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Effect of Magnetic field on Partial Discharge Initiated by Metallic Particle in Thermally Aged Natural Esters under AC and Harmonic Voltages

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ABSTRACT This paper reports the experimental and theoretical investigations of particle levitation voltage on thermally aged ester fluid, under AC and harmonic AC voltages, in the presence of both electric and magnetic fields (130 mT and 160 mT). The results indicate a higher sensitivity to identify partial discharge (PD) initiated due to particle movement in aged ester fluids with an ultra-high frequency (UHF) sensor than the fluorescent fiber technique. The cause for the reduction in sensitivity of PD detection due to the fluorescent fiber technique with thermally aged fluid is analyzed using steady-state fluorescent measurement. The reduction in the levitation voltage noticed under high-frequency AC voltages is much more severe than its impact under the fundamental frequency of AC supply voltage. In addition, the presence of a magnetic field reduces the magnitude of levitation voltage substantially. The UHF signals generated due to particle movement-initiated discharges with aged ester fluids indicate a shift in its dominant frequency of 0.9 GHz under the absence of a magnetic field to around 0.6 GHz with the effect of a magnetic field.

INDEX TERMS Ester fluid, fluorescence, magnetic field effect, partial discharge, particle levitation, thermal aging, ultra-high frequency

I. INTRODUCTION

Transformers are the essential component in the generation, transmission and distribution system where their reliable operation depends on the insulation system. Mineral oils, made from the intermediate range of petroleum-derived distillates, are the most widely used liquid dielectrics for transformer applications [1]. However, concerns have been raised in recent years about the existence of polynuclear aromatic hydrocarbons in mineral oils that are getting discharged into the environment in the case of a transformer leakage, fire or explosion [2]. Lately, ester-based dielectric fluids are gaining more importance in transformer applications. The enhanced flash point and fire point of ester fluids have resulted in higher cost-benefit considering its overall insulation lifetime [3]. Besides, they are biodegradable in nature, making them a desirable fluid for transformer operation. Continuous research is underway to better understand the behavior of ester fluid insulation. The

major focus is on their performance under a variety of electrical and thermal loads, as well as chemical processes such as oxidation and hydrolysis that occur in service [4, 5]. The increased expense of ester fluid limited their use in power and distribution transformers, as well as sites where additional environmental protection measures are required. Nevertheless, because of their higher thermal class, transformers filled with ester insulation may be positioned in close proximity to buildings, resulting in decreased space requirements [6] as per National Electric Code (NFPA 70). As a result, considering the growing need for eco-friendly power transformers for voltage ranges higher than 100 kV [7], the replacement of dielectric fluid must be done with necessary design adjustments for the efficient operation of ester fluids inside the transformer. The localized hot spots within the transformers increase the temperature of the oil by around 160°C [8], which catalyzes the degradation mechanisms. This aids the generation of various

contaminants, dissolved gases, and other aging products.

According to the CIGRE 157 report, a significant proportion of transformer failures are due to oil contamination with particles with few particles larger than 100 μ m in diameter [9]. These particles are typically introduced before energization during transformer assembly, transit as well as deterioration of pressboard and oil, internal discharge, and electromechanical vibrations during operation. Comparable to non-conducting particles, conducting particles are said to have a more negative impact on insulation performance [10]. The main cause of the damage in transformer insulation is the initiation of incipient discharges that gets triggered by the protrusions and sharp edges within the current-carrying conductors [11]. These discharges may also cause the protruded sharp tip to melt and fall into the transformer body, introducing micro-level contamination. Additionally, there is a possibility for the cellulose fibers from the pressboard insulating material to detach and float in the bulk volume of the liquid insulation, which leads to impurities that might be either conducting or non-conducting [9, 12]. On the application of an external electric field, these particles acquire a charge, where both the viscous and inertial forces can inhibit particle motion. In the present work, conductive copper particles are considered to understand the partial discharge (PD) activity initiated due to particle movement in thermally aged ester fluid. The usage of the ultra-high frequency (UHF) technique for identifying the PD activity due to particle movement for different voltage profiles has been reported in the literature [13, 14]. However, the impact of particle movement is not yet emphasized. On the other hand, the fluorescent fiber-based sensor is an intriguing technique that is gaining more importance nowadays for detecting PD activity [15]. However, for particle movement-initiated discharges, the choice of a proper fluorescent fiber for monitoring PD activity based on the physical parameters of the insulating fluid, as well as similarities with the UHF approach are not yet investigated.

Zhang et al. [16] analysed the outcomes of experiments on mineral oil and vegetable oil to determine how copper particles affected frequency-dependent and breakdown voltage characteristics. On the application of an external electric field, these particles acquire a charge, where both the viscous and inertial forces can inhibit particle motion. In transformers, the presence of a magnetic field along with the existing electric field, might affect the PD characteristics as per the classical electromagnetic theory. Martinez Tarifa et al [17] reported that the leakage flux density in power transformers varies from 60 mT to 700 mT and demonstrated the variation of magnetic flux by the finite element method (FEM). It is inferred that the direction of magnetic flux may take a variety of patterns with little change in magnetic flux density. Influence of magnetic field on partial discharge activity for ester fluid

showed a reduction in levitation voltage with increasing magnetic flux density [18]. Considering the above aspects of particle intrusions into the dielectric fluid and the existence of magnetic field inside the transformers, the present work examines the partial discharges with copper particle immersed in natural ester fluid with a steady magnetic field (130 mT, 160 mT). A sphere-plane electrode configuration is adopted to allow the alternating quasi-electric field to interact with the magnetic field orthogonally. Vegetable oils contain large concentrations of vitamin E and luminous fatty acids. Thus, the liquid properties are attributable to the change in chemical composition [19]. Therefore, spectroscopic investigations of ester fluids are interesting, thereby selecting a suitable fluorescent fiber for identifying incipient discharges.

Considering the above review of the literature on PD activity, the following experimental investigation was performed in the present work. (i) Steady-state fluorescence analysis on thermally aged ester fluid, (ii) Particle movement-initiated PD activity on aged ester fluid adopting both fluorescent fiber and UHF sensor with and without a magnetic field, (iii) Characteristics of UHF signals involved during PD activity.

II. EXPERIMENTAL DETAILS

A. THERMAL AGEING

The base fluid used in the current work was natural ester (MIDEL 1215) produced from soybean seeds. The thermal aging was conducted with the copper sheet wrapped around the pressboard substrate (1.5 mm thickness) and then submerged in a natural ester fluid inside a beaker. The weights of the pressboard, copper sheet, and oil (1:1:10) were kept identical to those in real-time power transformers. Based on the author's previous experience [20], thermal aging was carried out at 160°C as per IEC 62332-2 standard in a temperature-controlled convection oven in an open beaker with internal air circulation. Both the oil samples and the pressboard were taken out of the reaction mixture at different times maintaining their weight ratios and then inspected for further investigation. The aged samples were sampled at different aging duration including 24, 48, 72, 96, 250 and 500 hours in order to have a controlled aging history.

B. HIGH-VOLTAGE SOURCE AND SENSOR

Fig. 1 shows the schematic test setup used for detecting the particle levitation voltage. The different voltage profiles were generated with the use of function generator (Tektronix 3051C, 5 GSa/s, 50MHz). The generated signal is then fed to the high voltage Trek amplifier (model 20/20C) with an amplification factor of 4 kV providing a maximum output range limited ± 20 KV. The spherical electrode (1.5 cm in diameter) as a high voltage and a concave dish type electrode [14] was used as ground to maintain the particle accurately at the gap spacing between the electrodes. The metallic copper particle with a diameter of 0.5 mm is used in the

present work. The bottom electrode was made slightly concave in shape, to keep the particle in place.

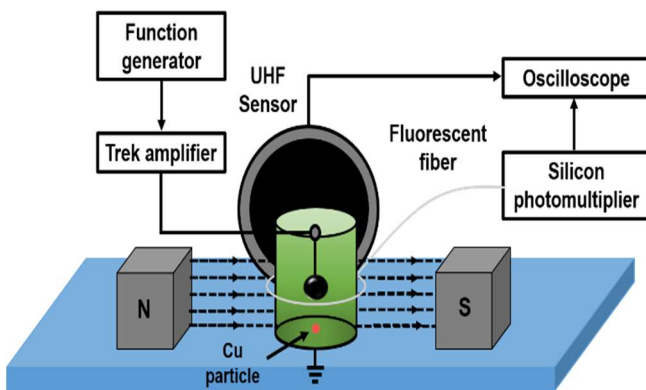


FIGURE 1. Schematic of the experimental setup used for PD activity.

The sphere-plane electrode arrangement is utilized to mimic the partial discharge activity in natural ester fluid. To compare the particle movement initiated partial discharge of natural ester fluid with that of mineral oil from the earlier work by the authors [21,22] without the presence of magnetic field, the distance between the high voltage and the ground electrode was maintained at 5mm whereas the diameter of the ground electrode was selected to be around 50 mm. The voltage at which the first discharge pulse is noticed in

oscilloscope from the UHF sensor/fluorescence fiber is considered as particle levitation voltage. The magnet is positioned at varying distances away from the test cell to modify the flux densities with symmetric gap spacing maintained on both sides. The magnetic flux density was measured using a gauss meter (DGM-202) at the center of the sphere electrode.

The experiments were performed in a completed dark room similar to the case inside the power transformers for better validation on fluorescence fiber results and the trigger level maintained was higher than noise level for its higher accuracy. Since the calibration procedure used for UHF sensor has already been proposed in comparison with the conventional IEC 60270 standards [23], the present work investigates the fluorescent fiber validation and its verification with respect to UHF sensor. The rate of rising of current involved due to PD initiated from surface discharge phenomenon is in the nanosecond range, with a frequency bandwidth in the UHF region and thus employing UHF sensors for its detection [24]. The signal output of the fluorescent fiber method is determined by the duration of luminescence involved during the discharge process. Obtaining the bandwidth of the fluorescence sensor is really a challenge and it depends on multiple factors including the bias voltage, positioning, intensity of light source, etc. As a first step, the use of fluorescent fiber for its use to detect PD activity, the PD events were mimicked by the use of a UV

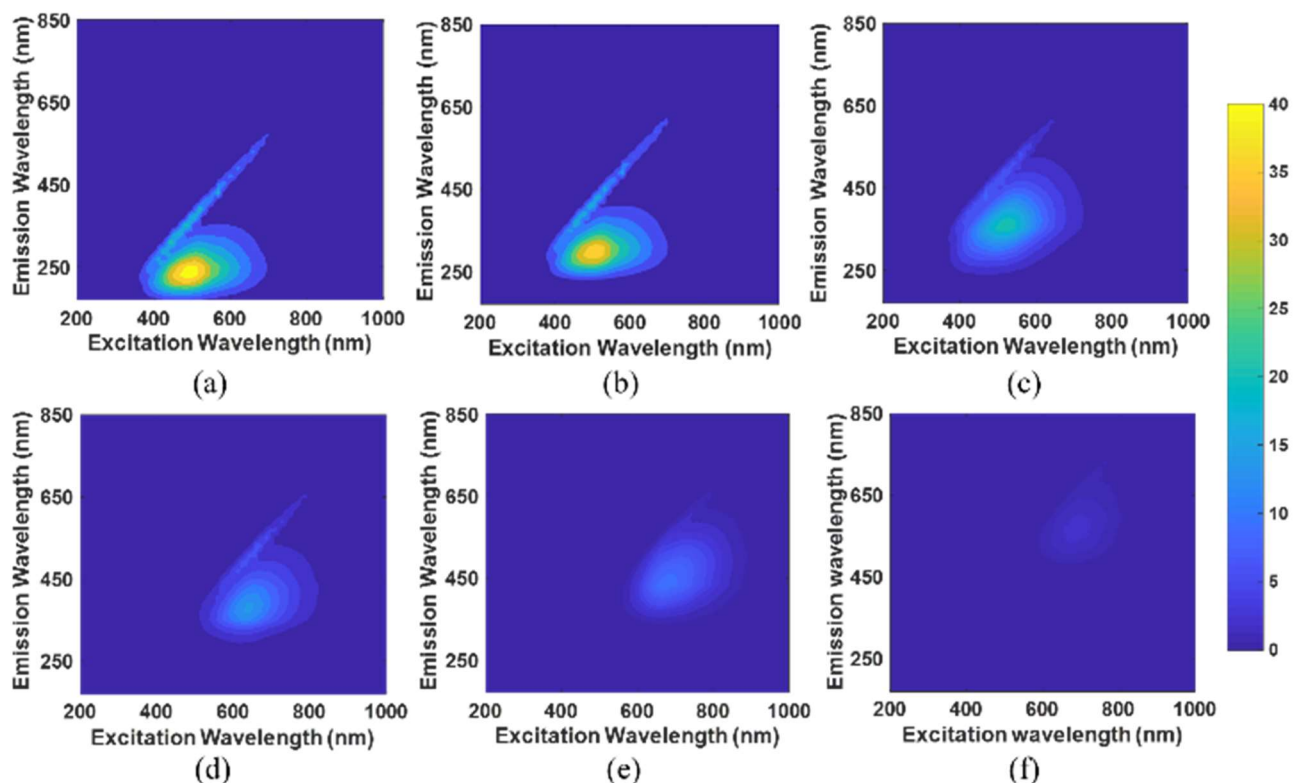


FIGURE 2. Excitation emission matrix of (a) unaged, (b) 48 hours aged, (c) 72 hours aged, (d) 96 hours aged, (e) 250 hours aged and (f) 500 hours aged.

LED source driven with different modulation frequencies. It was observed that a fluorescent optical fiber could sense the UV source up to modulation frequency of 5 MHz. The specification of SiPM indicate that the low light signals with rise times of few nanoseconds could be detected [25]. The fluorescent fiber sensor approach for PD activity during particle movement in ester fluid was studied using a white fluorescent fiber (1 m long and 1 mm diameter) with a silicon photomultiplier module. One end of the fiber is looped circling outside the test cell, orienting towards the gap spacing between the sphere-plane electrode, while the other end of the fiber is fed into the silicon photomultiplier module (biased at 28 V). A sleeve was used to encapsulate the fiber length away from the region of test cell equipment to reduce the external light from interfering with the actual signals. Along with fluorescent fiber, concurrent measurements are taken using a UHF sensor (3 GHz bandwidth) that is positioned at a distance of 20 cm from the discharge region for better accuracy [26]. Signals from both the sensor (fluorescent fiber and UHF) were recorded using a digital storage oscilloscope (bandwidth of 3.5 GHz and sampling rate of 40 GSa/s) and 50 Ω input impedance.

C. FLUORESCENCE SPECTROSCOPY STUDIES

The fluorescence measurements were performed by exciting through a xenon lamp (150 W) with measurements done using a spectrofluorometer (Horiba aqualog). Excitation wavelengths of 240–700 nm were observed at 10 nm intervals in the excitation-emission matrix fluorescence (EEMF) spectra. The emission wavelength was set in the range of 240–800 nm at an increase of 1.1 nm. To measure the change in the fluorescence characteristics of aged ester fluids, the liquid samples were taken at different time intervals and the degradation involved during thermal aging is understood.

III. RESULTS AND DISCUSSIONS

A. STEADY-STATE ANALYSIS OF FLUORESCENCE

Fig. 2 shows the excitation-emission matrix (EEM) of thermally aged ester fluid with the intensity of fluorophore indicated in the color scale. The ester fluids containing unsaturated fatty acids are dominant contributors to fluorescence characteristics where their excitation and emission wavelengths depend on their physicochemical properties [19]. The unaged ester fluid has its excitation and emission wavelength at 500 nm and 250 nm respectively. It is observed that increasing the aging time causes a shift in both excitation and emission wavelengths. The rate of change in its wavelength for the lower aging duration was minimal up to 72 hours and a significant shift was seen at higher aging durations of more than 96 hours. The increase in the percentage of excitation and emission wavelengths were respectively around 40% and 168% for 500 hours of aging duration. This prominent Stokes shift observed for the aged ester fluid demonstrates that understanding the characteristic changes in the insulating fluid's EEM spectra

may be a useful tool for assessing the fluid's quality in a real-life power transformer. Along with the stroke shift, the decrease in intensity of fluorophore indicated in the color scale as the fluid gets thermally degraded gives a visual indication of degradation in insulant properties. The absorption and emission peak of the fluorescent fiber utilized for detection of PD activity due to particle levitation movement in ester fluid must be limited to certain spectral wavelengths. To guarantee that fluorescent fiber detects the optical signal during PD, fluorescent species present in the ester fluid should have an excitation spectrum that is within the range of the developed PD. In comparison to conventional electric PD measurement, fiber-optic sensor-based PD detection can lower external electromagnetic noise [27], providing advantages over conventional techniques on its susceptibility to electromagnetic interferences. To make sure that the produced PD light signal is picked up by the fluorescent fiber, the excitation spectrum of fluorescent materials must fall within the range of the generated PD spectrum. To understand the spectral range of natural ester fluid, the fluorescence emission spectroscopy of the substance was first explored in the current work with its emission wavelengths observed in the range of 600–700 nm range. Today, a variety of research applications use a wide spectrum of plastic scintillating, wavelength-shifting, and light-transmitting fibers [28]. The red and white fiber belongs to a special class of fibers exhibiting a higher Stokes shift, with photons cascading from near UV to blue, then green, and finally towards yellow or red wavelengths [29]. The use of several fibers investigated for PD detection in transformers [30] is already documented in the literature but there is no database available for particle movement initiated partial discharges. Hence, in the present work, the white fiber has been chosen since it exhibits excitation and emission wavelengths similar to the natural ester fluid and it has a higher sensitivity than the red fiber [31]. Among the different fluorescent fibers used for PD detection, the red and white fibers correspond to higher wavelength regions where an increased Stokes shift is involved similar to the current results [28]. The fluorescence behavior of ester fluids differs from the mineral oil in terms of its excitation and emission wavelengths, which are to be tested with different fluorescent fibers. The type of fluorescent fiber best suited for identifying PD with a higher accuracy during particle movement can be selected from an understanding of the fluid's EEM spectra. Also, steady-state fluorescence spectroscopy can also be used to monitor the insulation status of liquid used inside the power transformer.

B. PARTICLE LEVITATION VOLTAGE

The current work uses both UHF and fluorescent fiber to study the particle levitation voltage. The voltage at which the first discharge pulse is noticed in the oscilloscope from the UHF sensor/fluorescence fiber is considered as particle levitation voltage. The experimental results of this particle movement are based on an average of 10 readings with a standard deviation of less than 3%.

1) IMPACT OF AC VOLTAGE ON PARTICLE MOVEMENT

The variation in the particle levitation voltage (PLV) of thermally aged ester fluids under AC voltage is shown in Fig. 3 for its effect with and without the addition of a magnetic field. On application of supply voltage to the electrode gap, the particle acquires certain charge and exerts force in the direction of electric field. Since the supply voltage is time varying, the particles will levitate and drops back to the ground electrode or due to the force, the particle hovers over the ground electrode. This process initiates incipient discharges [21]. During this process, the first signal captured using the UHF and fluorescence fiber is recorded as the Particle Levitation Voltage (PLV). Assuming the sphere plane configuration to exhibit a uniform electric field for the smaller gap spacing (5 mm), the charge obtained by the particle during its contact with the electrode is given by [32],

$$Q = \frac{2\pi^3}{3} \epsilon_0 \epsilon_r r^2 E \quad (1)$$

where ϵ_0 indicates the permittivity of free space (8.854×10^{-12} F/m), ϵ_r is the permittivity of the dielectric liquid, r is the radius of the metallic particle and E is the applied electric field between the two electrodes. From (1), when the particle gains a certain charge, it exerts an electrostatic force in the direction of the electric field. The peak magnitude of the input AC supply voltage forms a major role in the particle movement and as a result, once an AC voltage is applied, the levitated particle lifts from the ground by transferring the charge it has gained, resulting in partial discharge. On application of AC voltage, the particle levitates and continues to move close to the ground electrode with different combinations such as hovering near the ground electrode at its same position, displacement of particles sideways from their original position, to-and-fro movement, oscillatory movement between the gap without any contact with the electrode, and shifting of particles to low field zone [22].

A higher levitation voltage is observed on the ester fluids during the unaged conditions and a linear decrement in the voltage is noticed with the increase in the aging duration. The percentage reduction in the levitation voltage assessed using the UHF technique (Fig. 3a) is observed to be 22.11% and 40.99% for the aging performed around 250 hours and 500 hours respectively. The degradation of ester fluids during thermal aging along with an increased drag force exhibited by the particle is liable for the reduction in its discharges. The levitation voltage measured using fluorescence fiber (Fig. 3b) is higher than the UHF sensor indicating its lower sensitivity towards the detection of partial discharges caused by particle movement in the liquid.

In addition, the effect of the magnetic field (130 mT, 160 mT) showed a slight reduction in the levitation voltage compared to its influence without the magnetic field (0 mT) and the rate of change in the levitation voltage inferred through the UHF technique under the magnetic field followed a similar trend as that noticed without considering

the magnetic field. Although fluorescent fiber-based detection shows a better resistance towards electromagnetic interference [33], its accuracy towards detecting discharges upon the applied magnetic field was very much lesser and inconsistent compared to the UHF technique. The reduction in the intensity of fluorophore as observed from the steady-state fluorescence of aged ester fluids (Fig. 2) could be responsible for its less sensitivity towards the discharges and thus not suitable for its detection towards the PD activity due to particle movement in thermally aged ester fluids.

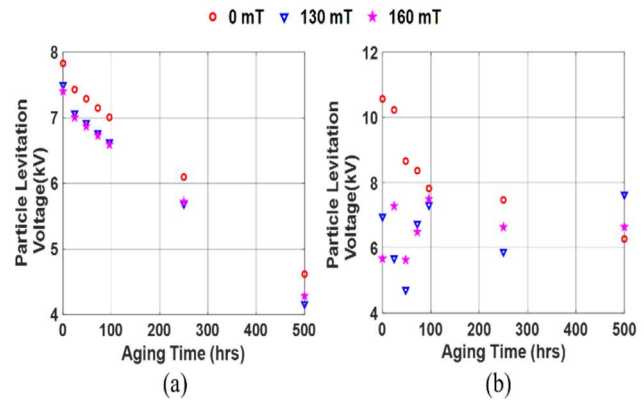


FIGURE 3. Variation in the particle levitation voltage of aged ester fluids with (a) UHF technique, (b) fluorescence fiber.

2) IMPACT OF HIGH-FREQUENCY AC VOLTAGES

Fig. 4 shows the effect of high-frequency AC voltages (3f, 5f, 7f) on the particle levitation voltage of thermally aged ester fluids. It is observed that particle starts levitating at lower voltages under high-frequency AC voltages compared to its effect under fundamental frequencies.

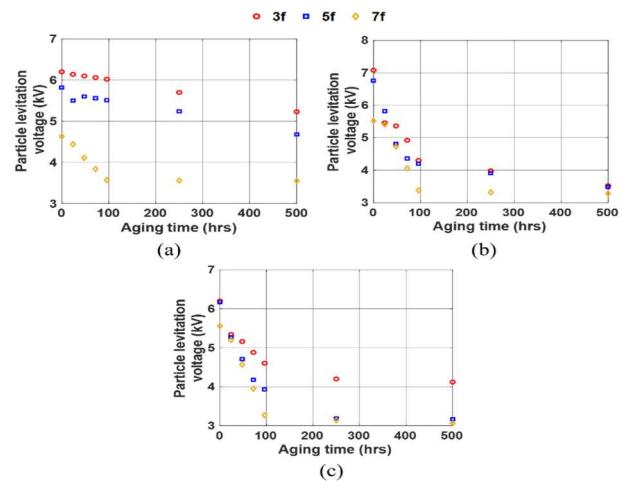


FIGURE 4. Variation in the particle levitation voltage of aged ester fluids under 3f, 5f and 7f with (a) 0 mT, (b) 130 mT, (c) 160 mT.

The amount of charge that the particle has acquired when it is sitting on the ground electrode does not vary with applied frequency. But once the particle is lifted from the

ground, it must traverse a specific distance in order to initiate a charge transport process which is a function of the applied voltage frequency.

Based on the observations, it is noticed that trajectories of the particle with different frequencies did not have much change significantly, indicating only a minimal variation in its particle levitation voltage. Also, with the impact of a higher magnetic field (130 mT and 160 mT), the particle starts levitating with a smaller gyro radius causing a strong interaction with the magnetic field lines. This phenomenon due to the electromagnetic field causes a partial bridging of the particle between the electrodes. This, results in discharges at a lower voltage (Fig. 4c) than its impact compared without a magnetic field.

3) IMPACT OF AC HARMONIC FREQUENCIES WITH TOTAL HARMONIC DISTORTIONS

Fig. 5 indicates the effect of different AC harmonic frequencies with minimum (4%) and maximum (40%) levels of total harmonic distortion (THD) on the particle levitation voltage of thermally aged ester fluids. This minimum and maximum level of THDs on third, fifth and seventh order harmonics were superimposed with fundamental frequency under zero phase shift conditions which are represented as $f+3f$, $f+5f$ and $f+7f$. The percentage THDs of each of these harmonics are represented in brackets with different symbols representing 4% and 40% THD levels.

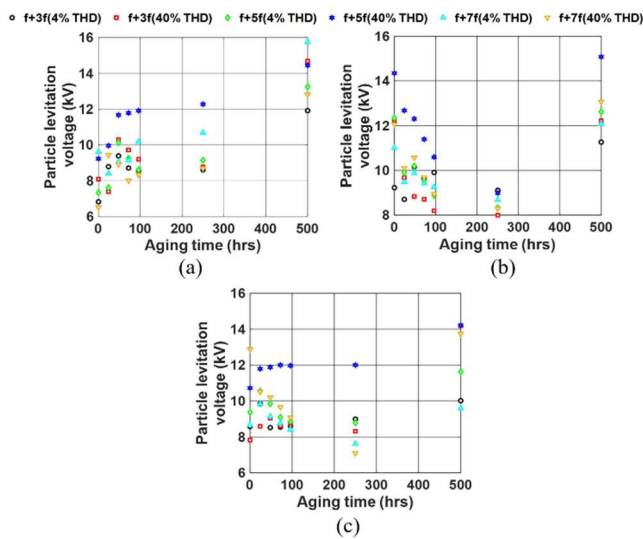


FIGURE 5. Variation in the particle levitation voltage of aged ester fluids under different harmonic AC voltage ($f+3f$, $f+5f$ and $f+7f$) and THDs (4% and 40%) with (a) 0 mT, (b) 130 mT, (c) 160 mT.

In the absence of a magnetic field (Fig. 5a), the effect of different harmonics and THDs had a minimal change in its levitation voltage up to 250 hours aging duration with a sudden shift noticed for 500 hours aging duration. On the contrary, the addition of a magnetic field (130 mT and 160 mT) showed a reduction in levitation voltage for the aging duration of up to 250 hours due to gyration of Cu particles around the magnetic field lines. Compared to the two levels of flux density studied towards the particle movement in

ester fluids, the effect of 160 mT (Fig. 5c) is noticed to be severe compared to 130 mT (Fig. 5b) showing a reduction in its levitation voltage. The increase in the levitation voltage associated with higher aging duration (500 hours) under all conditions (with and without magnetic field) could be related to the higher viscosity of thermally aged ester fluids [20] providing an increased drag force compared to the aging durations of less than 250 hours.

4) IMPACT OF MAGNETIC FIELD ON THE UHF SIGNAL

The signal pattern obtained from the UHF sensor during partial discharge activity owing to particle movement and its Fast Fourier Transform (FFT) is shown in Fig. 6. The peak-to-peak magnitude of UHF signals as noticed in Fig. 6a is higher with the addition of a magnetic field and thus responsible for the reduction in its levitation voltage compared to its influence without a magnetic field. The frequency content of the UHF signal spans from 0.3 GHz to 1 GHz, with 0.9 GHz as its dominating frequency without the existence of a magnetic field (0 mT). While considering the impact of discharges measured under the AC voltage profile, the UHF signal obtained with the impact of magnetic field (130 mT, 160 mT) has shown a change in its dominant frequency to around 0.5 to 0.6 GHz (Fig. 6b) specifically in comparison to its influence without the presence of the magnetic field, where the frequency is observed in the range of 0.9 GHz to 1 GHz.

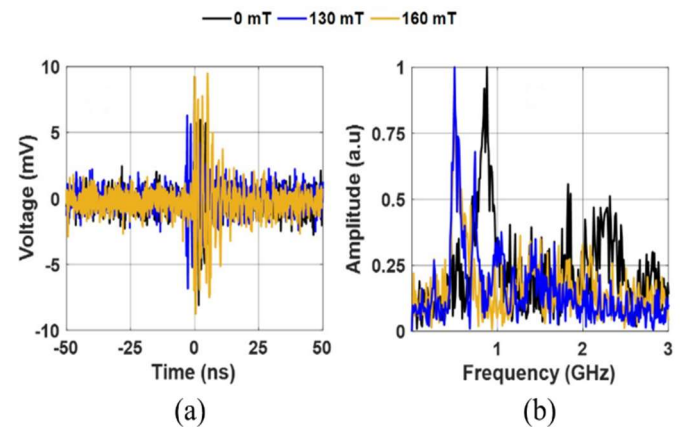


FIGURE 6. (a) Typical time domain UHF signal and (b) Fast Fourier Transform with and without a magnetic field.

This shift observed may be attributed to the electromagnetic interferences caused by particle movement and the drift produced due to $\vec{E} \times \vec{B}$. Also, there was not much variation in the frequency of the UHF signal for the PD activity measured under high-frequency AC voltages and harmonic frequencies with different THDs, whereas the addition of a magnetic field caused a frequency shift similar to that observed under AC voltages. Similar results were observed with higher magnetic field in mineral oil which is due to the spiral gyration (gyrofrequency) experienced by charge carriers [34]. The injected current pulse responsible for the generation of electromagnetic radiation during PD is

being distorted by the magnetic field, resulting in a shift in the frequency spectrum of UHF signals. Thus, it has been confirmed that the addition of a magnetic field during the particle movement-initiated discharges in ester fluids can mislead the insulation engineers while monitoring the incipient discharges occurring inside the power transformers.

C. THEORY OF MAGNETIC FIELD TOWARDS PARTIAL DISCHARGES

As discussed in Section 1, at any instant of applied AC voltage, the particle can acquire a charge based on its interaction with the electrode surface. The copper particle being non-magnetic in nature, does not get attracted to the alignment of the magnetic field. On the application of AC voltages with the addition of a magnetic field, the Cu particle drags at the ground electrode with a slow movement observed with the ester fluid. Apart from the above mechanism, there were multiple combinations of particle movement observed such as hovering near the ground electrode at its same position, displacement of particles sideways from their original position, to-and-fro movement, oscillatory movement between the gap without any contact with the electrode, and shifting of particles to low field zone. This is because when a magnetic field line crosses the copper particle inside the ester fluid, the electron charges that are present on the surface of the particle try to reorganize themselves and flow in a circular pattern perpendicular to the magnetic field as shown in Fig. 7.

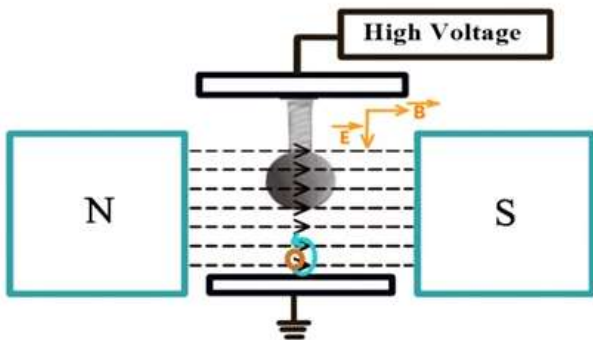


FIGURE 7. Magnetic field lines on the gyration of particles.

This motion of the particle leads to a pattern of flow [32] and the force transmitted from the surface charges of the moving particle causes drag in the fluid. The collection of the charged particle behaves in a collective way because of these forces. As explained (1), the particle experiences an electrical force that is proportional to the square of the particle radius, permittivity, and electric field applied. Along with this force, the particle also experiences a viscous force that is given by [32]

$$F_d = 6\pi r \eta v C \quad (2)$$

where η is the dynamic viscosity (mPa.s), r is the radius of the particle used for study, v is the velocity of the particle and C is the correction factor that attributes to non-linearity

in the drag caused by the levitation of particles. The electric force initiates the particle movement thereby absorbing the charges from the electrodes initiating the discharges but upon the addition of a magnetic field, an orthogonal force gets overlapped with the applied electric field. Hence, along with these forces, the charged particles behave in a collective way under the influence of a magnetic field getting affected by Lorentz Force \vec{F}_L as,

$$\vec{F}_L = q \cdot [\vec{v} \times \vec{B}] \quad (3)$$

where, q is the particle's electric charge, \vec{v} is the velocity and \vec{B} is the magnetic flux density. Since the direction of force expressed in (3) is the cross product of velocity and magnetic field, Lorentz force always acts perpendicular to the direction of motion which causes particles to move in a circular motion with the covering of orbital motion particles known as gyro-radius. Since this force acts perpendicular to the trajectory of the particle, it experiences a curved path with a gyro radius (R_g) until it forms a complete circle. When the intensity of the magnetic field is higher, it alters the trajectories of the particle which respond differently to the forces that are parallel and perpendicular to the direction of \vec{B} . This is known as magnetized plasma in which plasma tends to have anisotropic properties that react differently to these forces. Therefore, the total force that acts on the particle due to both electric and magnetic fields is given by,

$$\vec{F} = q \cdot [\vec{E} + (\vec{v} \times \vec{B})] \quad (4)$$

When the trajectory of the particle is such that it travels in a direction other than \vec{B} , it moves in a direction perpendicular to it, causing the particle to gyrate. In the presence of a uniform magnetic field, particle covers gyration radius [35], given by

$$R_g = \frac{\alpha}{\Omega} \quad (5)$$

where, α is the velocity and Ω is the gyro frequency, the frequency of moving charged particles which is directly proportional to \vec{B} . Thus, the reduction in the magnitude of the particle levitation voltage as observed from the experimental results can be related to the gyration of the particle as indicated in (5) which is dependent on the level of a magnetic field. In the range of magnetic field applied to understand the Partial discharge formed due to particle movement, its impact for variation in circular motion of the particle is not observed. In the range of magnetic field applied to understand the Partial discharge formed due to particle movement, its impact for variation in circular motion of the particle is not observed. Admittedly, further work is essential to confirm for any variation in particle movement causing PD variation, under time varying high electric and magnetic fields.

IV. CONCLUSION

- The particle levitation voltage is assessed using both UHF sensor and fluorescence fiber for different voltage

profiles such as AC voltages, high-frequency AC voltages, and harmonic frequencies with different THDs superimposed on the fundamental AC supply voltage. A linear reduction in the levitation voltage is observed under AC voltages with the increase in the aging duration using the UHF sensor but the sensitivity of fluorescence fiber towards particle movement-initiated discharges on aged ester fluids was very low compared to the UHF sensor.

- The reduction in the intensity of fluorescence for aged ester fluid along with the Stokes shift not only confirms its degradation of ester fluids during thermal aging but also provides an explanation for the less sensitivity of fluorescence fiber towards particle levitation voltage.
- A reduction in the levitation voltage is observed with an increase in the frequency of AC voltages and the impact of harmonic frequencies with different THDs. Further, a higher levitation voltage noticed for higher aging duration could be related to the higher viscosity of thermally aged ester fluids.
- The peak-to-peak magnitude of the UHF signal obtained during the particle movement on ester fluid indicated a shift from dominating frequency of 0.9 GHz to 0.6 GHz in the presence of a magnetic field, thus reflecting the electromagnetic interferences in the signal as well as drift in the particle movement caused due to cross product of electric and magnetic field lines.
- Further, the theoretical studies on the impact of the magnetic field on particle movement-initiated discharges were discussed indicating that the gyration of the particle tends to reduce the particle levitation voltage.

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