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Ultra-High Frequency Sensors for Detecting Partial Discharge in Power Cables

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Abstract

Partial discharge (PD) detection is vital for evaluating the health of power cable insulation, where failure can lead to significant disruptions. This study investigates the use of Ultra-High Frequency (UHF) sensors to detect PD signals, which typically occur in nanoseconds. The sensors operate in the GHz range and minimize interference by selecting frequencies above 400 MHz, where background noise is reduced. Through comparison with other detection methods, UHF sensors demonstrate superior sensitivity in measuring minor discharges, providing a reliable means for on-site condition assessment of high-voltage equipment. The study concludes that UHF sensors offer a practical solution for improving PD detection accuracy, particularly in challenging field conditions.

Keywords: Partial discharge UHF diagnosis Power cables Capacitive coupler XLPE insulation

1. Introduction

Power cables are vital for power transmission and distribution, offering benefits over overhead lines in aesthetics, environmental impact, and safety. However, their insulation can fail due to electrical, mechanical, and thermal issues. Partial discharge (PD) is a key concern, causing insulation degradation and potential equipment failure. PD refers to electrical discharges that don't fully bridge terminals and can cause severe damage if not detected and addressed.

The traditional techniques of PD detection, including electrical, acoustic, optical, and chemical methods, suffer from many shortcomings in real-world applications. Electrical sensors, though sensitive, generate much in the way of false alarms due to noisy signals and interferences [8]. Acoustic methods can ensure good performance in an artificially controlled environment; however, the sensitivity is poor and noise immunity is not satisfactory in an outdoor environment [23]. Thus, the demand for a reliable PD detecting approach in noisy conditions increases.

This work introduces a novel application of UHF sensors for the detection of partial discharge in power cables. Operating at GHz frequencies, UHF sensors have much higher sensitivity and lower background noise compared to conventional sub-400 MHz frequencies. Therefore, they have a better performance in detecting the events of partial discharge, especially within noisy environments. The key novelty of this study is the capability of the UHF sensor to decrease noise interference and obtain an accurate PD test in difficult conditions.

This research will address the problems of noise interference and low sensitivity in PD detection using UHF sensors. The comparison with the traditional method indicates that more accurate and reliable condition assessment can be obtained in high-voltage power equipment using UHF sensors. The present paper discusses the performance of UHF sensors versus other methods of detection and presents superior sensitivity and precision. Its results can enhance power distribution systems for improved reliability and safety. Better accuracy in PD detection provided by UHF sensors can prevent huge equipment failures, reduce downtime, and facilitate condition-based maintenance in high-voltage networks.

1.1. Sensors used in different frequency ranges

Capacitive and inductive sensors can distinguish between the electrical and magnetic aspects of the transient electric field from partial discharges [24]. They are designed to detect electromagnetic waves within a frequency range of 0.3 GHz to 3 GHz, ideal for studying high-frequency partial discharges [7].

This is a technique that uses high-frequency sensors with the main purpose of detection of discharge stacks in cables when carrying out online partial discharge testing [5]. A study indicates that external interference is normally below 400 MHz, hence UHF sensors above 300 MHz have advantages in reducing interference [9], [12]. The UHF method effectively detects on-site PD in gas-insulated switchgear, where poor terminations and joints are most likely to fail [11, 17]. Insulation failure that is left undetected can lead to serious consequences, including total failure [15]. High-voltage cables are subjected to higher failure rates from increased electric field stresses and PD phenomena [13].

Pulse discharge waveform under 1 ns with widths of a few nanometers implies high speeds of switching relevant for UHF PD detection [16]. The UHF PD technique follows the waveform capture with better SNR than that provided by conventional IEC60270 methods [18]. Furthermore, there are a number of unconventional coupling techniques adopted in HF and UHF spectrums such as coaxial cable sensors [3].

High-frequency current transformers are the main sensors for the detection of PD in cables. The HFCT sensors installed around the cable ground or core can detect PD over 5 km or more, depending on the condition of the cable and variation of impedance. It was estimated through research that about 97% of the incidents of cable PD occur at joints or terminations and some others in the insulation. The directional coupling sensors at cable joints detect small leaks while continuous tests measure impedance in the metal-earth screen [20].

2. Overview of capacitive couplers and other sensors in partial discharge detection

Install a capacitive coupler in a 66 kV XLPE cable. The diameter of insulation is 66 mm and diameter of conductor is 30 mm. Strip the metallic outer sheath along length L. A tin strip wraps around the cable, positioned Lb-La from the sheath. The top electrode is attached to the top face of the semiconductor, having a continuous dielectric to metallic screen transition to ensure minimum electrical stress. Bottom electrode connects to the ground plate, and in case of semiconductor layer, conduction properties vary with frequency [20].

Table 1. Comparison of several partial discharge test sensors

Sensor type	Detection Object	Freq. (MHz)	Detection Sensitivity	Insulation Connection
HFCT	Joint, Termination	0.1-100	1-5 PC	Earth cable or grounding wire
Capacitive coupler	Joint, Termination	1-100	1-5 PC	Link box, Insulation cylinder
Metal Foil Coupler	Joint, Termination	1-100	1-5 PC	Sheath Insulated Joint or termination
AE (Touch on)	Termination	0.02-0.3	50-100 mV	Epoxy Cylinder, GIS termination
TEV	Termination, power panel	1-100	100-200 mV	Epoxy cylinder, GIS termination
UHF (External)	Joint, termination	300-1500	10-100 mV	Epoxy cylinder, GIS spacer

Table 2. Environmental conditions of the test

Temperature	18.4 C
Humidity	45.5%
Pressure	853.0 Hpa

Table 3. Cable test specifications

U_n	20 Kv
Capacitance	263 Pf
Year of manufacture	2005
Cable length	2 m

Table 4. Specifications of HFCT sensor used in partial discharge test circuit on the cable sample

Frequency Range	1-100 MHz
Impedance	50 Ω
Material	Ferrite

Table 5. Partial discharge test values on 20 kV cable sample in Jihad University Laboratory of Science and Technology

Description	**Load (PC)**	**Partial discharge number**	**Test time (s)**	**Test voltage (kV)**
---	-3.5	114	0.999	5.5
---	5.2	1513	1	8.1
Decreasing	16.3	3454	1.001	11.5
Increasing	-4.5	1235	1	11.6
Increasing	10.4	3707	1	15.8
Increasing	11.2	4357	1	17.3
Increasing after 30s	63.1	1930	1	20
Increasing	23.4	7927	1	-20 inc.
Increasing after 3m	70.8	1715	1.001	21.2

The coupling capacitor allows the correct measurement of PD because it lets high-frequency signals pass through while impeding power frequency noise. This prevents the microvolts small-amplitude PD signal from being masked by stronger 50 or 60 Hz signals. The DC component is eliminated so that only HF PD signals reach devices such as HFCT. In this case, separation of the PD signals with power frequency signals and noise can hardly be done. The large power signal may saturate the HFCT; this may result in nonlinearities and measurement errors. This coupler has an insulated metallic electrode placed as a patch or circling the cable between the external semiconductor and the cable's metal sheath. In this setup, the influence of external noise is at its minimum, and the whole structure is buried under the ground sheath. A sensor of that structure is seen in Figure 2.

The UHF technique effectively detects PD in high-voltage equipment such as GIS, transformers, and cables. Recent studies aim to enhance its accuracy in transformer PD detection [23]. UHF sensors perform well in labs with minimal interference and show promise in field tests, maintaining low sensitivity to location changes. The UHF method allows the measurement to be made in a line directly. Capacitive sensors detect electrical transients, while magnetic transients due to PD are sensed by the inductive sensors [22].

The capacitive sensor was a 2-cm copper disk. Inductive sensor had two coils. The PD pulses were pre-amplified, filtered, and processed with a computer oscilloscope. Better SNR, using ultra-wideband signals, needs a measurement frequency over 500 kHz. The UHF technique is ideal for the inspection of power cable accessories like terminals and joints. In high-power cables, the allowable PD is less than 10 PC. The whole system comprises a sensor of UHF [21], a preamplifier, and the measurement arrangement of PD. The sensor is connected to the GIS cable terminal through coaxial cable with a high-pass filter that limits its range within 300 MHz. It connects to an amplifier to increase the SNR. The pre-amplifier output connects to the PD measurement and pulse processing unit [19].

2.1. The sensitivity of Ultra High-Frequency sensors in partial discharge tests

PD produces electromagnetic signals which may be detected using inductive sensors, such as High-Frequency Current Transformers. HFCTs are usually installed around the ground conductor of a Device Under Test and, therefore, allow for measurements at ground potential instead of high voltage. The advantages of this are much smaller, lower cost sensors compared to traditional coupling capacitors. HFCTs find very common use in monitoring of PD on medium and high voltage cable systems although they may be applied in other areas.

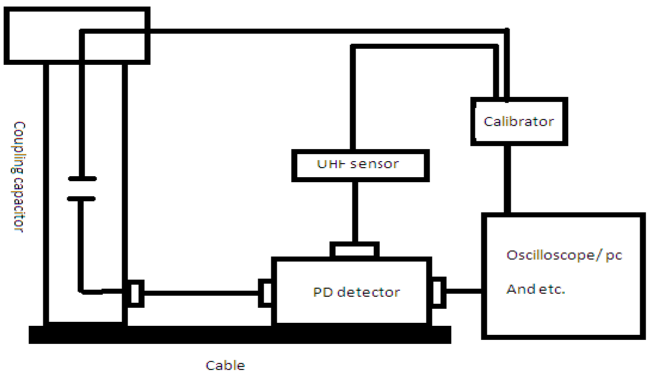

Fig.1. schematic Placement of capacitive coupler sensor on high-pressure cable

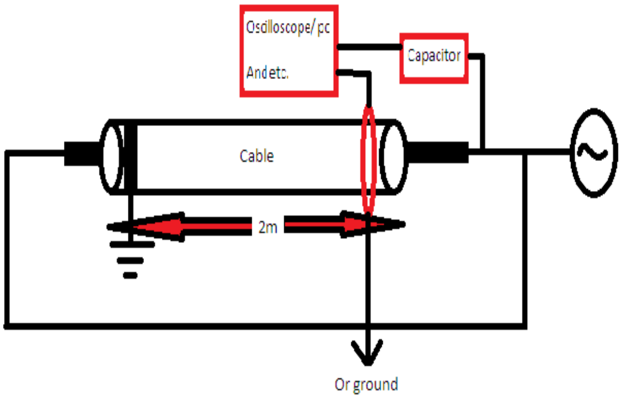

Fig.2. Test circuit using a capacitive coupler

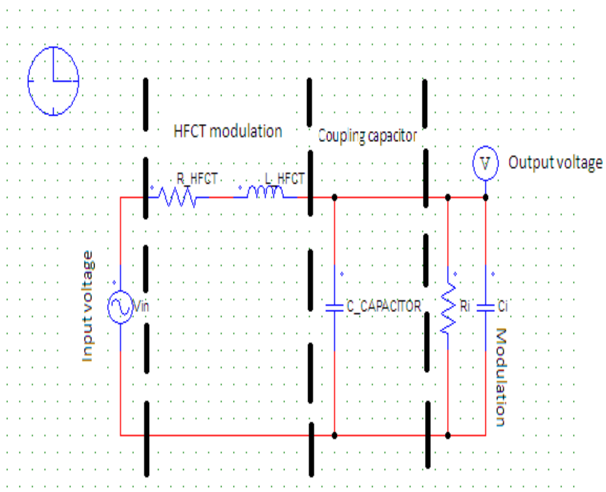

Fig.3. simulated HFCT and c-capacitor With PSIM computer application

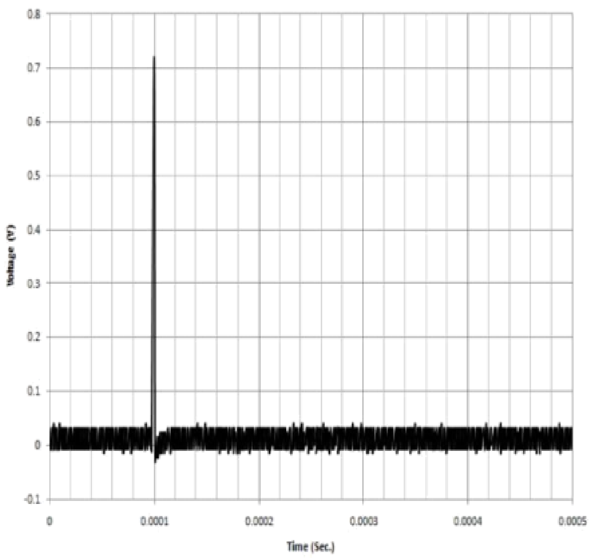

Fig.4. A sensor response in Standard Partial Discharge

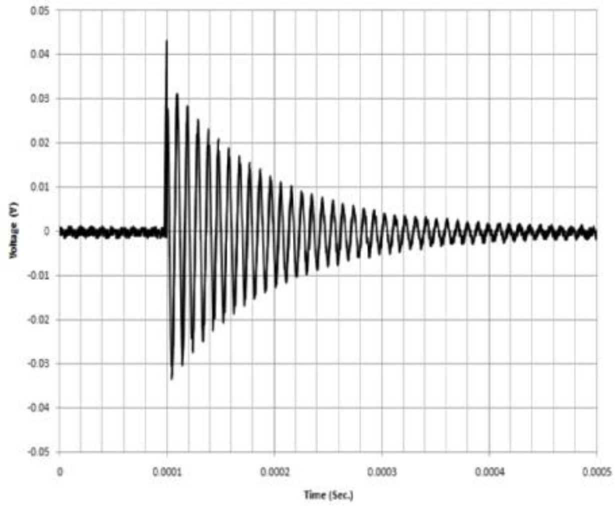

Fig.5. A sensor response in HFCT

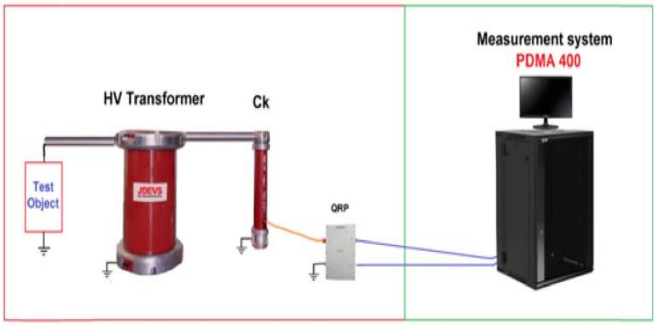

Fig. 6. Partial discharge circuit diagram block

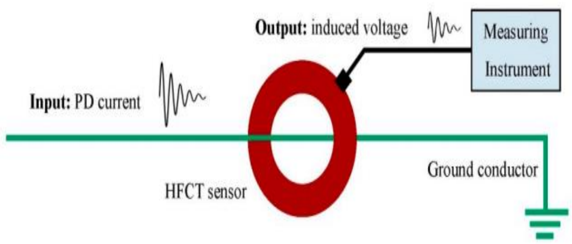

Fig. 7. Location of the HFCT sensor in the test

Fig.8. Test cable

Fig.9. Image of high voltage circuit when applying a voltage to measure partial discharge

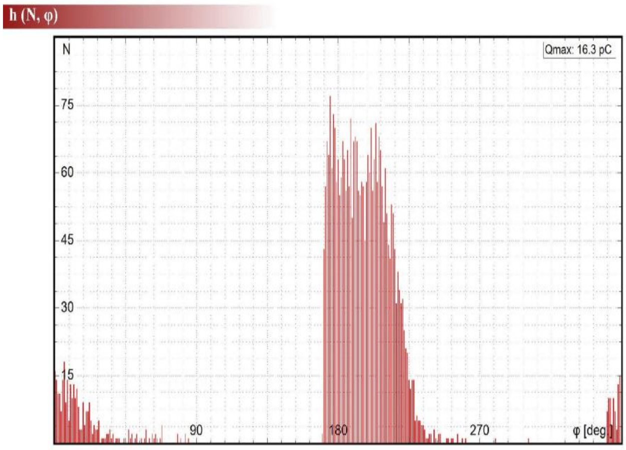

Fig.10. The figure of the number of partial discharges per phase at a voltage of 11.5 kV

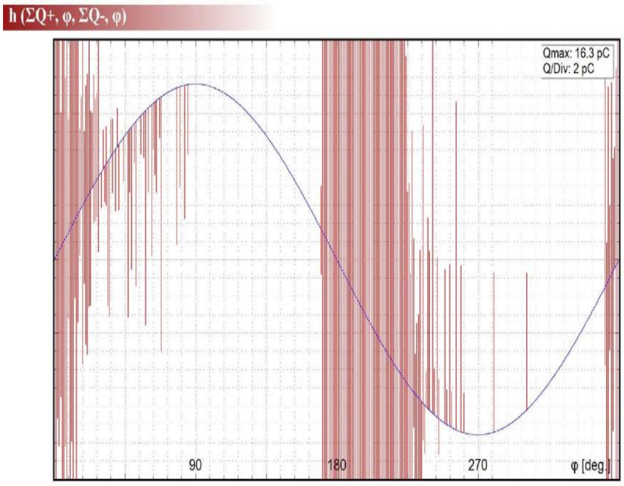

Fig.11. Total partial discharge load diagram in terms of phase at 11.5 kV

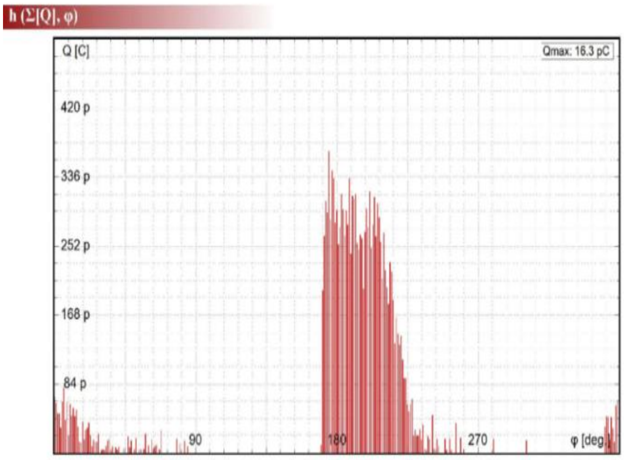

Fig.12. Total absolute magnitude diagram of partial discharge loads by phase at 11.5 kV

Ultra-high-frequency (UHF) partial discharge sensors are crucial for condition and location monitoring in high-voltage equipment insulation. The process of designing UHF sensors normally includes iterative production, mechanical testing, and adjustments. FDTD simulation enables the prediction of the frequency response of various designs of UHF sensors, thus simplifying the design work and making it possible to perform a parametric study regarding how component dimensions and materials affect sensor performance.

This is verified by the narrowband UHF sensor calibration system; whereby, step response provides the frequency conversion function. Temporal excitation applied in FDTD modeling yields effective reproduction of sensor output responses. Comparing simulated and laboratory results reveals small differences in the output frequency and response voltage, with which the effectiveness of the FDTD method for UHF sensor design and calibration is confirmed [19]. It helps to speed up sensor development with lower cost and performance optimization.

2.2. Extending capacitive coupling modeling for use in partial discharge tests in the power cable

These partial discharge field tests use high-frequency sensors to measure the PD load on cables. Sensors may couple to the cable through magnetic fields, such as HFCT, and electric fields, such as capacitive couplers. Capacitive couplers are mainly used owing to their high sensitivity and bandwidth, since HFCTs have limited capability regarding these factors. Capacitive sensors would be mounted inside cable joints and terminals. Testing online and offline is possible without modification of insulation design. HFCTs are normally set on to the ground belt of the cable for detecting sudden pulse changes due to partial discharges.

The cable insulation, equipment, and accessories tests must be performed online and offline. In the case of PD detection, these techniques are used along with capacitive couplers. The sensors capture the signals from high-frequency electromagnetic waves detected near cable joints. Assorted couplers ensure increased sensitivity and ease of use, while maintaining insulation integrity. Capacitive couplers are helpful for high-frequency detection within short lengths of cable, especially where more than one capacitor is used.

The effectiveness of the capacitive sensor was presented in a study on 12 kV XLPE cables. In the case of a 20 kV XLPE cable, the 25 mm capacitive coupler operates over a range from 100 MHz to 350 MHz with 0.2 sensitivity. The HFCT sensor has inductance and resistance, which reduce the noise. This is shown in the figures below.

3. Laboratory test performed on a 20-kV power cable sample with XLPE insulation

Experiments carried out at the study authenticated the assumptions made in the study. We applied variable voltages and tabulated the results. Disturbances resulted due to variable voltage cycles, but we took an authentic recording of data after recalibration of the system. Both methods of partial discharge tests are as follows: 1) OLPD or online partial discharge monitoring, and 2) multi-channel online test [6], [10]. The installation time was reduced by using portable wireless devices with rechargeable batteries to avoid damage to the equipment. The diagnostic equipment must switch rapidly between the UHF, HFCT, and Capacitive Couplers for the effective inspection of high voltage equipment. The cable joints and terminals are quite prone to partial discharge and faults [14]. Human errors in the installation of insulation often lead to a lot of faults. This is attributed to the fact that sensors can rapidly detect insulation defects in joints and terminals. The existence of voids in the terminals, free electrons in insulation, and surface discharges are usually the causes of these defects.

3.1. Perform the partial discharge measurement test

Generally, the 80% of the PD signals are weak and thus can't be detected, while the other 20% is masked by background noise and hence differentiation is tough. The nature of the detected charges and discharges gives information about free electrons. Most the partial discharge signals depict similar nature like those emanating from cavities or else for such reasons as indicated on Figure 10, showing signal accumulation with frequency [1].

Standard analysis devices can determine and predict the PD activities within a range of zero to 360-degree phase with great details of discharge volume, magnitude, and frequency [2]. UHF sensors show that surface discharges happen in the positive half-cycle, while corona discharges are associated with small amplitude and takes place in negative half-cycle related to electron movement and ionization.

Figure 11 shows the partial discharge signals caused by voids; although such a signal is difficult to distinguish. The test results make great references to identify partial discharges in different conditions [4]. The quantity of distribution pulses in every phase, expressed as Hn(φ), and the average and maximum pulse value, respectively expressed as Hqn(φ) and Hqm(φ), give an indication about the characteristic of the discharges and their development in time.

3.2. Measurement and pattern results at 11.5 kV

Experiments under natural conditions, such as those including electrical and mechanical disturbances in the lab, have demonstrated that these factors do not impede performance and that the proposed approach is effective. Results are not interfered with by telecommunications or low-bandwidth noises due to a hybrid method and the use of a Rogowski coil in wire grounding, whereby pulse patterns signal a partial discharge in insulation. These patterns are determined through distribution by amplitude, number, and maximum pulses concerning the phase of peak wave voltage [25]. The risk factors of cable failure most relevant are: 1) inception voltage of PD; 2) PD concentration. Figures 12 and 13 indicate that the UHF signal from the corona discharge has very small amplitude, with only the negative half-cycle of the wave visible due to electron release and ionization.

4. Conclusion

Conventional PD measurement methods following IEC 60270 standards are indeed very sensitive but not suitable for field or online applications in HV terminals and GIS power cables. This paper discusses UHF-based detection of PD as a practical alternative to conventional methods. The main focus was on the evaluation of some UHF PD-detection strategies for reliability against other methods.

A portable PD monitoring device with signal conditioning circuits, while noting appropriateness for UHF signals, was developed to satisfy on-site testing. Field tests validated its performance. The use of capacitive couplers with UHF channels was thereby found quite appropriate for the detection of PD in both HV and MV systems. Two case studies illustrated that the combination of capacitive couplers with UHF signals correctly identified the occurrence of PD along with its location. PRPD analysis with advanced features further refined identification with respect to PD pattern.

Key findings include:

Patterns of PD: The discharges are grouped into clear patterns, suspicious patterns, and pattern-free discharges.

Frequency Range: Frequency range is from 1 MHz to more than 300 MHz; well above noise frequency ranges for an accurate, error-free measurement.

Sensitivity: The sensors are able to detect discharges as low as 3 picocoulombs.

Defect Identification: This technique identifies deficiencies created by incomplete electrical discharging within cables.

Predictive Capability: This feature helps predict electrical and electromagnetic interference. Future research should explore integrating this technique with acoustic methods for enhanced precision, using sensors at longer distances, and combining multiple couplers with Time-Domain Reflectometry (TDR) for improved PD localization.

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