Research Article

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Impact of Harmonic Voltage on the Partial Discharge Properties of Eco-Friendly Nanofluid

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ABSTRACT

The Insulation is crucial in transformers to maintain electrical isolation between components and windings, ensuring safe and efficient operation. Mineral oil acts as both insulation and coolant in transformers. It is a substance that does not naturally degrade and can persist in the environment for an extended period if accidentally released. Therefore, Sunflower oil is used as a substitute for mineral oil. However, harmonic distortion is a common issue in power systems, leading to increased dielectric loss and partial discharge activity, ultimately causing insulation failure and equipment damage. Hence, it is vital to analyze the partial discharge performance of pure Sunflower oil under varying harmonic AC voltages to ensure the reliable operation of electrical devices. The study examines the partial discharge characteristics of a sunflower oil-based nanofluid under harmonic AC voltages, which is a blend of pure sunflower oil and SiO2 nanoparticles. Two nanofluid mixtures were created, one with a 0.01% mass ratio and the other with 0.05% sunflower oil. Various PD characteristics were evaluated, including Partial Discharge significance, starting voltage, duration of increase, maximum amplitude, Phase-Resolved PD sample, and frequency and time graphs of the Partial Discharge signal. All tests were carried out under IEC regulations. A comparison was made between the outcomes of Nano blended sunflower oil and natural sunflower edible oil. Experiments were conducted on partial discharges in Sunflower oil using specific harmonic superimposed AC Voltages, utilizing the third and fifth harmonics. The findings reveal that: a) PDIV value decreases with increasing harmonic order when using AC voltage with superimposed harmonics, b) PD characteristics are closely related to the voltage waveform, and the addition of Silica to sunflower oil results in reduced PD amplitude, pulse duration, and time duration compared to pure sunflower oil.

Keywords: Harmonics voltage; Sunflower oil; Partial Discharge (PD); Order of Harmonic; HVAC; PD repetition rate.

1. INTRODUCTION

The power transformer plays a crucial role in the power transmission system and must maintain a high level of reliability consistently. It is vital to closely monitor the dielectric properties of power transformers in all circumstances to ensure their proper functioning. Through partial discharge studies, even small variations in power transformer performance can be easily detected and analyzed to facilitate further investigation. Detecting Partial Discharges (PD) in high-voltage components is crucial for identifying issues with insulation systems that could potentially result in power transformer failures. PDs may manifest in gas spaces or within the oil of power transformers, depending on the underlying cause(Chandrasekar and Montanari, 2014). In transformer oil/pressboard insulation systems, the occurrence of PD is typically linked to the presence of air between the windings and the pressboard gaps (Cui *et al.* 2017).

Analyzing PD pulse waveforms can help study PD mechanisms; monitoring the insulation status involves examining phase-resolved partial discharge (PRPD) patterns (Nagendran *et al.* 2018). The Partial Discharge Inception Voltage (PDIV) is crucial for assessing the insulation quality of sunflower oil. The magnitude of PD is key in early detecting faulty thermal protection systems and evaluating manufactured items (Jin *et al.* 2015). Research indicates that studying discharge information in sunflower oil, such as streamer initiation and distribution, is achievable using an ultra-high frequency oscilloscope (300 MHz to several GHz). Employing a time-resolved PD measurement system can reveal the shape of the discharge pulse, linked to charge carrier movement. The PD rate of repetition within a single PD sequence influences one pulse pattern inhibition. The PD pulse pattern is defined by rise time, pulse duration, fall time, and pulse amplitude (Pompili *et al.* 2009; Cavallini *et al.* 2015).

Analyzing PD alerts in dielectric fluids can offer more information for revising HV additives where used, as PD can signal the existence of imperfections such as gaps in solid substances or gas-filled spaces and bubbles in fluids (Segal *et al.* 2000). Lewis further highlights that the inflow of electrons from the cathode into the insulator could result in localized warming and expansion of the insulator near the metal electrode. Krasucki applies this theory of bubbles to explore the breakdown process of liquid dielectrics. The text focuses on partial discharge caused by harmonic input, mainly from power electronics devices. Harmonic elements can disrupt circuit control and degrade plant insulation. These disruptions can alter waveforms and crests from the original sine wave, emphasizing the need for careful power isolation planning. Various methods are available to analyze partial discharge linked to harmonics. The system using acicular-plane electrode is widely employed in streamer research. This is due to the fact that an electrode needle can create an electrical field imbalance sufficient to cause dispersion of currents (Chandrasekar *et al.* 2020).

2. EXPERIMENTAL SETUP

2.1 Preparation Testing Specimens

Sunflower oil is filtered prior to mixing with 0.01% and 0.05% by weight of Nano SiO_2. The blend is then stirred for about 5 minutes (Uthirakumar *et al.* 2018; Chandrasekar *et al.* 2020a). Subsequently, the samples undergo ultra-sonication for roughly 15 minutes for processing. The systematically arranged oils are then heated at an elevated temperature to eliminate moisture from the samples. Following this, all samples are kept undisturbed for 36 hours to prevent nanoparticle clumping, which can cause settling at the liquid's bottom (Hwang *et al.* 2008).

Table 1. Sample details and its identity

Sample Identity	Sample Detail
SF-I	Pure Sunflower oil
SF-II	SF oil + 0.01% SiO_2
SF-III	SF oil+ 0.05% SiO_2

2.2 PD Testing Setup

In the present study, an acicular-planar electrode configuration is utilized to mimic corona discharge. PD assessments are performed in accordance with the testing procedure specified in IEC 60270. In Figure 1, a validation cell is shown featuring an N-P electrode layout. The needle tip possesses a curvature radius of 1.5 µm. While the pointed electrode is connected to a high-voltage power source, the flat electrode is effectively grounded. The grounded electrode consists of a1.5 mm thick chipboard, and the needle-flat electrode setup ensures a robust PD source. Partially discharged trials have been executed employing a Trek high-frequency High Voltage amplifier (version 50/12C) to create harmonically superimposed AC voltages, with the input signal being provided by an arbitrary waveform generator (BNC 65). Throughout this investigation, the resulting voltage is attained by summing up diverse harmonics of different amplitudes and orders to the fundamental alternating voltage.

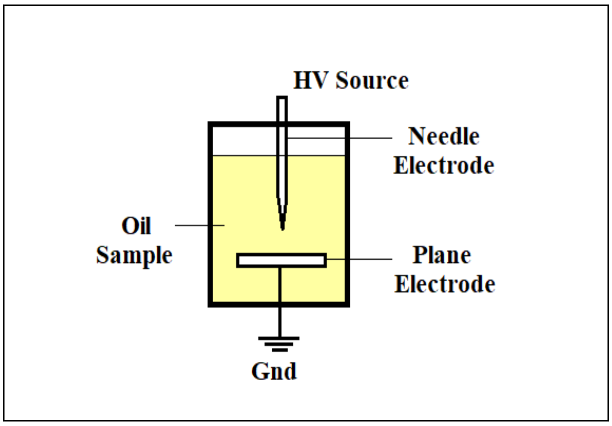

Fig. 1: Setup of the sample

Adjacent electrodes are spaced 2.5mm apart. PD signals were acquired by linking an HFCT sensor to the ground terminal of the test cell. A clip-on tool, the High-Frequency CT, is affixed to the GND wire of the test cell. The High-Frequency CT output links to the PD KIT and recording device. Partial Discharges are detected using a high-bandwidth tool, Partial Discharge BASE II, capable of capturing full Partial Discharge patterns at a sampling rate of up to 100MSa/s and a bandwidth of 0-50 MHz. Partial Discharge patterns are analyzed using advanced signal processing algorithms to identify potential insulation defects within the test cell. The PD KIT provides real-time monitoring and analysis of PD signals, allowing for early detection and prevention of potential equipment failures.

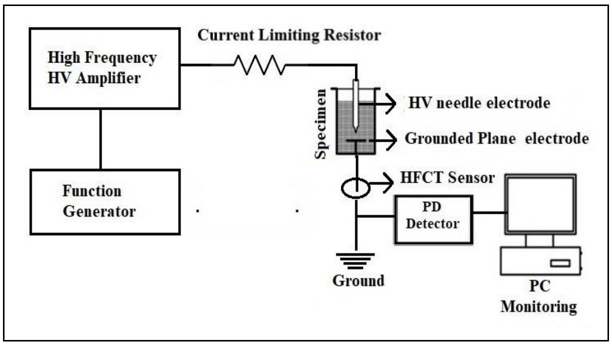

Fig. 2: Test apparatus for the study of partial discharge

Partial Discharge BASE II can categorize digitized PD pulse waves according to their PD waveform shape. This information is transmitted to a distant computer for analysis and evaluation. Figure 2 illustrates the complete test setup used in the partial discharge examination. In this setup, a high-frequency current transformer (HFCT) is used to capture PD signals along with a PD sensor, which is connected to a data acquisition unit (DAU). The DAU processes the captured signals and sends them to the BASE II system for advanced waveform analysis. This detailed analysis allows for the identification of potential issues and the early detection of partial discharge activity in electrical insulation systems.

3. RESULT AND DISCUSSION

3.1 Partial Discharge Inception Voltage

The inception voltage for partial discharges (PDIV) defines the critical threshold when partial discharges (PD) first appear in an insulation system. It is a key metric for assessing insulation effectiveness and electrical element breakdown behavior. Testing PDIV involves incrementally increasing voltage levels until partial discharges are detected, providing crucial insights into the reliability and performance of electrical insulation systems.

Thus, a needle-like and flat electrode setup was employed to reproduce consistent PD signals. An extra AC signal with harmonics is introduced to the primary signal to stimulate partial discharge in the sunflower oil. The primary signals stayed consistent at a fixed 50 Hz frequency with a magnitude of one, while the harmonic signal ranged from 0V to a maximum of 1kV utilizing various harmonic sequences. The specimens are subjected to testing by incrementally elevating the harmonic voltage applied until the primary PD pulse is detected in the PD sensor, with the cycle repeated every 10 minutes at the same voltage level. The voltage at which the initial primary PD pulse is detected is recorded as the partial discharge initiation voltage (PDIV). Typically, PDIV decreases with increasing harmonic orders. Figure 3 illustrates the fluctuation of PDIV in sunflower oil with a flat needle electrode configuration at different harmonic values of the applied voltage.

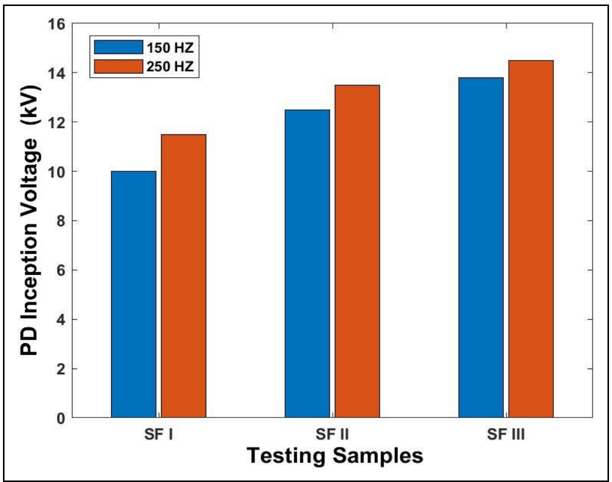

Fig. 3: PDIV analysis of sample SF-I, SF-II and SF-III at various frequencies

3.2 Partial Discharge Patterns

Partial discharge occurs within electrical insulation systems, leading to the creation of unique waveforms or patterns of electrical signals referred to as partial discharge (PD) patterns. The exploration of these patterns can offer vital insights into the properties and intensity of the partial discharges. The analysis of PD patterns typically involves advanced signal processing techniques, such as statistical analysis, frequency analysis, and time-domain analysis. Additionally, the evolution of PD patterns over time can provide valuable data for predicting potential failures and optimizing the performance of electrical assets.

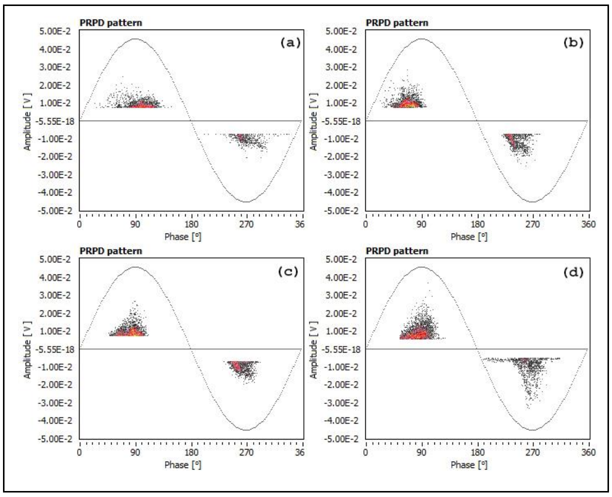

Fig. 4: PRPD model of Sample SF-I for the (a) 3rd harmonic at PDIV (b) 3rd harmonic at 125% of PDIV (c) 5th harmonic at PDIV (d) 5th harmonic at 125% of PDIV

To examine how PD patterns are affected by harmonic order, PD patterns were captured with 3rd and 5th harmonic components at designated voltage levels. The test voltage is gradually raised past the PD trigger level, and the PD waveform signals are captured for every 0.5 kV increment in voltage. This procedure is repeated for each harmonic sequence. To enhance the accuracy of the comparison, the phase-resolved partial discharge (PRPD) patterns of different harmonic values for both pure sunflower oil and Silica (SiO_2) blended sunflower oil are analyzed and compared. For each set of PD patterns captured, the amplitude, phase distribution, and apparent charge magnitude are thoroughly examined to discern any distinct differences between the 3rd and 5th harmonic components.

By meticulously studying the PRPD patterns of pure sunflower oil and Silica (SiO_2) blended sunflower oil under various harmonic conditions, a comprehensive analysis can be conducted to determine how the harmonic order influences the characteristics of partial discharge in these dielectric materials. This detailed investigation aims to provide valuable insights into the behavior of PD patterns and aid in the development of effective diagnostic techniques for assessing insulation quality in high-voltage equipment.

In Fig. 4, standard PD patterns at PDIV and 125% of PDIV with different harmonic orders are shown. Patterns (a and c) depict Partial Discharge inception voltages with 3rd and 5th harmonic orders in pure sunflower oil. Similar to PD design (b and d), the magnitude at the 3rd and 5th harmonic is 125% of PDIV. Patterns (b and d) represent Partial Discharge inception voltages in a sunflower oil mixture with 3rd and 5th harmonic orders. The PD inception voltage at the 3rd and 5th harmonic orders is calibrated to be 125% of PDIV, aligning with the standard set by patterns (a and b) in sunflower oil.

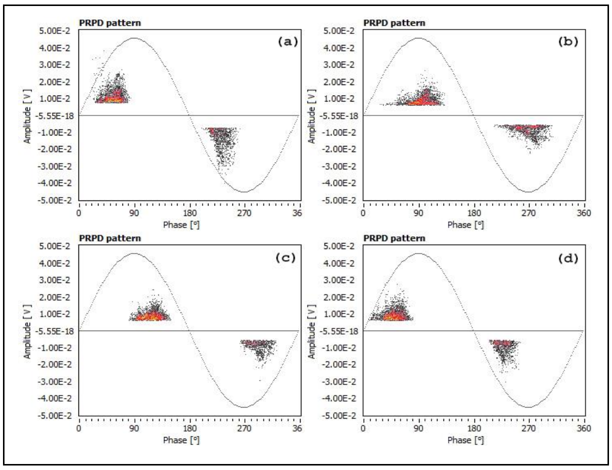

Fig. 5: PRPD model of sample SF-II for the (a) 3rd harmonic at PDIV (b) 3rd harmonic at 125% of PDIV (c) 5th harmonic at PDIV (d) 5th harmonic at 125% of PDIV

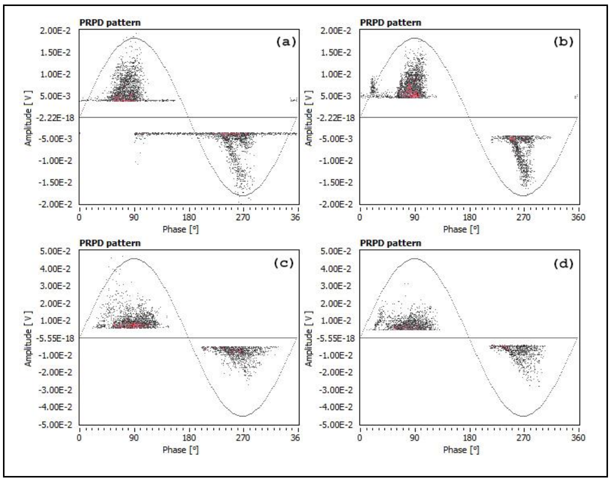

Fig. 6: PRPD model of sample SF-III for the (a) 3rd harmonic at PDIV (b) 3rd harmonic at 125% of PDIV (c) 5th harmonic at PDIV (d) 5th harmonic at 125% of PDIV

Figure 5 displays typical PD patterns at PDIV and 125% of PDIV harmonic voltages, showing different harmonic orders. The PDIV is achieved through PD patterns (a and c) at the 3rd and 5th harmonics for nano-scale sunflower oil of 0.01%. Similar to PD patterns (b and d), but with PDIV harmonic voltages at the 3rd and 5th harmonics increased by 125%. Similarly, PD patterns (a and c) can be seen in Figure 6 at PDIV for 0.05% Nano scale sunflower oil for the 3rd and 5th harmonics. Just like in PD pattern (b and d), the 3rd and 5th harmonic voltages are 125% times the PDIV. The PD pattern shown above suggests that there is more discharge activity for 125% of PDIV harmonic values compared to PDIV harmonic values. More discharge activity is seen with a larger quantity of harmonic sequences in harmonic sequences. The results indicated that adding silica to sunflower oil decreased the size of PD in comparison to pure sunflower oil. PD repetition rate Varies with respect to harmonic voltage and harmonic order.

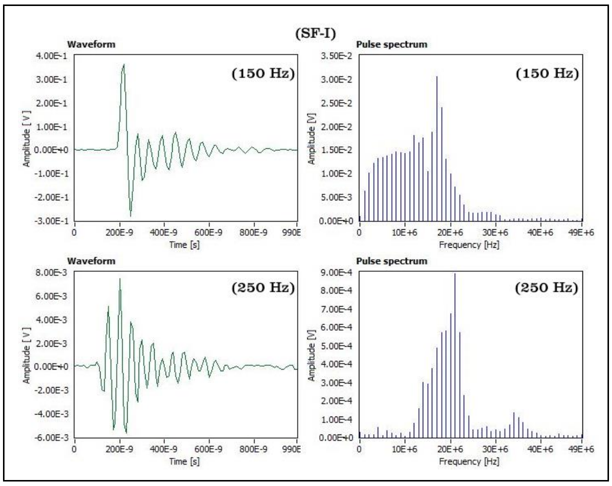

Fig. 7: Amplitude – Time frequency graph of testing sample SF-I for the 3rd and 5th order harmonics

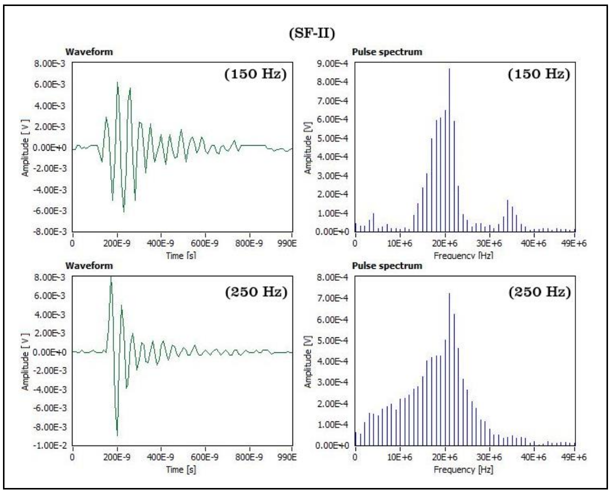

Fig. 8: Amplitude – Time frequency graph of testing sample SF-II for the 3rd and 5th order harmonics

3.3 Time Frequency analysis at Harmonics

The PD properties of the testing samples can be determined by analyzing the PD pulses in time and along with the frequency domain. Typically, understanding the time-frequency characteristics of PD signals requires analyzing the formation of PD pulse shape, rise time, frequency spectrum, and equivalent time-length figure.7 illustrates the time frequency graph of the sample S-I for the third and the fifth order harmonics. On increasing the frequency the rise time and frequency amplitude of PD pulse get decreased. That is the time frequency of third order seems to be higher when compared to the fifth order harmonics.

From observing the figure.8 it shows that PD analysis of the sample S-II that is 0.01% of silica nano solvent is added with the pure sunflower oil. From fig.8 we can understand about the rise time and frequency amplitude of the PD pulse on increasing the frequency from third order to fifth order there is a change in rise time and frequency amplitude of the PD pulse. This means on increasing the frequency the rise time and frequency amplitude of PD pulse is decreasing

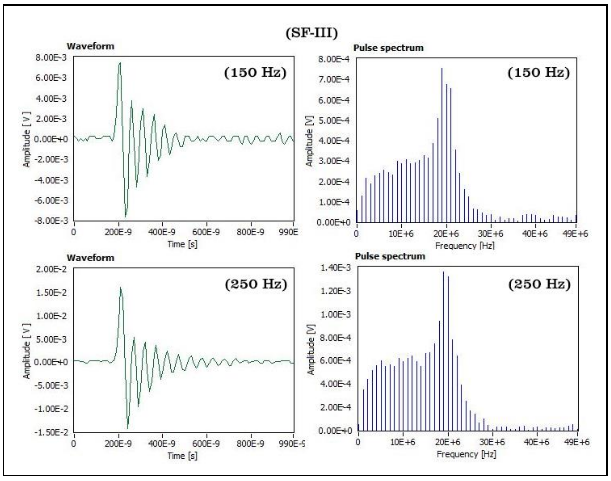

Fig. 9: Amplitude – Time frequency graph of testing sample SF-III for the 3rd and 5th order harmonics

Figure. 9 show the time frequency analysis of the Sample S-III i.e. 0.05% of silica nano particle is added with pure sunflower oil and from the time frequency graph we can see that on increasing the frequency from third order to fifth order there a decrease in rise time and frequency amplitude of the PD pulse.

On analysing the findings of the PD pulse waveform and geometry plane it shows the maximum range energy on the PD signals of the frequency. On comparing the results of the samples it is observed that wave form distortion in samples S-I is higher when compared to other two samples S-II and S-III that is wave form distortion is observed in pure sample is higher when compared to the samples in which silica nano filler is added. PD analysis shows distinction in the frequency range of pure sample and the silica added samples that is samples with and without nano fillers. The peak value of sample S-II is lower when compared with the sample S-I and the settling time distortion seems to be lesser in nano fluids. The nano samples S-II and S-III is compared, the sample S-I have the higher value in time length. It shows that the sample with nano filler have less effects on partial discharge properties.

3.4 Partial Discharge Repetition Rate Variation with Respect to Harmonic Order

The occurrence of sunflower oil recurrence varies based on Harmonic voltages. Figure.10 shows that the frequency of repetition rises with increasing voltage across different harmonic orders.

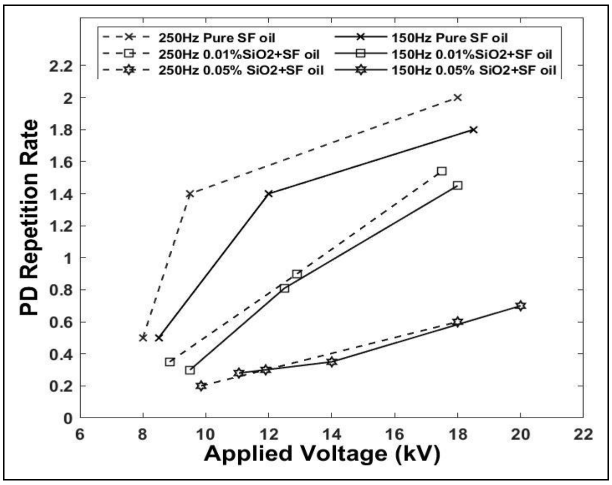

Fig. 10: PD repetition rate in accordance with harmonic voltages, Harmonic disposition for sample SF-I, SF-II and SF-III

4. CONCLUSION

This study shows the influence of harmonics and the fundamental voltage on sunflower oil's PD performance. Results show that PD amplitude decreases notably with increasing time, longer settling time, and higher repetition rate. The final result can be summarized briefly as:

a) As the harmonic order increases, the PDIV value decreases when an AC voltage with superimposed harmonics is used.

b) The PD pattern is closely linked to the provided voltage waveform, and the peak discharge size tends to increase with higher harmonic orders.

c) PDIV becomes superior to pure sunflower oil due to the inclusion of silica. The PD is somewhat lower in comparison to sunflower oil blended with SiO_2.

During partial discharge testing, researchers discovered that including harmonic orders in sunflower oil caused an escalation in partial discharge activity and a decrease in the oil's dielectric insulation capabilities.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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REFERENCES

Cavallini, A., Karthik, R. and Negri, F., The effect of magnetite, graphene oxide and silicone oxide nanoparticles on dielectric withstand characteristics of mineral oil, *IEEE Trans. Dielect. Electr. Insul.*, 22(5), 2592–2600 (2015). https://doi.org/10.1109/TDEI.2015.005016

Chandrasekar, S., Chandramohan, J., Montanari, G. C. and Uthirakumar, P., Developing eco-friendly nanostructured oil: Partial discharge and breakdown voltage characterization of transformer corn oil, *IEEE Trans. Dielect. Electr. Insul.*, 27(5), 1611–1618 (2020a). https://doi.org/10.1109/TDEI.2020.008992

Chandrasekar, S., Kasi Viswanathan, P., Uthirakumar, P. and Montanari, G. C., Investigations on Novel Carbon Quantum Dots Covered Nanofluid Insulation for Medium Voltage Applications, *J. Electr. Eng. Technol.*, 15(1), 269–278 (2020b). https://doi.org/10.1007/s42835-019-00316-5

Chandrasekar, S. and Montanari, G., Analysis of partial discharge characteristics of natural esters as dielectric fluid for electric power apparatus applications, *IEEE Trans. Dielect. Electr. Insul.*, 21(3), 1251–1259 (2014). https://doi.org/10.1109/TDEI.2014.6832272

Cui, L., Chen, W., Vaughan, A. S., Xie, B., Li, J. and Long, Z., Comparative analysis of air-gap PD characteristics: Vegetable oil/pressboard and mineral oil/pressboard, *IEEE Trans. Dielect. Electr. Insul.*, 24(1), 137–146 (2017). https://doi.org/10.1109/TDEI.2016.005911

Hwang, J. G., O'Sullivan, F., Zahn, M., Hjortstam, O., Pettersson, L. A. A. and Liu, R., Modeling of Streamer Propagation in Transformer Oil-Based Nanofluids, In: 2008 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, IEEE, Quebec City, QC, Canada, 361–366 (2008). https://doi.org/10.1109/CEIDP.2008.4772777

Jin, H., Morshuis, P., Mor, A. R., Smit, J. J. and Andritsch, T., Partial discharge behavior of mineral oil based nanofluids, *IEEE Trans. Dielect. Electr. Insul.*, 22(5), 2747–2753 (2015). https://doi.org/10.1109/TDEI.2015.005145

Nagendran, S. and Chandrasekar, S., Investigations on Partial Discharge, Dielectric and Thermal Characteristics of Nano SiO2 Modified Sunflower Oil for Power Transformer Applications, *J. Electr. Eng. Technol.*, 13(3), 1337–1345 (2018). https://doi.org/10.5370/JEET.2018.13.3.1337

Pompili, M., Partial discharge development and detection in dielectric liquids, *IEEE Trans. Dielect. Electr. Insul.*, 16(6), 1648–1654 (2009). https://doi.org/10.1109/TDEI.2009.5361585

Segal, V., Rabinovich, A., Nattrass, D., Raj, K. and Nunes, A., Experimental study of magnetic colloidal fluids behavior in power transformers, *Journal of Magnetism and Magnetic Materials*, 215–216, 513–515 (2000). https://doi.org/10.1016/S0304-8853(00)00205-5

Uthirakumar, P., Devendiran, M., Yun, J.-H., Kim, G. C., Kalaiarasan, S. and Lee, I.-H., Role of carbon quantum dots and film thickness on enhanced UV shielding capability of flexible polymer film containing carbon quantum dots/N-doped ZnO nanoparticles, *Optical Materials*, 84, 771–777 (2018). https://doi.org/10.1016/j.optmat.2018.08.016