Breakdown voltage and thermal performance of nanofilled transformer oil considering natural and forced cooling systems

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Abstract
Effect of adding nanofillers on transformer oil breakdown voltage and its thermal performance finds a great interest from researchers and scientists. The impact of oil circulation considering oil forced cooling method on nanoparticles stability in transformer oil is investigated. The stability is considered from breakdown voltage and thermal performance points of view. Titanium dioxide (TiO2) nanoparticles are chosen due to the safety of TiO2 nanomaterial as well as its good performance. First, the optimal concentration of nanosized TiO2 at which maximum breakdown voltage of nanofilled transformer oil is determined and chosen to study the effect of oil circulation on breakdown voltage as well as thermal performance of nanofilled oil. Two reduced experimental models are designed. The first model consists of a galvanized steel tank containing TiO2-nanofilled transformer oil, at the pre-determined optimal concentration. This tank is designed to simulate the natural oil cooled transformer. However, the second model that uses a similar tank is designed to simulate a forced cooled transformer. This model consists of a tank containing TiO2-nanofilled transformer oil, at the pre-determined optimal concentration, and an oil pump. Breakdown voltage and thermal performance considering the two adapted models are measured in a time period of 60 days.

1 | INTRODUCTION

Transformers have an indispensable role in electrical power systems. They can be classified into dry and oil cooled transformers. In fact, oil cooled transformers have more wider spread than dry ones due to their greater advantages especially in the cooling process. Oil cooled transformers can be divided into natural and forced cooled transformers according to the nature of cooling system design. Hence, there is no any oil forced circulation occurs with natural cooling type. However, a forced oil circulation is performed using oil pump for forced cooled type that is extensively used for large power applications.

For the two types, natural or forced cooled, transformer oil has a vital role in insulation as well as cooling processes. Therefore, many recent researches give a focus on improving dielectric strength as well as thermal properties of transformer oil using nanotechnology [1–17]. In these researches, breakdown voltage of transformer oil is increased by adding small loadings of nanosized metal oxides such as TiO2, ZrO2, Al2O3, SiO2, CdS etc. Also, adding nanosized metal oxides improves the thermal properties of transformer oil [15–17]. Therefore, adding nanosized metal oxides to transformer oil can reduce the transformer size for the same ratings.

Although all conducted researches in this field illustrate improved dielectric and thermal properties of transformer oil nanofluid, field application of this oil still finds a great problem. This is demonstrated by Elsad et al. [18], hence breakdown voltage of TiO2 nanofilled oil decreases by about 33% after 1 month from sample preparation. This problem arises due to the instability of nanofillers inside the prepared oil [18]. So, many researches are presented to improve nanofillers’ stability inside oil by adding surfactants during the preparation of nanofluids [12]. In fact, adding surfactants to nanofluids improves the stability of nanofillers inside nanofluid. However, the instability...
problem that leads to deposition of nanofillers at the tank bottom is still found. From our point of view, this problem represents the major hindrance behind field application of nanofluids.

Until now, the instability problem of nanofillers inside transformer oil is evaluated for natural cooled systems (systems without any forced oil circulation). Therefore, the objective of this paper is to study the effect of forced oil circulation on breakdown voltage and thermal properties of transformer oil nanofluid. Circulation process is expected to improve the stability of nanofillers inside transformer oil nanofluid.

The effect of forced oil circulation on breakdown voltage and thermal performance of nanosized TiO₂ filled transformer oil is presented. TiO₂ is chosen due to its good performance and safety \[19, 20\]. It gives higher improvement in breakdown strength compared to other oxides such as ZrO₂ and SiO₂ as presented in ref. \[14\]. Also, adding TiO₂ nanoparticles to transformer oil increases its thermal conductivity that leads to a better thermal performance \[21, 22\]. At first, the optimal TiO₂ loading, loading at which maximum breakdown voltage occurs, is experimentally determined. Then, TiO₂-based nanofluid is prepared at the determined optimal loading. Breakdown voltage and thermal performance of the prepared nanofluid are studied considering two cases. These cases are the natural (no circulation) and forced oil circulation processes. Performance of transformer oil nanofluid considering the two cases is experimentally evaluated depending on building two reduced experimental models. The first model consists only of a galvanized steel tank containing TiO₂ nanofilled transformer oil, at the pre-determined optimal concentration. This tank is designed to simulate the natural oil cooled transformer. However, the second model is designed to closely simulate a forced cooled transformer. The forced model consists of a galvanized steel tank containing TiO₂-nanofilled transformer oil, at the same pre-determined optimal concentration, and an oil pump. Breakdown voltage and thermal performance are measured for the nanofilled oil of both models considering the effect of time (60 days are considered) on nanofillers stability. Finally, conclusions and recommendations of this work are introduced.

## 2 DETERMINATION OF NANOSIZED TiO₂ OPTIMAL LOADING

In this section, the optimal nanosized TiO₂ loading (loading at which maximum breakdown voltage occurs) is experimentally determined. The size of nanosized TiO₂ used is 100 nm. This large nanosize is chosen to take the worst conditions as the sedimentation velocity \(V\) of nanofillers inside nanofluid depends on nanofiller radius as illustrated from Stoke’s law \[23\]:

\[
V = \frac{2R^2}{9\mu} (\rho_p - \rho_L) g,
\]

where \(R\) is the nanofiller radius, \(\mu\) is the dynamic viscosity, \(\rho_p\) is the nanofiller density, and \(\rho_L\) is the liquid medium density, and \(g\) is the gravity acceleration.

The used TiO₂ nanomaterial is purchased from US Research nanomaterials, Inc. It has a purity of 99.9%. Its nanoparticle size (100 nm) is confirmed through the transmission electron microscope (TEM) characterization (see Figure 1) that is given in the supplied material datasheet \[24\]. Five concentrations are prepared: 0, 0.005, 0.009, 0.015, and 0.03 wt%. The preparation is carried out by adding the required amount of nanosized TiO₂ to new NYNAS mineral transformer oil. The mixture is stirred for a period of 30 min. Then, the mixture is sonicated for a period of 30 min using an ultrasonic homogenizer. At this stage, the transformer oil nanofluid is prepared, but there is a possibility of micro void formation. Therefore, the nanofluid is left in a vacuum chamber for about 24 h before testing to degas the prepared nanofluid. The preparation method is simply clarified by the flowchart of Figure 2. After the preparation of nanofluid at the aforementioned loadings of TiO₂, breakdown voltages (B.V.) of the prepared samples are measured. Breakdown voltages of the tested samples are measured according to ASTM D1816 standard at 500 V/s rate of voltage rise. Also, a space gap of 2 mm is chosen between the two electrodes of the test cell. Breakdown voltage is measured 10 times with a period of 2 min between each two consecutive breakdowns. The average breakdown voltage is computed and plotted for each oil sample. Also, breakdown voltages at 10% and 50% probabilities are evaluated based on Weibull probability function.

Table 1 shows the average breakdown voltage, breakdown voltages at 10% and at 50% probabilities considering the different concentrations of TiO₂. From this table, it is shown that the addition of nanosized TiO₂ results in increasing breakdown voltage until an optimal loading of 0.015 wt%. The maximum percentage increase in average breakdown voltage reaches 50.8% at this optimal loading. Also, increase in breakdown voltages at 10% and 50% probabilities is observed until optimal loading of 0.015 wt% as declared in Table 1 and Figure 3. The increase in breakdown voltage comes due to charge trapping process of nanofillers that results in an increased voltage required for breakdown \[11, 13\]. Increasing the TiO₂ loading higher than the optimal loading results in a decrease in breakdown voltage due to electric field distortion resulted from charged nanoparticles \[14\].

![FIGURE 1 Transmission electron microscope (TEM) characterization of the adapted TiO₂ nano-material [24]](image-url)
Preparation of transformer oil nanofluid is carried out at the optimal concentration (0.015 wt%) to be used in the next sections.

### 3.1 Experimental models

Two similar galvanized steel tanks are manufactured to simulate power transformer tank. Dimensions of the manufactured tanks are shown in Figure 4. Each tank represents a reduced model to simulate the real transformer tank. Ten litres of TiO$_2$ nanofilled transformer oil are prepared and poured in each tank. The TiO$_2$ nanofilled transformer oil is prepared considering the optimal concentration (0.015 wt%) that is pre-determined in Section 2.

It is worth to mention, one of the two tanks is left in free air to simulate the natural oil cooled transformer. However, the other tank is equipped with a forced oil circulation system as

![Figure 3 Weibull distribution curves for base and nanofilled oil](image)

**Figure 3** Weibull distribution curves for base and nanofilled oil

### 3 EFFECT OF OIL CIRCULATION ON BREAKDOWN VOLTAGE AND THERMAL PROPERTIES OF TRANSFORMER OIL NANOFLUID

In this section, the experimental models required to evaluate the performance of nanofillers considering the effect of oil forced circulation are presented. Also, breakdown voltage and oil thermal performance are evaluated considering the effect of nanofluid forced circulation on it.

![Figure 4 Dimensions of experimental tank](image)

**Figure 4** Dimensions of experimental tank

![Nanosized TiO$_2$ Transformer Oil](image)

**Figure 2** Preparation of transformer oil nanofluid

**TABLE 1** Effect of TiO$_2$ loading on breakdown voltage (B.V.) of nanofilled transformer oil

| Loading, wt% | 0   | 0.005 | 0.009 | 0.015 | 0.03 |
|--------------|-----|-------|-------|-------|------|
| Average B.V. | 10.28 | 11.14 | 13.2  | 15.5  | 11.21 |
| B.V. at 10% probability | 9.25 | 9.7   | 12.1  | 13.8  | 10.1 |
| B.V. at 50% probability | 10.25 | 10.9  | 13.35 | 15.7  | 11.25 |

Preparation of transformer oil nanofluid is carried out at the optimal concentration (0.015 wt%) to be used in the next sections.
Illustrated schematically in Figure 5. This figure shows a use of oil pump (inlet gear pump, 10 L/h) with other required fittings (such as pipes) in order to circulate the oil inside the second tank. This forced circulation is carried out to closely simulate the forced oil cooled transformer. For more illustration, a photograph of the two designed experimental models is shown in Figure 6.

Breakdown voltage measurements are carried out by taking an oil sample (500 mL) from each tank every 5 days. The breakdown voltage of each sample is measured considering the same procedure presented in Section 2 for a period of 60 days. However, thermal performance for the two models is evaluated based on heating as well as cooling process as adapted in refs. [17, 25] as shown schematically in Figure 7. For more illustration, a photograph shows the experimental setup used to measure thermal performance for the two models is shown in Figure 8. Hence, oil sample of 500 mL is heated in a glass beaker using a heater of 20 W power. During the heating process, temperature is measured using a calibrated temperature sensor for a period of 60 min with a reading of every 10 min. Also, temperature of the prepared samples is recorded during the cooling process starting from the same temperature of 80 °C. Oil temperature is recorded during the heating and cooling processes for pure and nanofilled oil at 0.015 wt% after preparation of samples (just before the circulation process). This evaluation is carried out to show the effect of adding nanosized TiO₂ on the thermal performance of nanofilled oil. Temperature measurements are carried out again considering a pure sample of natural cooled system and a sample of forced cooled system at the end of circulation period (60 days). These measurements are carried out to show the effect of oil circulation on thermal performance of the adapted systems. The obtained results from breakdown voltage and thermal performance tests are recorded and analysed as follows.

### 3.2 Breakdown Voltage Results

The evaluation of breakdown voltage is carried out based on average breakdown voltage as well as breakdown voltages at 10% and 50% probabilities. Figure 9 shows the variation of average breakdown voltage, considering the two systems, with a duration of 60 days. From this figure, average breakdown voltages decrease with time for natural cooled system. Hence, the average breakdown voltage is reduced from 15.5 (at the beginning of test) to 10.83 kV at the end of testing period (60 days). This means a decrease in average breakdown voltage by about 30%. It can be shown that a significant decrease in average breakdown voltage occurs. The same performance is
achieved considering 10% and 50% breakdown probabilities as illustrated in Figures 10 and 11, respectively. Regarding the forced cooled system, average breakdown voltage is seemed to be constant during the test period. Hence, breakdown voltage is found to be 15.5 kV at the beginning of test. While, it is found to be 15.4 kV at the end of testing period (60 days). Also, the breakdown voltage at 10% and 50% probabilities are seemed to be constant considering the forced cooled system as declared in Figures 10 and 11.

Figure 12 shows the difference between breakdown voltages of forced and natural cooled systems for the measurement period (60 days). From this figure, it is found that the breakdown voltage considering the forced cooled model is significantly greater compared to the natural cooled one. Also, the difference between breakdown voltages between the forced and natural cooled systems increases until it reaches a constant value. Therefore, the forced cooled system gives a better performance compared to the natural cooled one.

The decrease in breakdown voltage with natural cooled model comes due to the instability problem of nanoparticles inside transformer oil. This instability occurs as the particle weight (gradational force) is greater than the upward buoyant force (viscous force) from oil as illustrated schematically in Figure 13a. Therefore, gradual sedimentation of nanoparticles occurs. This causes gradual decrease in breakdown voltage of natural cooled system as the amount of nanoparticles decreases gradually in oil. This is validated as oil breakdown voltage considering the natural cooled model at the end of measurement period (60 days) reaches 10.83 kV which is close to the measured voltage of pure oil (10.28 kV) that illustrated previously in Table 1. However, the breakdown voltage considering the forced cooled model is constant at a higher value of 15.5 kV. This comes due to a greater stability of nanoparticles inside oil. This stability occurs as a result of circulation force exerted from the pump as illustrated schematically in Figure 13b. This force reduces the probability of nanoparticles sedimentation at
the bottom of the tank. Figure 14 shows a photograph of oil sample taken from the tanks of the two models at the end of test period (60 days). From this figure, oil sample taken from the natural cooled system seems to be free from nanoparticles. This comes due to sedimentation of nanoparticles at the bottom of the natural cooling tank. However, oil samples taken from forced cooled system have milky colour. This results from the effect of nanoparticle suspension in oil.

3.3 Thermal performance results

Most of nanofillers have a significant effect on thermal performance of oil nanofluid [26–30]. Therefore, the effect of nanofillers on thermal performance of nanofilled transformer oil is evaluated. This evaluation is carried out based on the aforementioned heating and cooling processes. Figure 15 shows the variation of oil temperature with 60 min heating time. It can be seen that the decrease in oil temperature of nanofilled transformer oil is greater than in the base oil. The high thermal performance of nanofilled oil comes due to the increase in its thermal conductivity compared to base oil [26–30].

To evaluate the effect of oil circulation on thermal performance of nanofilled oil, it is important to evaluate it considering the two adapted models. This evaluation is carried out based on the aforementioned heating and cooling processes after circulation test. Figure 17 shows the variation of oil temperature during the 60 min heating for base oil, a sample from the natural cooled system and a sample from the forced cooled system. It can be seen that the increase in temperature of circulated oil sample is lower than in the natural cooled sample as well as base oil. The same performance is achieved during the cooling process as declared in Figure 18. This means that the thermal performance of the forced cooled system is better than the natural cooled system. This comes due to the better distribution of nanoparticles inside oil of the forced cooled system. The better
distribution of nanoparticle inside oil of forced cooled system comes due to circulation force from the circulating pump that reduces the probability of nanoparticles sedimentation process as illustrated in Figure 14.

4 | CONCLUSIONS

Studying the stability of nanoparticles inside transformer oil considering natural as well as forced oil cooling systems has been presented. The effect of oil circulation on breakdown voltage considering 60 days has been investigated. Also, the thermal performance of the two studied systems has been experimentally evaluated based on two built reduced models and the following points have been concluded:

- A reduction in breakdown voltage of nanofilled transformer oil has been observed during the test period considering the natural oil cooled system.
- Approximately, a constant breakdown voltage of nanofilled transformer oil has been found during the test period considering the forced oil cooled system.
- A better thermal performance of the forced oil cooled system has been observed compared to the natural cooled one.
- Nanofilled oil circulation has improved the stability of nanoparticles inside transformer oil.

5 | RECOMMENDATIONS

In the light of the obtained promising results considering stability of nanoparticles inside transformer oil of the forced cooled model, the following recommendations are suggested:

- Use of nanofilled transformer oil with forced cooled transformers should be deeply studied in order to be applied in the field.
- Investigation of proper methods to enhance the stability of nanoparticles inside the transformer oil of natural cooled transformers.

REFERENCES

1. Lan, Q., et al.: The study on TiO$_2$ nano-powder’s influence on the power frequency breakdown properties of transformer oil. Adv. Mater. Res. 1070–1072, 1001–1006 (2015)
2. Yuxiang, Z., et al.: Insulating properties and charge characteristics of natural ester fluid modified by TiO$_2$ semiconductive nanoparticles. IEEE Trans. Dielectr. Electr. Insul. 20(1), 135–140 (2013)
3. Yuefan, D., et al.: Effect of electron shallow trap on breakdown performance of transformer oil-based nanofluids. J. Appl. Phys. 110(10), 104104 (2011)
4. Yue fan, D., et al.: Effect of semiconductive nanoparticles on insulating performances of transformer oil. IEEE Trans. Dielectr. Electr. Insul. 19(3), 770–776 (2012)
5. Jin, H., et al.: AC breakdown voltage and viscosity of mineral oil based SiO$_2$ nanofluids. In: IEEE Conference on Electrical Insulation Dielectric Phenomena (CEIDP), Canada, pp. 902–905. IEEE, Piscataway, NJ (2012)
6. Katiyar, A., et al.: Effects of nanostructure permittivity and dimensions on the increased dielectric strength of nano insulating oils’ Colloids Surf. A 509, 235–243 (2016)
7. Thabet, A., et al.: Investigation on enhancing breakdown voltages of transformer oil nanofluids using multi-nanoparticles technique, IET Gener. Transm. Distrib. 12(5), 1171–1176 (2018)
8. Sabihah, N.A., et al.: Breakdown performance of transformer oil in the presence of single phase nanocrysralline ZnO and nano-partial substitution, IET Sci. Meas. Technol. 13(5), 737–745 (2019)
9. Ghoneim, S.S.M., et al.: Evaluation of dielectric breakdown strength of transformer oil with BaTiO$_3$ and NiFe$_2$O$_4$ nanoparticles. Electr. Eng. 101(2), 369–377 (2019). https://doi.org/10.1007/s00202-019-00788-8
10. Abd-Elhady, A.M., et al.: Effect of temperature on AC breakdown voltage of nanofilled transformer oil. IET Sci. Meas. Technol. 12(1), 138–144 (2018)
11. Sima, W., et al.: Effects of conductivity and permittivity of nanoparticle on transformer oil insulation performance: Experiment and theory, IEEE Trans. Dielectr. Electr. Insul. 22(1), 380–390 (2015)
12. Atiya, E.G., et al.: Dispersion behavior and breakdown strength of transformer oil filled with TiO$_2$ nanoparticles. IEEE Trans. Dielectr. Electr. Insul. 22(5), 2463–2472 (2015)
13. Ibrahim, M.E., et al.: Effect of nanoparticles on transformer oil breakdown strength: Experiment and theory. IET Sci., Meas. Technol. 10(8), 839–845 (2016)
14. Samy, A.M., et al.: On electric field distortion for breakdown mechanism of nanofilled transformer oil. Int. J. Electr. Power Energy Syst. 117, 105632 (2020)
15. Pugazhendhi, S.C.: Experimental evaluation on dielectric and thermal characteristics of nano filler added transformer oil. In: International Conference on High Voltage Engineering and Application, Shanghai, China, September 17–20 2012
16. Mansour, D., Elsaeed, A.: Heat transfer properties of transformer oil-based nanofluids filled with Al2O3 nanoparticles. In: International Conference on Power and Energy (PECON), 2014
17. Abd-Elhady, A.M., et al.: Dielectric and thermal properties of transformer oil modified by semiconductive CdS quantum dots. J. Electron. Mater. 45(10), 4755–4761 (2016)
18. Elsad, R.A., et al.: Loading different sizes of titania nanoparticles into transformer oil: A study on the dielectric behavior. J. Sol-Gel Sci. Technol. 93(3), 615–622 (2019) https://doi.org/10.1007/s10971-019-05159-0
19. Yang, L., Hu, Y.: Toward TiO2 nanofluids—Part 1: Preparation and properties. Nanoscale Res. Lett. 12(1), 417 (2017)
20. Yang, L., Hu, Y.: Toward TiO2 Nanofluids—Part 2: Applications and challenges. Nanoscale Res. Lett. 12(1), 446 (2017)
21. Dombek, G., et al.: The study of thermal properties of mineral oil and synthetic ester modified by nanoparticles TiO2 and C60. In: Proceedings of the 2014 ICHVE International Conference on High Voltage Engineering and Application, pp. 1–4. Poznan, Poland, 8–11 September 2014
22. Arun Ram Prasath, R.T., et al.: Dielectric and thermal conductivity studies on synthetic ester oil based TiO2 nanofluids. In: 2017 3rd International Conference on Condition Assessment Techniques in Electrical Systems (CATCON)
23. Hiemenz, P C. and Dekker, M: Principles of Colloid and Surface Chemistry, Vol. 188. M. Dekker, Co., New York (1986)
24. (https://www.us-nano.com/inc/sdetail/47163, Jul 2020)
25. Du, B.X., Li, X.L.: High thermal conductivity transformer oil filled with BN nanoparticles. In: IEEE: International Conference on Liquid Dielectrics, Bled, Slovenia, June 2014
26. Taha-Tijerina, J., et al.: Electrically insulating thermalNano-oils using 2D fillers, ACS Nano 6(2), 1214–1220 (2012)
27. Polykrati, A.D., et al.: Thermal and electric conductivity of insulating oils with magnetite nanoparticles. In IEEE International Conference on High Voltage Engineering and Application (ICHVE), Athens, Greece, 10–13 September 2018
28. Abarishi, M., et al.: Fabrication, characterization and measurement of thermal conductivity of Fe3O4 nanofluids, J. Magn. Magn. Mater. 322(24), 3895–3901 (2010)
29. Kiran, M.R., Babu, S.R.: Experimental investigation on natural convection heat transfer enhancement using transformer oil-TiO2 nanofluid, IRJET 5(7), 1412–1418 (2018)
30. Huang, Z., et al.: Electrical and thermal properties of insulating oil-based nanofluids: A comprehensive overview, IET Nanodielectr. 2(5), 27–40 (2019)