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Analyzing the Relationship Between UHF Partial Discharge Signal Features and Transferred Charge

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ABSTRACT: The ultra-high frequency (UHF) technique offers significant advantages over the conventional partial discharge (PD) measurement method, particularly for online monitoring, 3D localization, and immunity against noise. However, its primary limitation lies in the challenge of calibration due to the impact of various factors such as PD source locations, antenna characteristics, and transformer structures including, active part and tank wall, on the received UHF signals. Currently established parameters such as signals peak-to-peak and energy of signals do not provide a meaningful correlation between received UHF signals strength and factors such as distance and antenna radiation pattern. Addressing these gaps, this paper introduces a novel parameter: the first arrived signal (FAS), derived from the short-time Fourier transform (STFT) of UHF signals. Experimental results demonstrated the capability of the FAS to correlate meaningfully between signal strength and distance from the source, as well as antenna radiation pattern and polarization. The proposed parameter is then utilized to estimate conventional transferred charge using the received UHF signals. Results indicate promising estimation accuracy, particularly when electromagnetic waves directly reach the antenna. This approach offers the potential for a more precise estimation of conventional PD transferred charge, enhancing the capabilities of the UHF method in assessing insulation system health conditions.

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1- Introduction

Partial discharge (PD) is a phenomenon that occurs in high-voltage and medium-voltage equipment as a result of the existence of a defect in the insulation system [1]. The presence of the PD in high-voltage and medium-voltage assets accelerates the insulation system degradation which leads to insulation failure and in some cases breakdown of high-voltage or medium-voltage equipment [2-4]. IEC60270 standard provides a technique for detecting PD activity in the insulation systems by employing a standardized measuring circuit that can specify the severity of PD in pico-coulombs (pC) [5]. Although the conventional PD measurement method quantifies PD transferred charge, it suffers from limitations such as low sensitivity, and inability to accurately locate PD within the volume of high voltage (HV) apparatus, especially for power transformers [6].

In order to overcome the drawbacks of the conventional PD measurement method, new approaches such as acoustic, ultra-high frequency (UHF), and chemical techniques have been introduced in recent years [7]. The UHF method has been popular in recent years to monitor PD in gas-insulated switchgear and transformers. The rise time of the PD signals in the originated location is less than 1 ns which excites electromagnetic waves in the frequency range 300 MHz to 3 GHz [8] which comes in the range of UHF. The UHF PD detection approach outperforms the conventional method in certain cases. For example, in the UHF method, High-frequency disturbances will be suppressed due to the electromagnetically shielded measurement environment [9]. Furthermore, the ability of online monitoring and 3D localization [10] over 1D localization [11] makes the UHF approach practically useful in condition monitoring of high-voltage equipment, particularly in gas-insulated switchgear and power transformers [9].

The main drawback of the UHF method relates to the calibration of the measured value. This means that the measured UHF signal alone cannot thoroughly determine the health status of the high-voltage device. Several investigations have been established to find a correlation between acquired UHF signals and apparent charge which is measured in conventional method [12-14]. Various reasons influencing the measured UHF PD signals magnitude have been examined in [15]. The factors include PD source type, distance from the PD source to the antenna location, antenna polarization, antenna radiation pattern, and transformer structure. The calibration error of each factor has been calculated through experimental tests and the overall error was big enough to state that the calibration of UHF method is not possible.

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A comprehensive study on the UHF signals induced by internal discharge within GIS showed that, in addition to other factors such as PD location and antenna characteristics, the void length also can influence the received UHF signals for this type of PD source [16]. Although the results showed that increasing the void size leads to increasing the peak-to-peak value of the UHF signal, the impact of the PD inception voltage have not been considered in this paper. It is preferable to investigate the impact of various factors on the ratio of the UHF signal's value to the conventional apparent charge, rather than focusing solely on the UHF signal's value.

The calibration of the UHF PD measurement method has been conducted in a manner similar to the conventional IEC60270 method, despite the unknown structure of the transformer from any PD measurement perspective [17]. The proposed method in this paper focused on the calibration of the UHF measuring sensor, the measuring instruments, and cables. The measuring instruments and cables are calibrated as in the IEC 60270 method by injecting an impulse in the cable and receiving the response of that in the measuring instrument. The calibration of the antenna is performed using a gigahertz transverse electromagnetic (GTEM) cell, which applies a plane electromagnetic wave to the antenna. Subsequently, the ratio of the applied field to the voltage on the terminals of the antenna is defined as the antenna factor (AF) [17, 18]. This procedure aims to compensate for the influence of the UHF probe's sensitivity in the calibration of the UHF method. However, the applicability of this approach is questioned due to the complex structure of the transformer, which differs from the controlled environment of the GTEM cell. The reflections and refractions that occur when the UHF probe is inserted into the transformer, as a result of the tank's geometry, cause mutual impedance and reactance effects that are not fully accounted for in the GTEM cell [19].

In the context of the calibration of the UHF method, researchers have encountered significant challenges due to high calibration error. These errors stem from various factors, as previously discussed. However, a critical gap that remains unaddressed across existing references is the compensation of calibration errors which have not been considered in any reference.

In this paper, the partial discharge initiated electromagnetic (EM) wave propagation in the power transformer tank including the inside structure such as the active part, has been interpreted. Then, actual UHF partial discharge signals have been captured in different case studies to study the effect of different factors, such as distance and antenna radiation pattern, on the received UHF signals. To find a meaningful correlation between the UHF signal's magnitude and transferred charge, a new parameter extracted from the short-time Fourier transform (STFT) of UHF signals has been introduced, and the results have been compared to other parameters introduced before. Then, based on the reasonable correlation between the new parameter and the factors that generate calibration error, compensation of errors seems possible. Finally, in the last section, the PD charge estimation using the UHF method based on the newly introduced parameter has been conducted.

2- EM Waves Propagation Inside Transformer Tank

Partial discharge refers to localized electrical discharges that occur without bridging between two conductors. In simpler terms, it's a phenomenon where electrical energy is released in a specific area without fully connecting two separate conductive paths. The electrons and the charged particles are accelerated due high electric field due to a PD defect that causes the impulses with a rise time of lower than 1 ns [20]. The frequency range of the impulses covers from lower than 100 kHz to higher frequencies in the range of UHF (up to 3 GHz). Lower frequencies in the range of lower than 50 MHz flow as current signals in the measuring circuit, while higher frequencies in the range of higher than 300 MHz emit electromagnetic waves that propagate inside the transformer tank. Initiated EM waves propagate from the defect location in every direction and travel through the space. The emission of EM waves within the shielded tank can experience different effects such as reflection from metallic parts, refraction, and attenuation. In order to examine the EM wave behavior inside the rectangular cavity (transformer tank), the Maxwell equation is considered and to be solved21]]. This equation has different solutions (modes), which depends on the shape and size of waveguides. These modes are categorized as two types in rectangular waveguides:

Transverse electric (TE) mode, which has no electric field component in the propagation direction.

Transverse magnetic (TM) mode, which has no magnetic field component in the propagation direction.

Let us consider a rectangle with dimensions of *a, b, c,* in which $c > a > b$ and the EM wave propagates in the direction of z. For TM mode the electric field along the propagation path should not be zero, then the solution form of E_z is as Eq. (1):

$$E_z = E_0 \sin\left(\frac{m\pi x}{a}\right) \sin\left(\frac{n\pi y}{b}\right) \cos\left(\frac{p\pi z}{c}\right) \quad (1)$$

in which, m, n, p are mode numbers and indicate dependency on the coordinates. Then two types of modes for different resonance frequencies are shown based on the indices of *m, n,* and *p* like TE_{mnp} for TE mode. Based on the form of solution and none-zero value of E_z, TM_{110} is the dominant or lowest resonance frequency for TM mode. This dominant frequency for TE mode is $TE_{101.}$ Propagation of EM waves inside the rectangular cavity leads to creating the withstanding waves that the resonance frequency of these withstanding waves for the cavity is expressed as Eq. (2) [22]:

$$f_{mnp} = \frac{c}{2\sqrt{\mu\varepsilon}} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{c}\right)^2} \quad (2)$$

where, ε and μ are medium permittivity and permeability, respectively, and c denotes the speed of EM waves.

3- First Arrived EM Wave

As discussed earlier in section 2, UHF PD signals in the way to reach the receiving antenna, experience reflection and refraction due to metallic walls and active part inside the transformer structure. Parameters, such as peak-to-peak of signals are influenced by the aforementioned reflection and refractions. Therefore, analyzing the received signals using the parameters introduced so far cannot justify their behavior in relation to distance, antenna radiation pattern, and even antenna polarization. To overcome this drawback, a novel parameter named first arrived signal (FAS) is introduced in this paper that considers the first arrived EM waves that reach the antenna location.

The FAS works based on the principle of wave propagation inside the power transformer. In light of the fact that EM waves propagate in a straight path, then, the first signal received by the antenna is minimally influenced by the structure of the tank. In order to extract the FAS from the UHF PD signals, first the short-time Fourier transform (STFT) of the signal should be calculated. The STFT formula is as Eq. (3) [23]:

$$STFT(\tau, f) = \int_{-\infty}^{+\infty} x(t) w(t-\tau) e^{-j2\pi ft} dt \tag{3}$$

where, $x(t)$ is the UHF PD signal, $w(t)$ is the window function, commonly Gaussian window.

Using of STFT offers notable advantages over the original PD pulses. One of the key benefits lies in the ability of the STFT matrix to effectively capture the joint time-frequency information of PD pulses, surpassing the limitations of relying solely on individual time or frequency representations. Moreover, by projecting the original PD pulses onto amplitude levels in the time-frequency plane, the STFT-amplitude matrix eliminates the influence of pulse polarity [24].

Given that the Short-Time Fourier Transform (STFT) presents both time and frequency data at the same time, it allows for the analysis of the propagation of each frequency band of the electromagnetic (EM) wave. Fig. 1 shows the procedure of extracting the FAS from the UHF PD signal (Fig. 1(a)). Fig. 1(b) presents the STFT of UHF signal and shows that EM waves are propagated inside the transformer tank in different frequency bands. The frequency band of the received signal is determined by specific antenna characteristics and a parameter known as the scattering parameter (*S11*). This parameter is defined as the ratio of reflected power at the antenna terminal to the total input power of the antenna [15, 25]. The *S11* of measuring antenna has been presented in Fig. 2, which has been measured using an 8 GHz vector network analyzer. Based on a thorough examination in Fig. 1(b) and Fig. 2 it is clear that the frequency bands received dominantly by the antenna, correspond to frequencies with lower value of return loss. Therefore, the main frequency bands that the antenna receives the UHF PD signals lie in the 200 MHz to 300 MHz and 400 MHz to 800 MHz. In each frequency band, several reflections of EM waves from the tank walls and active part have been reached to the antenna. Among these reflections, the wave that arrives first exhibits the closest resemblance to the wave radiated from the PD location.

In order to achieve the characteristics of the first arrived UHF PD signals, primarily, the arrival time of the UHF PD signal should be determined as seen in Fig. 1(a), and then, the STFT matrix is calculated for a signal from its onset time to a preset end time of the signal (here is 500 ns). In the second stage, variation of the STFT matrix at a particular frequency (Trend graph) is extracted over time. The first peak value in the extracted graph is the desired parameter in this context. Fig. 1(c) shows the location of the first peak of the trend graph. The first peak is not always the maximum value. Depending on the location of the PD source and propagation characteristics of UHF signals could be lower than the maximum value or equal to that. To determine the arrival time of the UHF PD signals, the method that was introduced in [26] is employed in this paper, which finds the change point of the signal by minimizing the contrast function. The STFT has been calculated for up to 1 GHz frequency band and a time duration of 500 ns. The choice of frequency to extract the trend graph depends on some factors. The first one relates to the advantages of lower frequencies against higher frequencies in UHF PD measurement [15, 27], which the main on them is the attenuation of UHF signals at higher frequencies is higher than lower frequencies. Besides, as seen in Fig. 1 (b), the number of reflections in higher frequencies is more than in lower frequencies, and finding the first peak in higher frequencies will be challenging. Therefore, the frequency with the lowest return loss in the range of 200 MHz to 300 MHz, i.e. 252 MHz is selected as shown in Fig. 2.

4- Experimental Setup

The setup employed to capture both electric and UHF PD signals consists of two main parts. The first part is designed to capture electrical PD pulses through a coupling capacitor and a wideband high-frequency current transformer (HFCT) up to 400 MHz. This frequency band is far more than the required conventional method frequency band (lower than 50 MHz) to evaluate the transferred charge of PD activity [28]. The required frequency band to evaluate the apparent charge of PD activity is lower than 1 MHz [28], then the HFCT satisfies the required frequency band. The main component of the second part is the monopole antenna, which is inserted inside the transformer tank through a DN80 oil drain valve. The transformer tank size is 1596×856×1236 mm. In order to capture the PD signals, an oscilloscope with a sampling of 10 GS/s for each channel and up to 5 GHz bandwidth has been utilized. Fig. 3(a) depicts the PD measuring circuit in a voltage source employed to apply high voltage to PD defect inside the transformer tank. The monopole antenna inserted inside the drain valve has been shown in Fig. 3(b). Moreover, Fig. 3(c) shows the details of the measuring circuits for conventional electrical and UHF methods, in which 100 pF

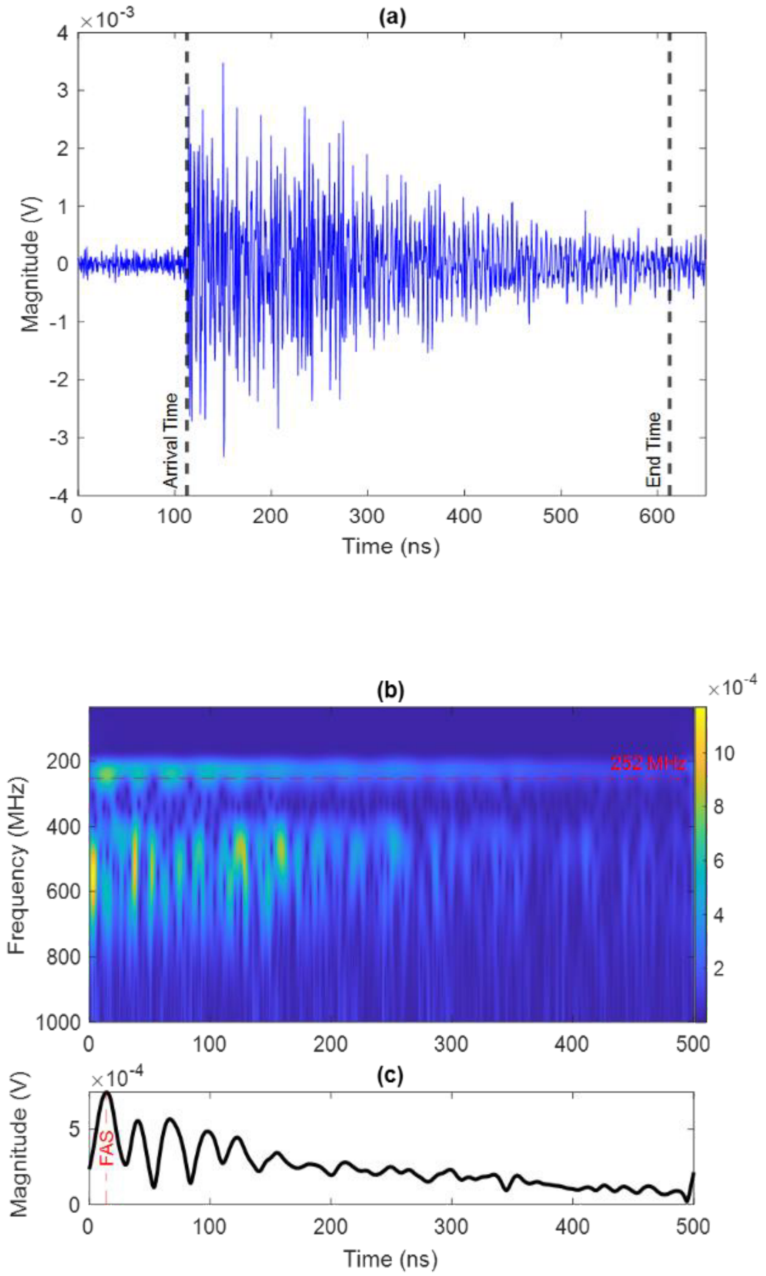

Fig. 1. First arrived UHF signal extraction procedure. (a) captured UHF PD signal (b) short time Fourier transform of the UHF signal (c) trend graph at 252 MHz.

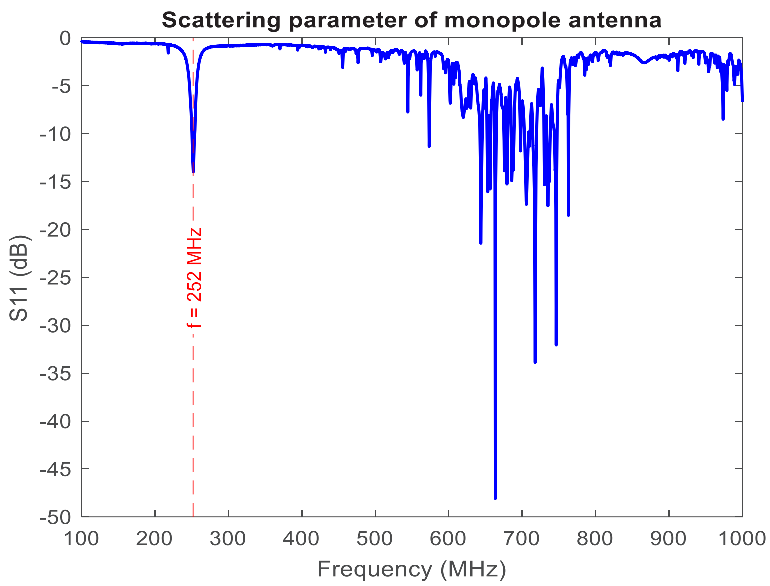

Fig. 2. S11 of monopole antenna

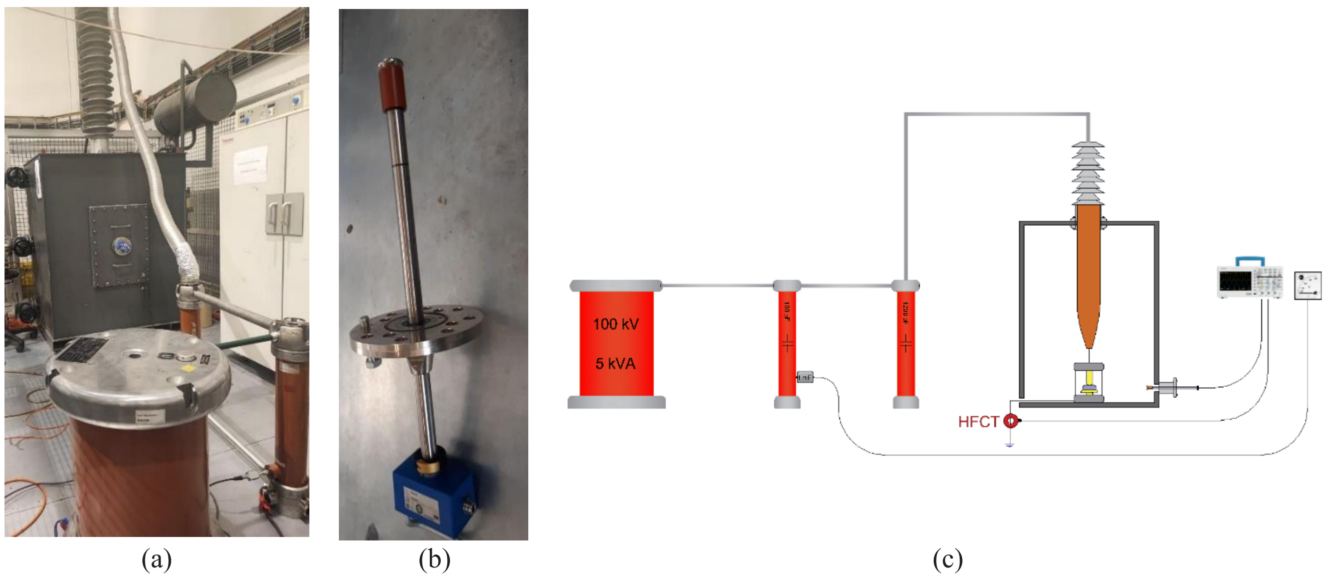

Fig. 3. PD measurement setup (a) PD measuring setup connection to the transformer tank (b) monopole antenna (c) detail of the PD measuring circuit for electrical and UHF methods.

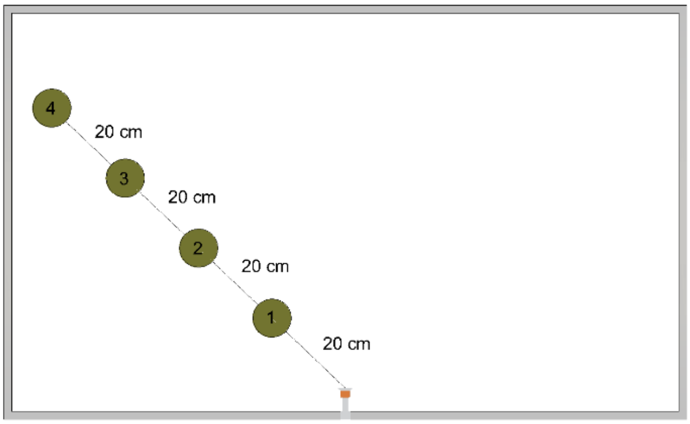

Fig. 4. PD source placed apart from the antenna at different locations, all in the same direction

and 1200 pF capacitors are used as AC voltage dividers and coupling capacitors, respectively.

5- UHF Signals Quantification

As previously mentioned in section 2, EM waves emit from PD location and experience several reflections and refractions before reaching the antenna. These effects can diminish the reasonable correlation between the strength of the received UHF signals by the antenna and the location of the PD source with respect to the probe. For instance, an increase in the distance between the location of PD source and the antenna may not consistently yield a decrease in the received signal intensity. In order to investigate the behavior of the different parameters on the quantification on UHF PD signals, five parameters have been extracted from captured UHF signals and stated as follows:

- Peak to peak amplitude of UHF signal (V_{pp}): calculated as the negative peak to positive peak of UHF signal.
- UHF Signal energy (V_{SE}): calculated as the square root of the average of the signal components powered by 2.
- Mean of UHF signal spectrum in the selected frequency range (V_{sf}): calculated as a mean of the frequency spectrum of UHF signal in the frequency range of 190 MHz to 260 MHz [15].
- Peak to peak of UHF signal in the selected frequency range (V_{ppl}): calculated as the peak to peak of UHF signal in the frequency range of 190 MHz to 260 MHz.
- First arrived UHF signal (V_{FAS}): calculated as mentioned in section 3.

In order to investigate each parameter behavior in different cases, the factors that impact the magnitude of the received UHF signals including, a distance of PD source from the probe, antenna radiation pattern, and antenna polarization, have been considered in the subsequent sections.

5- 1- Distance effect

To study the behavior of each parameter due to variation of distance between the antenna and PD source location, a PD source of corona type has been placed in four different locations, all at the same angle and different distances with respect to the antenna. The four positions are evenly spaced 20 cm apart from each other and antenna. Fig. 4 shows the top view of the transformer tank and PD source placement and different distances from the antenna.

In order to capture PD signals at different locations, the voltage level was gradually raised until the initiation of PD pulses, and then a number of 100 PD pulses from HFCT and UHF antenna were recorded. Following this, the ratio of each parameter to q (apparent charge) has been calculated for 100 captured signals. Fig. 5 shows the normalized value of the ratio for each parameter to q versus distance from the antenna location. Moreover, the theoretical ratio has been calculated by Friss law, and has been presented in Fig. 5. The Friss law describes the received power by the antenna in relation to the different factors such as distance from the transmitter, frequency, and antenna gain [29]. The Friss law formula is presented in Eq. (4):

$$P_r = P_t G_r G_t \left(\frac{\lambda}{4\pi d} \right)^2 \tag{4}$$

in which, P and G represent power and gain, while the

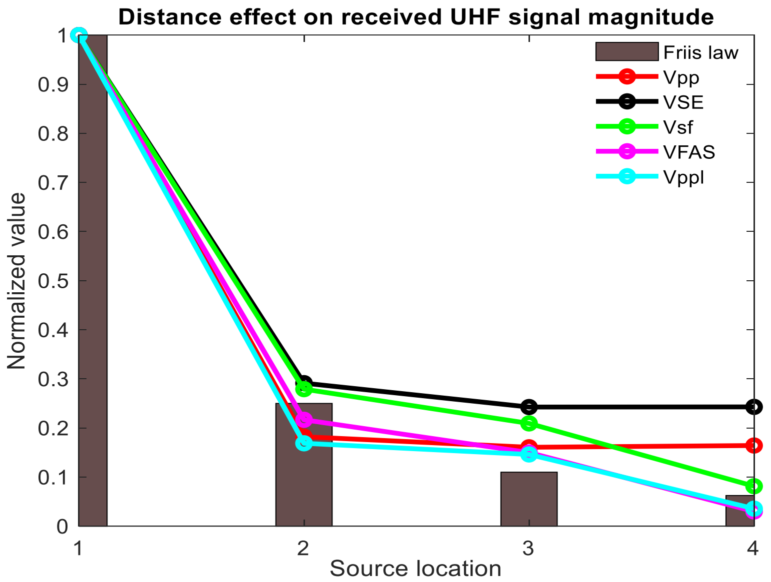

Fig. 5. Received UHF signal ratio to q versus distance from the antenna

Table 1. RMS of error for different distances of UHF parameters

Parameter	*RMS of error*
V_{pp}	0.0662
V_{SE}	0.1184
V_{sf}	0.0572
V_{FAS}	0.0237
V_{ppl}	0.0480

subscripts r and t indicate the transmitting and receiving antennas, respectively. The symbol λ also represents the wavelength, and d denotes the distance between the transmitting and receiving antennas.

As illustrated in Fig. 5 the strength of the captured signals decreases as the distance increases for all parameters except V_{pp} in location 4. However, only V_{FAS} and V_{ppl} closely align with the theoretical values. V_{sf} exhibits a diminishing trend with distance increasing but significantly differs from Friis formula predictions. Conversely, V_{pp} and V_{SE} inadequately explain the distance effect on the received signals magnitudes. Table 1 illustrates the root mean square (RMS) of error, indicating deviation from the Friss formula value for each parameter. It shows that the error value for V_{FAS} is lower than other parameters and demonstrates that the proposed parameters are logically correlated with distance variation.

5- 2- Antenna Radiation Pattern

The radiation pattern of monopole antennas is not uniformly distributed in all directions. Typically, they exhibit one or more main lobes where the maximum power is radiated or received. In this study, Far-field analysis in the CST microwave studio was employed to simulate antenna radiation patterns. Fig.6 illustrates the gain pattern of the antenna. This pattern was obtained by simulating the probe positioned at the lower middle of the tank wall using far-field analysis of CST microwave studio at the frequency of 250 MHz. The geometry of the simulation includes the wall that the antenna is inserted through the bottom wall, and the antenna structure, which is created by a perfect electric conductor (PEC) for simplicity. The UHF probe is a conical monopole antenna with a dielectric-covered head with a diameter of 39 mm and a length of 55 mm as presented in

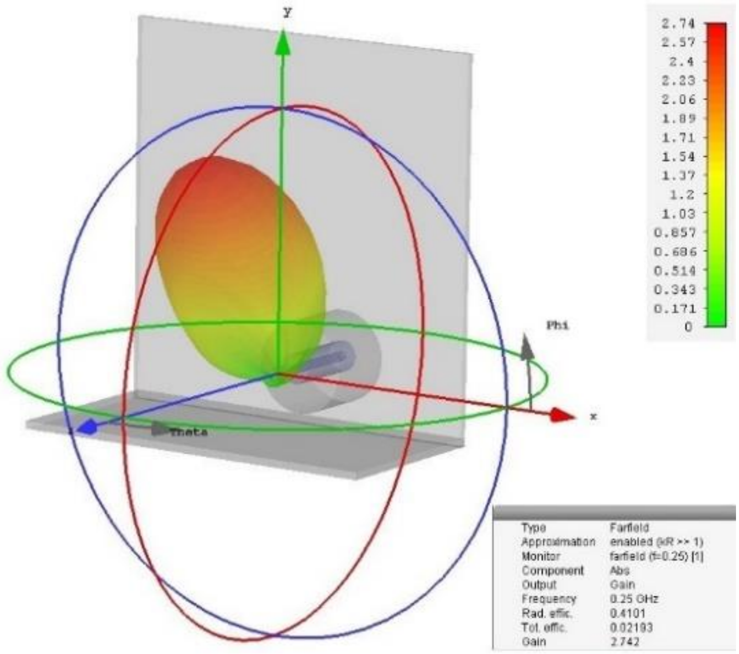

Fig. 6. Monopole antenna radiation pattern at the frequency of 250 MHz

Fig. 3 (b). More detailed information about the antenna can be found in [30].

In order to investigate the antenna radiation pattern influence on the received EM waves magnitude, an experiment was designed to capture UHF PD signals at various angles and the same distances concerning the antenna. Fig. 7 shows the top view of the transformer tank where the PD source type of corona has been placed at different angles with the same distance of 50 cm from the antenna. The experiment has been designed for two values of phi = 0 and phi = 40 degrees. Fig. 8 and Fig. 9 show the normalized ratio of the UHF parameters to the apparent charge at different angles with respect to the antenna at phi = 0 and phi = 40, respectively. At phi = 0, V_{FAS} and V_{ppl} can adequately track changes in antenna gain as the source location varies, while, at phi = 40, only V_{FAS} can track the antenna radiation pattern. Conversely, V_{pp}, V_{SE}, and V_{sf} cannot effectively model an approximate trend with respect to antenna gain. Table 2 and Table 3 represent the RMS of error, indicating the deviation of parameters from normalized antenna gain, for phi = 0 and phi = 40, respectively. The error has been calculated for two cases of 250 MHz and 500 MHz of simulated antenna radiation patterns in which for lower frequency-based parameters only 250 MHz has been used.

As illustrated in Table 2, the lowest error belongs to V_{ppl} among all parameters, while the V_{FAS} stands in the second place of best parameters at phi = 0. On the other hand in Table 3 at phi = 40, the V_{FAS} is the best parameter among all parameters based on the calculated errors. However, the main reason of the considerable deviation of V_{FAS} from the antenna gain at locations 2 and 4 in Fig. 8 is attributed to the antenna polarization that will be explained in the subsequent section.

5- 3- Antenna Polarization

Antenna polarization is a parameter that refers to the orientation of the electric field component emitted by the antenna. The polarization of the antenna can be linear, in which the electric field oscillates in a plane horizontally or vertically. However, elliptical polarization occurs when the electric field vector traces an elliptical path during propagation. A circular polarization is a special case of an elliptical one. The axial ratio (*AR*) is a dimensionless parameter that is used to describe the quantity of antenna polarization and is defined as Eq. (5) [15].

$$AR = 20\log\left(\frac{E_{\max}}{E_{\min}}\right) \tag{5}$$

where E_{max} and E_{min} are the maximum and minimum values of the electric field vector on the path of tracking. In circular polarization, the axial ratio (*AR*) is zero, while in linear polarization, the *AR* is infinite, and represented as 100. For elliptical polarization, the *AR* falls in a range between 0 and 100.

Polarization mismatch and misalignment between the

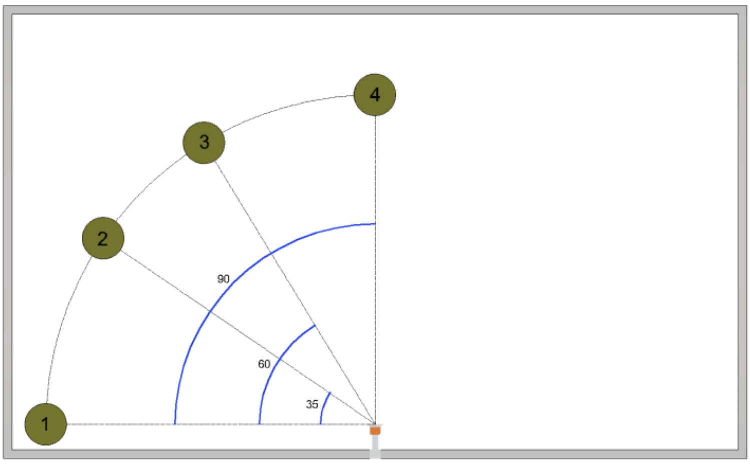

Fig. 7. PD source placing at different angles, all in same distance from antenna

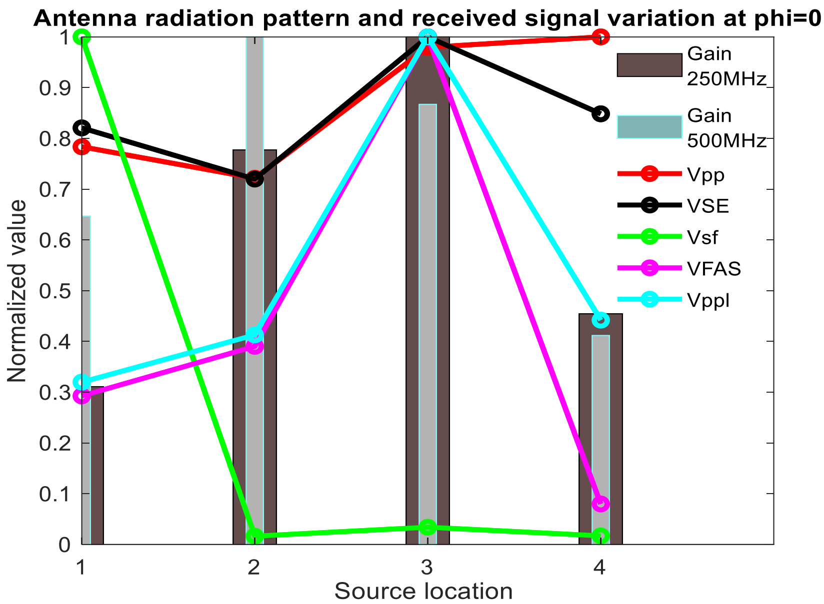

Fig. 8. Received UHF signal at different angles in respect to the antenna, phi = 0.

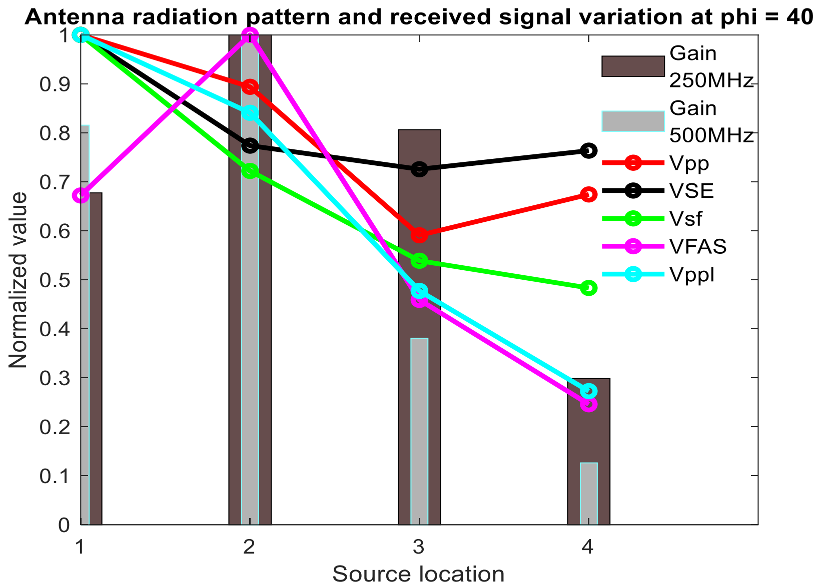

Fig. 9. Received UHF signal at different angles in respect to the antenna, phi = 40.

Table 2. RMS of error for different angles of UHF parameters, phi = 0.

Parameter	*RMS of error (250 MHz)*	*RMS of error (500 MHz)*
V_{pp}	0.3664	0.3378
V_{SE}	0.3210	0.2788
V_{sf}	0.7358	-
V_{FAS}	0.2278	-
V_{ppl}	0.1803	-

Table 3. RMS of error for different angles of UHF parameters, phi = 40.

Parameter	*RMS of error (250 MHz)*	*RMS of error (500 MHz)*
V_{pp}	0.2837	0.3147
V_{SE}	0.3087	0.3974
V_{sf}	0.2684	-
V_{FAS}	0.1860	-
V_{ppl}	0.2539	-

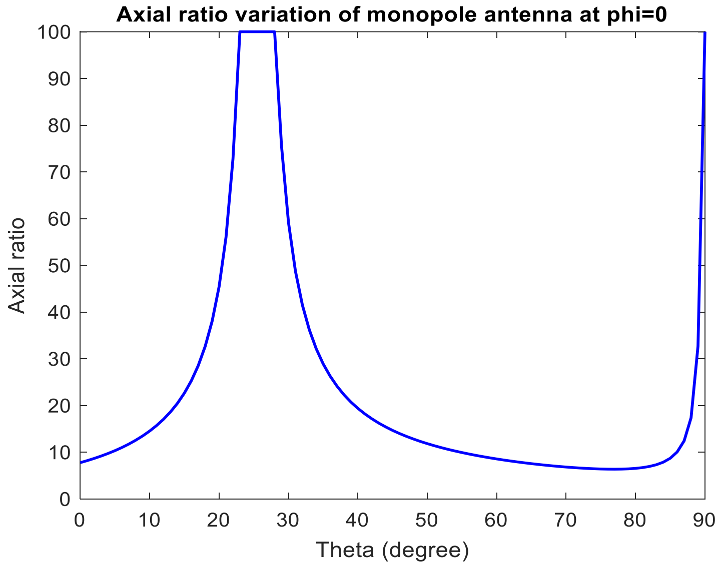

Fig. 10. AR of monopole antenna variation at phi = 0

transmitting and receiving antennas cause polarization loss. To quantify this loss, a specific parameter known as polarization loss factor (*PLF*) has been introduced, and it is defined as Eq. (6) [29]:

$$PLF = (p_w \cdot p_a)^2 \quad (6)$$

where, p_w and p_a are the polarization vector of the receiving antenna and incident wave, respectively. The *PLF* falls in the range of 0 to 1. When the polarization vectors are perpendicular to each other, the *PLF* is 0. Conversely, when the antennas have the same polarization and are perfectly aligned, the *PLF* is 1, which means polarization loss is zero.

Fig. 10 shows the axial ratio of the monopole antenna inside the transformer tank at phi = 0, which has been simulated in CST microwave studio. It is clear that the monopole antenna, is linearly polarized along with the antenna axis and near 25 degrees of theta axis. On the other hand, the needle in the corona discharge model acts as a monopole antenna. Therefore, if the antenna and needle electrode are aligned in parallel, the polarization loss will be diminished, but in the case of orthogonal placing of monopole antenna and PD source, the polarization loss will be maximized.

The polarization effect in Fig. 8 can be seen at positions 2 and 4, in which the strength of the received UHF signal has been decreased, due to the perpendicular placement of the antenna and PD source axis. But in the other locations where polarization is more elliptical, the polarization loss has declined and the received UHF signals follow the correlation with antenna gain.

In order to explore the polarization effect on the received UHF signals by the antenna, in Fig. 7 at location 4 and phi = 0, the corona discharge was placed in parallel with respect to the antenna. The results on V_{FAS} indicated that when the polarizations of the monopole antenna and incident wave are oriented in the opposite direction (perpendicular), the strength of the received PD signal is reduced to half or, in the case of linear polarization, to one-fourth of what it is when the polarization is aligned in parallel.

6- PD Charge Estimation

Upon analyzing the results, it was clear that among the parameters presented for modeling the behavior of received UHF PD signals under different factor variations, the V_{FAS} proved to be the most effective method for establishing a relationship between the factor variation, and the magnitude of the received UHF signals. Therefore, it seems that the method could be used as a suitable parameter to estimate the PD transferred charge using the captured UHF signals and information about the PD source characteristics such as PD type and location. Moreover, the estimation of maximum charge as employed in [15] could be carried out this time using V_{FAS}. The method in [15] for estimating the maximum possible charge, is based on finding the worst case of received UHF signals by placing the PD source type with the lowest energy at the furthest distance and opposite polarization with respect to the antenna and then finding the maximum transferred charge based on the worst case correlation of UHF signals and PD transferred charge. In this paper the worst case will be found by considering the correction factors as in the lowest value for distance, antenna radiation pattern, and polarization.

The following steps present the apparent charge and maximum charge estimation method using V_{FAS} for corona discharge. Obviously, the method could be extended to other PD source types. In order to estimate the PD transferred charge using captured UHF signals, two steps should be carried out.

1- Step 1 (Factory test): Placing a desired PD source type inside the transformer tank at a predefined position, and measuring the conventional electrical PD signals through coupling capacitor and detection impedance (or HFCT) and UHF signals through an antenna. Then, the ratio of V_{FAS} to the PD transferred charge could be calculated. The ratio is called the reference ratio (R_0).

2- Step 2 (Site test): In the UHF PD measurement phase, correction factors are calculated for both distance and antenna radiation pattern at the PD source location compared to the reference location. For example, if the distance from the PD source to the antenna location is 2 times of the distance of the reference location to the antenna, then as in the Friss law, the correction factor for distance will be 4 to compensate attenuation due to the double distance from the antenna. Also for the radiation pattern if the radiated power at the position of the measured location is 2 times of the reference location, then the correction factor will be 0.5. The correction factors actually compensate for the ratio of the V_{FAS} to the apparent charge for the measuring location based on the reference location. As a result, the ratio of V_{FAS} to the PD transferred charge for the measured PD source location (R) is expressed as Eq. (7):

$$R = KR_0 \frac{G_0}{G} \left(\frac{d}{d_0} \right)^2 \tag{7}$$

while, d and G represent the distance from the antenna to the PD source location, and the gain of the antenna along the specific angle with respect to the antenna, respectively. The subscript ‘0’ is used to denote the reference location. Additionally, the coefficient K is introduced to address the impact of antenna polarization, and its value typically falls within the range of 0.25 to 1, based on the AR value of the antenna at the specific angle. For AR values lower than 10 which the antenna is nearly polarized circular, the K is set to 1 and for AR values higher than 90, in which the antenna is nearly polarized linear, the K is set to 0.25. For The locations with the related AR between 10 to 90, the K is set to 0.5. These values are set based on the experimental results and for different types of PDs could be different.

The process of estimating the maximum transferred charge follows the same steps as the apparent charge estimation, with a notable distinction. In this case, the PD source location is chosen under the assumption of the worst-case scenario. This includes selecting the furthest distance from the antenna within the tank, the least favorable antenna gain concerning the tank’s perspective, and setting K to 0.25 as the worst case of polarization loss. The advantage of this method to find out the worst case over the method introduced in [15] is that here it is not required to place the PD source at the worst case with respect to the antenna, and the worst case is determined by specifying the lowest possible correction factors for the desired parameters. Fig. 11 shows the flowchart of the estimated apparent charge and maximum possible charge inside the transformer using the novel introduced parameter. As seen in Fig. 11, at the first step in the factory test, the PD source is placed inside the transformer tank to capture conventional and UHF signals simultaneously to calculate the R_0. At the site tests, which are online tests during the operation of the transformer, the measured UHF signals are utilized to estimate the apparent charge and maximum possible charge using Eq. (7) by applying correction factors on the distance and antenna characteristics based on the reference location.

To assess the validity of the proposed method, three metal cylinders have been placed inside the tank to model the transformer structure. Fig. 12 displays five different locations inside the tank where that PD source was placed, and also the reference location with the red circle. The results of the transferred charge and maximum charge estimation for five locations using the UHF method have been presented in Table. 4. According to Table. 4, not only the maximum estimated charge is higher than the real charge in each location, but also the deviation from the real charge is more than 10 times. The estimated maximum charge seems reasonable, and the significant deviation from the apparent charge is attributed to considering the worst case of each factor, which guarantees the apparent charge inside the transformer insulation system is not higher than the maximum charge.

In the case of estimating the PD transferred charge, the accuracy of estimation significantly depends on the path of electromagnetic waves emitted by the PD source to reach the antenna. If these waves directly reach the antenna without any obstacles, the estimation accuracy will be close to the actual value. An instance demonstrating this scenario is location 3, where the PD charge closely has been estimated in comparison to the actual PD value. Conversely, when there is an obstacle between the PD source and the antenna, the accuracy of estimating the PD apparent charge diminishes notably. For instance, at location 1, where the active part lies precisely between the PD source and antenna, the estimated charge is much lower than the real charge. This highlights that the presence of an obstacle between the PD source and the antenna causes significant attenuation in the received PD signal. In cases where there is no direct obstruction between the PD source and the receiving antenna as in locations 4 and 5, but the path of the electromagnetic waves to the antenna is indirect, the estimation of the charge also remains promising.

7- Conclusion

In conclusion, this paper presented the EM wave propagation concept within the transformer tank. To investigate the received PD signal behavior based on

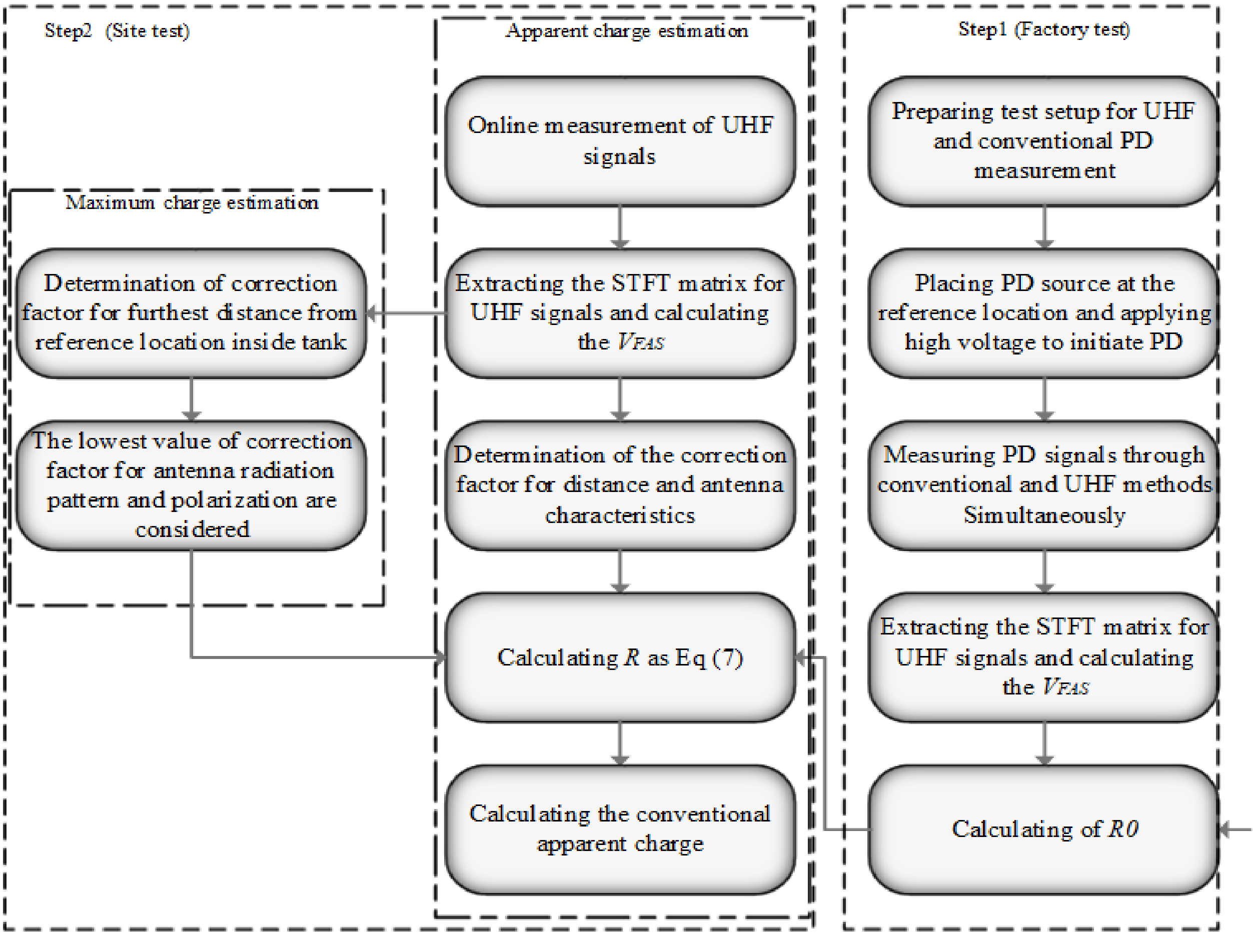

Fig. 11. Flowchart of PD apparent charge and maximum charge estimation using the novel VFAS parameter

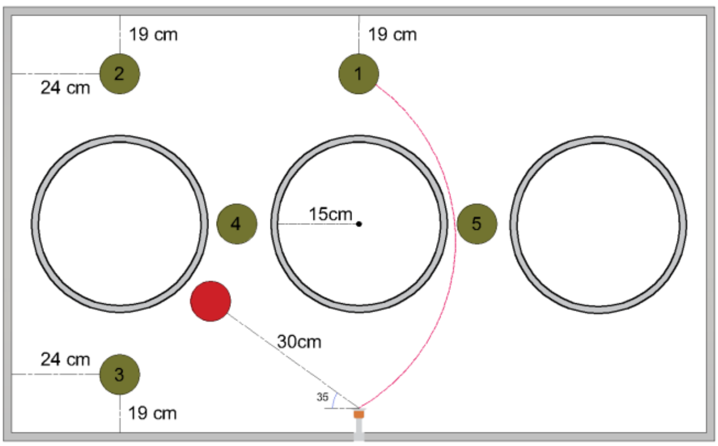

Fig. 12. PD source inside transformer tank model with active part

Table 4. Estimated PD transferred charge value compared to real charge value

PD source location	*measured charge (nC)*	*Estimated charge (nC)*	*Max estimated charge (nC)*
1	0.1665	0.0425	1.82
2	0.1788	0.1038	4.2
3	0.205	0.2551	2.5
4	0.1639	0.1276	6.13
5	0.1877	0.1185	5.92

factors such as the distance of the PD source from the antenna position, the antenna radiation pattern, and antenna polarization, five parameters were introduced. Among the parameters, the V_{FAS} was introduced in this paper for the first time and uses the first peak value of the short-time Fourier transform trend at a specific frequency (here 252 MHz) as the new parameter to quantify the UHF method. The results indicated that V_{FAS} shows better behavior of the received signals compared to other parameters. Hence, it was utilized for estimating the transferred charge, showing that the more directly the received signal reaches the antenna, the higher the accuracy in estimating the transferred charge at the partial discharge location. Although the estimated charges may exhibit a notable deviation from the actual charge, this method could prove beneficial for the long-term monitoring of power transformers. It helps track changes over time for PD based on the estimated results of the apparent charge, allowing for the assessment of the transformer health condition in different periods of time.

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Appendix A

Abbreviations:

UHF:	Ultra high frequency	GTEM:	Gigahertz transverse electric field
PD:	Partial discharge	EM:	Electromagnetic
STFT:	Short time Fourier transform	TE:	Transverse electric
FAS:	First arrived signal	TM:	Transverse magnetic
AF:	Antenna factor	HFCT:	High frequency current transformer
PEC:	Perfect electric conductor	AR:	Axial ratio
PLF:	Polarization loss factor	RMS:	Root mean square
HV:	High voltage		

Parameters & Variables:

E:	Electric field	V_{pp}:	Peak to peak value of the UHF signal
m, n, p:	Propagation mode numbers	V_{SE}:	Energy of the UHF signal
f:	Frequency	V_{sf}:	Mean of UHF signal spectrum in the range of 190 MHz to 260 MHz
c:	Speed of EM wave	V_{ppl}:	Peak to peak of the UHF signal in the frequency range of 190 MHz to 260 MHz
ε:	Permittivity	V_{FAS}:	Peak of the first arrived signal as in Fig. 1
μ:	Permeability	d:	Distance
t:	Time	AR:	Axial ratio value
x:	PD signal	PLF:	Polarization loss factor value
P:	Radiated Power of the antenna	p:	Polarization vector
G:	Gain of the antenna	R:	Ratio of V_{FAS} to apparent charge
λ:	Wavelength	K:	Correction factor for antenna polarization
w:	Window function for STFT	q:	Apparent charge of PD