, partial discharge that occur between the cable neutral and semi-conductor are often severe enough to be detected by both offline and online methods. The TDR has been efficient though the challenges are minimal (Algwari, and Saleh, 2021).

4. CONCLUSION

The paper reviewed the system and test aspects of PDs along underground power cables. Further, various methods of PD detection were established, peculiarities, challenges pertaining treeing in cables as well as merits and demerits of each method were explored. In light of the above, the Time Domain Reflectometer (TDR) method of detecting partial discharge in insulation of underground cable failure has proved to be satisfactory method of detection as off-line method require very low frequency range of damped alternating current for its test while the online method require cost intensive sensors for PD measurement .Although, more research trend should be directed towards PD interpretation, evaluation parameter, affecting factors for its behavior, this review has been able to reach a conclusion that the TDR can be recommended for use by engineers albeit minimal challenges.

Conflict Of Interest

The authors agree that there is no conflicting interest as regards the publication of this article.

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