Titania-based transformer nanofluid: a study on the synthesis for enhanced breakdown strength and its humidity ageing

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Abstract: Researches on the transformer oil-based nanofluids to determine its suitability for replacing the conventional liquid insulation has been consistently happening for more than a decade. Yet, to prepare an optimum blend of transformer oil-based nanofluid with the stability compliance and superior breakdown (BD) characteristics is still a key issue to be addressed. So to achieve the higher BD voltages (BDVs) with good stability, the nanoparticle and surfactant weights dispersed in the oil should be optimised to at least possible critical levels. In this work, dielectric BD characteristic of mineral oil dispersed with TiO\textsubscript{2} nanoparticle and surfactant cetyl trimethyl ammonium bromide (CTAB) is been studied with the applied AC and DC high voltages, which is termed as titania-based transformer nanofluid (TTNF) for this study. Series of TTNF samples were synthesised with different weights of TiO\textsubscript{2} nanoparticle and CTAB, and the partial discharge inception voltage, AC and DC BDV were experimented to ascertain the optimum concentration level. Results show that the AC and DC BDV enhanced up to 36.23 and 43.07%, respectively, for the TTNF prepared with 0.00562 wt% of TiO\textsubscript{2} and its 1% weight of CTAB, which was stable for around eight weeks.

1 Introduction

Adaption and improvisation of the traditional power system network towards microgrid, smart grid etc. poses several challenges in the design of power transformers. As it is deployed in the voltage level transitions, it is considered to be an essential component in the power system, and its reliable and safe operation becomes vital. The statistical reports say that 75% of the transformer collapses are attributed to its insulation problems, which reduces the normal expected service life of 35 years to almost half proportion of it [1]. So the insulating liquid is one among the vulnerable component that could not be ignored when redesigning the transformer to the current trend. This leads a thrust for the search of an alternative and/or next-generation liquid insulation with improved physiochemical parameters, despite the dominancy of mineral oil (MO) as transformer insulation and cooling medium in the industry for about several decades.

Provisions to apply the nanotechnology into the high-voltage engineering field, probes the researchers to get oriented towards the development of nanodielectric fluid or simply transformer nanofluids (TNFs), on improvising the MO with nanoparticles dispersed into it. In the year 1998 Segal et al. [2] experimented the first TNF with magnetite nanoparticles called ferrofluid and observed its impulse withstand voltage in needle-sphere geometry got enhanced up to 50% than that of MO. In addition, the 60 Hz AC withstand voltage stood close with that of MO, with a significant resistance for its humidity ageing, whereas the mechanism behind such uncharacteristic behaviours in the dielectric property was unknown by then. Later investigations on streamer propagation and other pre-breakdown (BD) mechanisms of TNF through mathematical models and simulations revealed the impact of the nanoparticle’s charging dynamics on the reduced streamer velocity and BD enhancement [3, 4]. Later researches investigated the other side of ferrofluid that the dispersed nanoparticles does get oriented to the applied magnetic field to form the aggregates, which was also observed when its nanoparticle level exceeds certain volume concentration in the fluid. The dielectric BD strength got adversely affected in both the cases [5].

From then on, several research experiments were carried out in MO with semi-conductive and non-conductive nanoparticle such as SiO\textsubscript{2}, TiO\textsubscript{2}, ZrO\textsubscript{2}, ZnO, BaTiO\textsubscript{3} and Al\textsubscript{2}O\textsubscript{3} etc. for different particle sizes, to improve its essential attributes like dielectric BD strength and thermal conductivity [6–14]. The studies further progressed with the different particle morphology [15], insulation oils [16–21], voltage profiles, electrode configurations and partial discharge investigations [22–30]. Jin et al. [7] observed the enhanced AC BD strength in silica nanoparticles dispersed MO, and proposed a mechanism that the hydrophilic nature of the particle surface adsorbs the moisture from MO which has the large influence on its BD characteristics. The mechanism was justified by modifying the particle surface with a surfactant called silane (Z6011) to make it as hydrophobic. Mansour et al. [31] experimented with TiO\textsubscript{2} and Al\textsubscript{2}O\textsubscript{3} nanoparticles dispersed in MO, and found a better enhancement in BD strength for titania comparing to alumina. The electronegative nature of titania justify the mechanism of entrapping the higher mobility streamer electrons in the shallow trap and de-trap it as slower electrons and thereby reducing the probability of BD occurrence. The BD enhancement in alumina is attributed to its interfacial zone formed with fluid when it gets polarised, as it does not possess the ability to attract and trap the electrons.

Under the applied lightning impulse voltage (LIV), TiO\textsubscript{2} nanofluids enhances the positive BDV and decreases the negative BDV which is attributed to the bush-like shape of pre-BD streamers with dense branches, and the tree-like shape of streamers with longer branches, respectively [10]. Lv et al. [15] investigated the impact of particle morphology on nanofluid’s dielectric BD properties under the LIV, with spherical and rod-shaped TiO\textsubscript{2} nanoparticles modified with oleic acid. The bush-like shaped pre-BD streamers that emanate from the fluid with nanorods found to enhance the positive impulse BDV by 55.5%, which is 1.23 times higher than spherical particles. Zhong et al. [16] prepared the ester oil-based TiO\textsubscript{2} nanofluids for the study the AC BD and partial discharge characteristics and observed a 31% BD improvement due to charge transport mechanism and increase in shallow trap density of nanofluids, which was justified with help of pulse electroacoustic and thermally stimulated current techniques. Cavallini et al. [9] investigated the partial discharge inception, magnitude and repetition rate under different voltage profiles for the MO-based nanofluid prepared with SiO\textsubscript{2}, graphene oxide and...
magnetite. Silica nanofluid showed the lowest PD magnitudes and recurrence rates compared with the other two when tested with AC, positive DC and negative DC voltages.

Das et al. [17] investigated the lightning impulse BD trend of MO and synthetic ester-based silica nanofluids with Type-I and Type-II electrode setup. BD enhancement with respect to particle loading is found to be linear in Type-I system whereas it showed as an initial enhancement in Type-II system up to 15% and 12% in case of MO and ester-based nanofluids, respectively. Peppas et al. [12] studied the AC BD strength of the MO and natural ester-based ferrofluids with three different electrode configurations viz. Rogowski, Rogowski-plane and point-plane configurations. Upon further investigations with the statistical analysis of the experiment result data with four different distributions viz. normal, Weibull, Gumbel and generalised extreme value (GEV) function, the BD data mostly followed Weibull and GEV.

Nor et al. [18] dispersed the TiO$_2$ nanoparticles with palm oil and coconut oil to examine its AC and Lightning BDV under quasi-uniform and non-uniform fields. Such nanofluids exhibited a slight increase in AC-BDV and a higher enhancement in lightning BDV under non-uniform fields, whereas the quasi-uniform field does not exhibit a clear pattern. Madavan and Balaraman [19] optimised the particle loading in nanofluids prepared with SiO$_2$, Fe$_3$O$_4$ and ZnO nanoparticles in MO and natural esters like sunflower oil and rapeseed oil, and the 0.25 volume fraction of conductive Fe$_3$O$_4$ nanoparticles found to have the superior performance characteristics in all the cases. Fernández et al. [20] evaluated the dielectric characteristics of the TiO$_2$ and ZnO dispersed vegetable oil which was subjected to accelerated ageing, and stated that the particles may act as hotspots to promote the thermal degradation of the oil, which was understood from the increased values of ageing indicators like dissipation factor, acidity and resistivity.

Among the different types of nanoparticles TiO$_2$ is found to be more effective and beneficiary due to its excellent chemical stability, non-toxic, and good dispersibility in polar and non-polar fluids which is an essential prerequisite for the nanofluid applications [32–34]. In view of BD strength enhancement, TTNF is prone to stability issues that cause a serious deterioration in its electrical properties which mainly occurs when nanoparticle loading in base oil exceeds a certain level. As it is likely to reduce the effective particle surface area in the base fluid, it tends to form the aggregates due to a strong vanderwaals attraction force and settles down [35–37]. Atiya et al. [35] investigated the dispersion and BD strength of titanias-based transformer nanofluid (TTNF) samples prepared for four different weight percentage of TiO$_2$, Fe$_3$O$_4$ and ZnO nanoparticles with palm oil and rapeseed oil, and the 0.25 volume fraction of conductive Fe$_3$O$_4$ nanoparticles found to have the superior performance characteristics in all the cases. Fernández et al. [20] evaluated the dielectric characteristics of the TiO$_2$ and ZnO dispersed vegetable oil which was subjected to accelerated ageing, and stated that the particles may act as hotspots to promote the thermal degradation of the oil, which was understood from the increased values of ageing indicators like dissipation factor, acidity and resistivity.

When it comes about to review specifically about the TTNF, it is essential to discuss in brief right from the nature of existence of TiO$_2$. The three crystal phases of TiO$_2$ are named Brookite, anatase and rutile, with its unique physical and chemical properties. Brookit is said to have unstable crystal properties hence, it has meagre industrial value, whereas anatase and rutile nature of titania crystals has good chemical stability and no toxicity. The experimental observations and the relevant theories verify that the TiO$_2$–anatase has higher BD strength than the TiO$_2$–rutile, in spite of the literature indicates the usage of rutile crystals mostly [37].

3 Titania nanofluid synthesis – key components

Preparing a homogeneous mixture of nanoparticles with the base fluid is an art and it essentially lies on synthesis of a stable nanofluid with the maximum extracted beneficiary properties of titania.

Nanofluid synthesis can simply be classified as the one-step and two-step method, and it does have a meagre difference as the name implies. In two-step synthesis of nanofluids, the prepared nanoparticles are dispersed in the base fluid, whereas the one-step method accommodates the nanofluid synthesis with its particle preparation process. In fact, some common methods for nanoparticle preparation can be upgraded to the one-step method if a base fluid container could replace its dry particle collector. The one-step method provides the more stable nanofluid since it eliminates the processes of drying, storage and transportation. Both the methods have its own advantages and demerits, but still, the two-step method is widely used for TNF preparation owing to its cost-saving potential, since it has been upgraded to industrial scale production [41–43]. The major classification of nanofluid synthesis is shown in Fig. 1.
3.1 One-step method

In vapour deposition method, a bulk solid raw material is made to evaporate in a container in the presence of inert gas under low pressure. Also, then a cooling liquid film condenses it to get settled in the base fluid. In order to attain the high boiling point temperature of titania, this is modified as pulsed wire explosion method to have the high-voltage electric pulses for heating.

Submerged arc method provides a very high temperature to establish an electric arc with controlled temperature and pressure, to vapourise the titania rod submerging into base fluid in the vacuum space. It is then condensed to synthesise the well-dispersed TNF with fine nanoparticles size ranging <20 nm.

Chemical method is to synthesise TNF from the titania precursor and a suitable solvent through chemical reactions. Titania powder can be dispersed in the desired base fluid without drying process, and synthesised by just changing the base fluid, hence obtaining a highly stable nanofluid. In spite of that, such methods are potentially capable of synthesise some by-products in the base fluid, which limits its detailed application as the one-step method.

So, as far as the TNF synthesis for the transformer liquid insulation process, and synthesised by just changing the base fluid, hence obtaining a highly stable nanofluid. In spite of that, such methods are potentially capable of synthesise some by-products in the base fluid, which limits its detailed application as the one-step method.

Fig. 1 Classification of nanofluid synthesis

3.2 Two-step method

In this synthesis method, the nanoparticles are prepared separately and then dispersed in required base fluid physically or by some other means. As it is a step by step synthesis method, the nanoparticle preparation and nanofluid synthesis are not done concurrently, hence it may undergo serious effects on its stability due to agglomeration in case of excess particle loading. Most of the researches optimises its particle loading at first and then utilises some major dispersion techniques like surface modification, mechanical stirring and ultrasound agitation to ensure a stable nanofluid [6, 9, 19, 20, 30, 45].

3.2.1 Nanoparticle preparation: Nanoparticles are prepared by Sol-Gel method (SG), Solvothermal and hydrothermal method etc. SG is widely used in the field of nanotechnology due to its versatility on the product yield that ranges from gels to fibres and, cast solid to nanopowder, just by controlling the process parameters. As the name implies, Sol that was formed due to hydrolysis and polymerisation of the titanium precursor and a solvent mixture undergoes the polymerisation process to evaporate the solvent to form the gel. The obtained gel is further heated and calcinated to obtain the fine powder of nanoparticles ranges from 20 to 50 mms. Water to precursor molar ratio, drying temperatures and, addition of peptising agents in the mixture has a direct relation on the particle size of titania. Morphology of the particles can be controlled by using non-aqueous solvents instead of water or isopropanol with the titanium tetra isopropoxide, to have a slow reaction rate and better control on it.

The hydrothermal method can prepare very fine particles of sizes averaging 10 nm, which involves heating the precursor in teflon autoclaves with or without peptising agent, whereas the solvothermal method has the same synthesis process without using the water [44].

3.2.2 Nanofluid synthesis: Dispersing nanoparticles in the base fluid to synthesise nanofluid is a bit challenging process in the two-step method, and the task lies in preparing the well-dispersed nanofluid which could be stable for a long period of time. Due to the high surface energy of nano-sized particles, it tends to agglomerate and form clusters in the base fluid when dispersed. However, there exist some physical and chemical treatments to minimise this problem, such as magnetic stirring, ultrasonic agitation, surfactant addition and pH control of base fluid [34].

Magnetic stirring is a technique to apply the strong shear force on the clustered particles to break it and disperse well in the base fluid. Ultrasonic agitation technique is comparatively good than the other physical methods, which applies the ultrasonic frequency waves to break the agglomerated particles and reduce the intermolecular interactions to get the homogeneous mixture in the liquid. Apart from such conventional physical procedures, there exist some surface modification techniques to improve the dispersion through a chemical treatment. Addition of surface-active agents encapsulates the nanoparticle in such a way to reduce the clogging and aggregation of particles. The other technique modifies the pH value of the dispersing medium to customise the particle’s environment in such a way to attain the higher zeta potential [34, 44].

In spite of all, the application type and user's instinct decide the usage of techniques either separately or in conjunction. Most of the research work involves the nanofluid synthesis with different combinations of the techniques, and the hierarchical flow of procedure is shown in Fig. 2. Yet, there is no standards are set to recognise the superlative blend of combining the techniques to achieve the optimal dispersion.

The general procedure of titania nanofluid synthesis is shown in figure involves, drying nanoparticles, stirring and ultrasonication with the capping agent. Particles are dried in a heating oven for 2–3 h up to a maximum of 150°C, to get rid of the moisture completely. It is then mixed in the base oil dispersed with the surfactant, through magnetic stirring to get encapsulated by the capping agent. Further, it undergoes ultrasonic agitation for up to 3 h with a continuous cycle, to break up the particle clusters and provide better encapsulation [31, 35].

4 Dispersion stability

The previous section made a brief note on the basic techniques deployed in nanofluid synthesis with good dispersibility. This
section discusses the technicality behind those procedures and its significance in enhancing the dispersion strength of the nanofluids.

4.1 Magnetic stirring

Magnetic stirring is a primary process in breaking the nanopowder cluster by applying high shear force. Magnetic pellet immersed in the particle–oil mixture spins in its own axis by the external magnetic field to provide a whirling action. It is experimentally observed that the stirring time has a certain impact on particle aggregation over time, as the time period less than 15 min is found to have a sudden rise in particle size. The stirring time period of 30 min to 3 h is found to have a good dispersion sustained for around 15 days with the particle size up to 30 nm [46]. Certain works are highly satisfied with stirring procedure alone for the nanofluid synthesis whereas, many researchers accompany ultrasonication following the stirring process to get an effective capping of surfactant [47, 48].

4.2 Ultrasonic homogenisation

Magnetic probe and bath sonication are the two types of ultrasonic agitation deployed for nanofluid synthesis, where the studies reported to have better dispersion efficiency in bath sonication. Sonication time of either up to 30 min or around 2–3 h is found to have a good dispersion sustained for around 10 days with the particle size up to 20 nm. Ultrasonic probe submerged in the particle–oil mixture provides better sonication energy than the bath sonicator whilst, the higher energy exerted in the immediate particle size up to 20 nm. Ultrasonic probe submerged in the particle–oil mixture provides better sonication energy than the bath sonicator whilst, the higher energy exerted in the immediate interfacial zone around the probe tip disturbs the adsorption balance of the surfactant [46].

4.3 Steric stabilisation

A simple procedure to enhance and sustain the dispersion strength of a nanofluid is the particle’s surface modification technique by adding surfactants. It is a capping agent that encapsulates the particle surface with its hydrophilic head and reduces the interfacial tension between liquid–solid interfaces. Hence, the rise in zeta potential causes repulsion between nanoparticles suspended in the base fluid, and also a rise in thermal resistance of the liquid–solid interface is observed. The surfactant diffused into the liquid–solid interface reduces the nanoparticle agglomeration due to Van der Waal's attraction, as its kinetics getting limited. However, a critical quantity of surfactant addition is required since, the lesser amount does not cap fully and, the excess amount forms a double chain around the surface of nanoparticles, which will cause agglomeration figure. Based on the polarity of the head, surfactants are classified as anionic, cationic, non-ionic and amphoteric surfactant [49].

5 Stability analysis parameters

This section deals with the methodology to evaluate the dispersion stability of the nanofluid where, the sedimentation method, zeta potential verification, ultraviolet (UV)–visible spectral analysis and electron microscopy images are identified as familiar tools and metrics available in practice.

5.1 Sedimentation method

Sedimentation method is a very simple and elementary procedure to evaluate fluid stability through visual inspection. The prepared nanofluid samples are left idle for a certain time period to get settled, and the volume of sediment deposited for respective samples indicates its stability. Height of the deposit with respect to time indicates the particle's sedimentation velocity of the nanofluids with different particle concentrations. The synthesis of TNF where the nanoparticle concentration is a critical factor to attain the higher electrical properties, this method may be inappropriate and insufficient for the stability analysis [50, 51].

5.2 Zeta potential verification

Another significant and critical metric for assessing nanofluid stability is the zeta potential, whose magnitude is an apparent indicator of the dispersion stability of any colloidal particles suspended in a liquid medium. To make a clear discussion on it, the nanoparticles will acquire a charge through several mechanisms when it is suspended in a polar or a dielectric liquid which provides an electrostatic repulsive force in the suspension. Some significant charging mechanisms are (i) dissociation of acidic or basic surface groups of a particle to form a negatively or positively charged surface, respectively. (ii) Unequal dissolution of ions from the crystal lattice that gives rise to a net surface charge. (iii) Adsorption of charged polymer molecules of either cationic or anionic surfactants gives rise to a surface charge [52].

So the net charge developed at particle surface will orient the ion distribution in its vicinity in the bulk solution. It is capable of concentrating the counter ions from the solution around the particle surface with two layers to form an EDL, which has a region of ions that are firmly attached close to the particle surface called stern layer or Helmholtz layer. In addition, another region diffused with the bulk solution forms an entity of mobile ions randomly distributed with an imaginary boundary, is known as the diffuse layer. Shear or slipping plane forms an interfacial boundary between two regions where an electric potential is generated due to electro-kinetic phenomena is called zeta potential. Such an electro-kinetic potential occurs from the Brownian motion of particles in the solution, which gives rise to the relative motion of the rigid stern layer and the mobile entity of the double layer. This
nanopowder is shown in Fig. 3. (a) SEM image of titania nanoparticle, (b) Test cell with needle (top)-plane (bottom) electrode configuration.

### Table 1 Transformer MO specification

| Properties                  | Typical values |
|-----------------------------|----------------|
| density at 29.5°C (max)     | 0.89 g/cm³     |
| kinematic viscosity (max) 40°C | 7.8 to 8.2 cSt |
| flash point (min)           | 158°C          |
| pour point (max)            | −60°C          |
| water content               | 0.0015 wt%     |

The magnitude of zeta potential in the millivolt (mv) can directly assess the dispersion stability of any colloidal system. Nanofluids with zeta potential >+30 mv or <-30 mv is said to be reasonably stable and, the magnitude ranges from −5 to +5 mv tend to coagulate soon [53, 54].

5.3 UV–visible spectral analysis

The properties of nanoparticles which are sensitive to shape agglomerated size and its concentration level, makes the UV–visible spectral analysis as a reliable and effective tool for investigating the nanofluid stability. It is a quantitative technique to characterise the dispersion stability, which is based on the fact that the light intensity varies when it passes through a nanofluid owing to its absorption and scattering. A wavelength spectrum of 200–900 nm is passed through the sample to be studied that is filled in a glass or quartz cuvette, and the intensity of light beam before and after passing through the cuvette is measured to quantify the absorbed and scattered light. The absorption spectrum of a sample shows the constituent particles and its largely populated size, through its different absorbance peaks. To be more clear, the sample consists of particles with different absorption characteristics will have its own peaks at different wavelengths. Dispersion stability of the nanofluid is identified from the intensity of the absorbance peak which decreases correspondingly as the particles get destabilised in the fluid and broadens as the particles get aggregated [43, 55, 56].

6 Experimental studies

This section explains the procedural way to ascertain the optimal level of TiO$_2$ nanoparticles and the surfactant CTAB, to be dispersed in the transformer MO in order to achieve the enhanced dielectric BD strength. Anatase TiO$_2$ nanoparticle (spherical, average particle size of 10–20 nm, 99.9% pure) used in this work was procured from Nano Research Lab (NRL). TEM image of nanopowder is shown in Fig. 3a ensuring its average particle size as 10–20 nm. Commercially available transformer MO as per the IEC standards was purchased for this work, and its properties are shown in Table 1. Cationic surfactant CTAB (extra pure-analytical grade) was procured from Sisco Research Laboratories.

6.1 Samples preparation

As mentioned earlier in this section, the used chemicals were procured commercially hence all the nanofluid samples for this work were synthesised from the two-step method. TiO$_2$ nanoparticles weighed for the sample preparation are dried at 150°C for about 3 h in a heating chamber, to get rid of the moisture to a maximum extent. It is dispersed in MO with the magnetic stirrer for 30 min, and then further diffused with the Ultrasonic probe homogeniser for 2.5 h. The first series samples were prepared in this manner for the titania of 0.00281, 0.00562 and 0.00842 wt%, respectively. All these samples were tested for the PDIV for AC and DC-voltage profiles, and the results were recorded. The titania weight that exhibited the highest PDIV magnitude was fixed for preparing the second series of nanofluid samples as per the procedure shown in Fig. 2. The CTAB weighed for 1, 2 and 3% of the fixed titania weight was mixed in MO with the magnetic stirrer for 30 min, before dispersing the titania into it. These three samples were tested for PDIV for AC and DC voltage profiles, and the one which exhibited the highest PDIV was tested for AC and DC BDVs, to ascertain as the optimal blend of TTNF.

6.1.1 Samples with different humidity hours: Sokolov and Koch [57] in 2008 have detailed the possibilities and sources of moisture ingress in the transformer insulation system. There exist certain methods to develop moisture in the oil samples, and to feed moisture into the oil samples as per the procedure shown in Fig. 2. The CTAB weighed for 1, 2 and 3% of the fixed titania weight was mixed in MO with the magnetic stirrer for 30 min, before dispersing the titania into it. These three samples were tested for PDIV for AC and DC voltage profiles, and the one which exhibited the highest PDIV was tested for AC and DC BDVs, to ascertain as the optimal blend of TTNF.
**Table 2** PDIV magnitudes of Nanofluid samples with and without surfactant CTAB

| Sample series     | Weight percentage of TiO$_2$ with MO (sample series 1) | PDIV, kV AC DC | PDIV, kV AC DC |
|-------------------|---------------------------------------------------------|----------------|----------------|
| 0 (virgin MO)     | 0.000281 (0.025 g/l)                                     | 7.29 7.75      | 8.2 8.52       |
| 0.00562 (0.05 g/l) | 10.5 11.5                                               | 8.41 8.71      |                |
| 0.00842 (0.075 g/l) | 13.8 17.52                                              |                |                |
| percentage weight of CTAB in g/l | 0 (without CTAB)                                     | 10.5 11.5       |                |
| 0.00562 wt% (0.05 g/l) of TiO$_2$ (sample series 2) | 1 (0.05 mg/l)                                           | 13.38 17.52    |                |
| 2 (0.10 mg/l)     | 13.8 17.52                                              | 12.37 16.95    | 12.23 15.46    |
| 3 (0.15 mg/l)     | 12.37 16.95                                             |                |                |

**Table 3** PDIV and mean BDV magnitudes of TTNF samples

| Sample                | AC, kV PDIV BDV | DC, kV PDIV BDV |
|-----------------------|-----------------|-----------------|
| virgin mineral oil    | 7.29 15.65      | 7.75 20.75      |
| 0.05 mg/l of CTAB and 0.0045 wt% of TiO$_2$ dispersed in mineral oil | 12.86 19.5 | 17.10 23.13 |
| 0.05 mg/l of CTAB and 0.00562 wt% of TiO$_2$ dispersed in mineral oil | 13.8 21.32 | 17.52 29.69 |

**Table 4** Mean BDV magnitudes of TTNF samples with different humidity hours

| TTNF sample with different humidity hours | Mean BDV |
|-------------------------------------------|----------|
|                                           | AC, kV   | DC, kV   |
| 0                                         | 21.32    | 29.69    |
| 1                                         | 14.11    | 15.16    |
| 2                                         | 13.85    | 14.39    |
| 3                                         | 12.15    | 13.86    |
| 4                                         | 11.12    | 13.2     |

**6.2 PDIV and BDV test**

The high-voltage DC test setup to experiment with the dielectric BD strength of the samples are shown in Fig. 4. It has an autotransformer with 100 kV, 50 mA high-voltage output and a couple of capacitors (10,000 pF) and diodes. The test cell is directly connected to the transformer output for the AC test voltages and it is measured from the capacitance divider connected to it. Samples are filled without any air bubbles in the test cell shown in Fig. 3b which has the needle-plane electrode configuration with a 5 mm gap between the needle electrode of tip radius about 50 µm and the plane electrode of 5 cm diameter.

The nanofluid samples without CTAB were tested for the corona inception threshold with AC and DC voltages, and the recorded results are tabulated in Table 2, which shows the PDIV magnitudes are high for 0.00562% TiO$_2$ weight in MO. The results obtained from the second series of nanofluid samples with CTAB are also shown in Table 2, which indicates the CTAB with 1% of 0.00562% TiO$_2$ weight dispersed in MO showed a highest PDV threshold magnitude. This particular sample was then tested for AC and DC BDV to ascertain this amalgamation as the optimal blend of TTNF, and the results are shown in Table 3. The results of the third string of samples prepared from this TTNF with different humidity hours of moisture ingress tested for PDIV and dielectric BD is shown in Table 4. The graphical representation of the tabulated results is shown in Fig. 5.

### 7 Results discussion with relevant theories

PDIV for different titania weights dispersed in MO with and without CTAB is shown in Table 2. It infers the inception of corona in MO has been prolonged with the addition of TiO$_2$ nanoparticles, is attributed to its electronegative property which is a measure of the ability to attract the electrons. It obstructs the progress of fast propagating electrons of corona whose velocity is relatively low under DC or AC voltages, towards BD process. However, still the quantity dispersed is the decisor to achieve the superior electrical properties owing to the reduction of inter-particle distance that raises the Van der Waals attraction force [35, 60]. The result shows the higher PDIV magnitudes for 0.00562 wt% of titania hence 0.05 g/l is considered as the optimal quantity to be dispersed, above which the TTNF agglomerates and deteriorate the nanofluid properties. CTAB addition prevents the coalescing of TiO$_2$ nanoparticles by encapsulating the particle surface with its hydrophilic head which reduces the intermolecular interaction. However still the amount dispersed should be precise, since the hydrophobic tails of CTAB molecules which are aligned normal to it, may form the double chains with the molecules adsorbed to other particles, if its quantity exceeds a critical level [35, 50]. The result shows the 1% of titania weight extends the PD inception to the maximum extent and its BD test results are shown in Table 3. It shows 36.23 and 43.07% enhancement in dielectric BD strength than the virgin oil for AC and DC voltages, respectively, and comparatively higher than the other near-precise values TTNF blend that was done for verification purpose.

It is known that the partial discharges deteriorate the oil properties through its created by-products, which poses an adverse effect in its BD characteristics [61]. The obstruction of corona propagation and the charge transport process in semi-conductive nanoparticles are the predominant mechanisms behind such enhancements, alongside the impact of oil–particle interfacial zone. The fast-moving electrons trapped and de-trapped in its hopping charge transfer process in the shallow traps, loses its energy and hence velocity. As the shallow trap density is higher for titania, the charge gets dissipated rapidly into the TTNF than MO, hence the
corona gets sabotaged and the BD process is delayed [38, 39, 62, 63]. On the addition of CTAB, the hydrophilic head adsorbed on the particle surface and the hydrophobic tail projected normal to the oil forms an interfacial zone as shown in Fig. 6. The oil chains aligned normal to the particle surface forms a stiff layer to polarise where the electrons lose energy, and hence delaying the initiation of BD process [31].

The results of humidity ageing of the prepared TTNF are shown in Table 4. It shows a steep decrease in the PDIV and BD threshold once the moisture is developed, and follows with a declining trend.

The electrons propagating with high velocity under high-voltages interacts with the water molecules and releases the free electrons due to its inherent polar nature. So the raise in free-electron density offers the conducting path in TTNF and increases its electrical conductivity, which leads to the reduction of BD voltages [37].

8 Conclusion
Experimental procedure for synthesising an optimal blend of TTNF with a superior dielectric BD strength has been proposed in this study, aided with an informative review on its synthesis and dispersion procedure. Also, the humidity ageing was done for TTNF and its impact on the BD characteristics has been studied and discussed. To recognise a simple and effective synthesis technique to enhance the BD characteristics with good dispersion strength could be a scope of this research.

Transformer MO blended with 0.00562 wt% of TiO$_2$ and its 1% of CTAB, enhances its AC and DC dielectric BD strength by 36.23 and 43.07%, respectively. This TTNF blended with the utmost care and conscious with the mentioned levels of TiO$_2$ and CTAB in MO exhibited exceptional stability for around eight weeks. The BD characteristics of the prepared TTNF show a declining trend for its
humidity ageing, and its BD threshold decreases significantly once the moisture is developed.

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