Improvement on the characteristics of transformer oil using nanofluids

S. Sumathi and R. Rajesh

Transformers play an important role in transmission and distribution systems. Even to this day, 75% of high-voltage transformer failure is the outcome of improper dielectric insulation. The reliable operation and ageing characteristics of the transformers mainly depend on the insulation material. Mineral oil has been used as an insulation and coolant for almost a century in power transformers. Due to the development of extra high voltage and to cope with the increasing demand in voltage level, a nanofluids-based transformer oil is proposed here. In this work, nanoparticles such as aluminium oxide, molybdenum disulphide and titanium dioxide are used with transformer oil to analyse the various critical characteristics like dielectric strength, acidity, interfacial tension, viscosity, flash point and fire point of the power transformer. The observed results show that the proposed nanofluids-based transformer oil provides better performance than the normal transformer oil.

The growth of high voltage applications such as generation, transmission and distribution has raised demands on the reliability and high performance of the insulating material to deal with more dynamic and unstable operating conditions. It is because insulation is the main factor affecting the performance of electrical appliances. Normally mineral oil or vegetable oil was used for regular electrical applications in the past. However, it did not meet the requirements for extra high-voltage applications such as thermal withstanding ability, ageing characteristics and handling of high voltage levels[1–3]. In addition, it lacks biodegradability and its availability is diminishing day by day[4]. The growth in power demand calls for more research and development on insulation.

Maintaining constant power supply is important for power system engineers. Transformer is the most important component in a transmission and distribution network system that requires high level of insulation to maintain constant power supply. The existing transformer statistics reveals a typical working lifetime of nearly 17–18 years, which is half of the predictable lifetime of transformer and 75% of transformer failure is due to improper dielectric insulation[5]. Similarly data collected between 1956 and 1999 examined the factors in detail that affect the characteristics of the transformer insulating oil due to ageing[6].

Mineral oil-based transformer oil does not meet the requirements of high-power transformers for distribution. To meet the high thermal stress and dielectric strength, nanomaterials-based dielectric material was proposed. Choi[7] proposed the term 'nanofluids' in 1995. In high voltage electrical insulation research, a nanofluid or nanoliquid refers to any combination of an insulator with a nanomaterial. Initially, nanomaterials were used in solid polymers to improve the lifetime and a similar method was extended to liquid insulators to improve thermal conductivity and dielectric strength[8,9]. Nanofluids are considered as the next-generation heat transfer fluids, as they offer exciting new possibilities. A detailed review on the preparation, characterization and preparation of nanofluids-based insulation is available in the literature[10–12]. Significantly, the heat-transfer capabilities and stability of a suspension are more in nanoparticles compared to conventional particles, due to their much larger surface-to-volume ratio[13,14]. Okabe *et al.*[15] studied the different characteristics of transformer oil for several days of heating, comprehensive assessment of ageing and saturation tendency due to increased ageing. Further, an increase in dielectric strength of the transformer oil-based nanofluids with different volume concentrations has been achieved[16,17]. Since the development of modified transformer oil by Du *et al.*[18], considerable research has been carried out on nanofluids based on transformer oil[19–22]. In the present study, titanium dioxide (TiO_2), aluminium oxide (Al_2O_3) and molybdenum disulphide (MoS_2) nanoparticles-based transformer oil composition is proposed to improve the transformer oil characteristics. TiO_2 is an attractive material for a component of nano-suspension. It is stable against higher strengths of the electric field and the dielectric constant is relatively high. TiO_2 has been widely used and studied owing to its cost-effectiveness, strong oxidizing power, non-toxicity and long-term photostability[23–25]. There are three crystalline polymorphs of titanium, viz. anatase, brookite and rutile. Among them, anatase is an important phase as it attracts more attention for its use as pigments, gas sensors, catalysts and nanofluids[26,27]. Al_2O_3 has good dielectric strength and better thermal shocking capacity. MoS_2 has particles ranging from 1 to 100 μm, which is common for dry lubricants. It also has high lubricant stability up to 350°C (refs 28, 29). A variety of oils and gases are used with MoS_2, because it retains good quality of the lubricant, is highly cost-effective and easily available.

Synthesis of nanomaterials

The commercially available TiO_2, Al_2O_3 and MoS_2 of average grain size 50–70 μm with 97.6–98.7% level of purity were used for this study. Each particle was separately ground using ball mill of 100 mm diameter and balls of different diameters were used to achieve maximum collision energy. Steel balls with varying diameter (10–25 mm) were used and speed of the drum was maintained at about 350 rpm to reduce grain size of the particles between 60 and 70 nm. The mode of operation was through a variable frequency drive whose frequency was 50 Hz. A shaft with arms rotating at high speed was used to agitate the material. Samples of TiO_2, Al_2O_3 and MoS_2 with 0.025% weight concentration were chosen, and each sample was kept for 5 h in a magnetic stirrer.

The technical basis for selecting the concentration at 0.025% level to prepare the nanofluid was to achieve better stability, obtain homogenized particles by avoiding higher concentration and avoiding uneven particle size. The low concentration values were chosen based on the literature[30–32]. Different low concentration values were also tested, but 0.025% concentration produced the optimum result compared to other values.

Measurement of characteristics of nanofluids-based transformer oil

The characteristics of transformer oil and nanofluids-based transformer oil were measured. Each measurement was carried out five times and mean value presented to maintain accuracy of the measurements.

Dielectric strength

The breakdown voltage (dielectric strength) is one of the most significant factors that defines the insulation oil performance in transformer and is a measure of its ability to withstand electrical stress without failure, pressure, temperature, humidity and electrode configuration. The dielectric strength of the transformer oil should always be high[33–39]. Moisture, solid particles, bubbles and acidity are important factors which affect the dielectric strength of oil.

The test method of IEC 156 involves applying an AC voltage at a controlled rate to two electrodes immersed in the insulating fluid[40]. The gap is a specified distance (2 mm). When the current arcs across this gap, the voltage recorded at that instant is the dielectric breakdown strength of the insulating liquid. Contaminants such as water, conducting particles and sediment decrease the dielectric strength of the insulating oil.

Figures 1 and 2 show the schematic diagram of dielectric strength measuring equipment and Figure 3 shows the circuit arrangement of dielectric strength measurement.

The voltage was slowly increased and maintained at 30 kV for 1 min. It was then checked whether the oil sample could withstand the specified voltage. If it failed at a voltage less than 30 kV, that voltage was recorded as the breakdown voltage. Then the voltage was increased once again until such time that there was a breakdown, and that particular voltage was recorded. If breakdown strength is less than 30 kV, the oil must be sent for reconditioning[41]. Nowadays, transformer oil breakdown strength of more than 65 kV is available[42–45]. Table 1 shows that TiO_2-based transformer oil has higher breakdown strength compared to Al_2O_3 and MoS_2-based transformer oil. Figure 4 is a graphical chart comparison of the results.

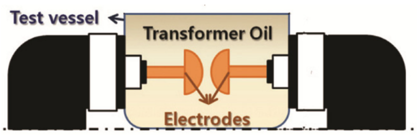

Figure 1. Schematic diagram of front view of dielectric strength measuring equipment.

Figure 2. Schematic diagram of dielectric strength measuring equipment.

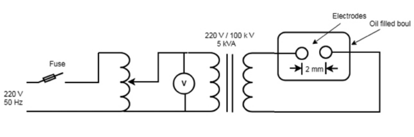

Figure 3. Circuit diagram of dielectric strength test.

Acidity

Acidity is a measure of organic and inorganic acids present in the oil and is expressed in terms of milligrams of potassium hydroxide (KOH) required to neutralize the total free acids in 1 g of oil. The acidity level of the transformer oil is measured using standard ASTM D974 (ref. 46).

The total acidity of the oil is expressed as neutralization number, which is defined as the amount of potassium hydroxide (mg) required to completely neutralize the acids present in 1 g of oil. Acids in the oil originate from oil decomposition/oxidation products. Acids can also come from external sources such as atmospheric contamination. These organic acids damage the insulation system and can produce corrosion inside the transformer when water is present. The transformer oil used in this study contains practically no acids if properly refined. In pure transformer oil, there should be no acid content. However, in most cases, there will be some acid content. The result expresses the amount of KOH (mg) required to neutralize the acidity of 1 g of sample

$$\text{Total acidity} = (A \times N \times 56.1)/W \text{ mg of KOH/g of oil}, \quad (1)$$

where A is the amount of KOH solution (ml) used in titration, N the normality of KOH solution used for titration and W is weight of the sample.

From the observation of colour it is possible to determine pH value with the help of a colour chart (Figure 5). Table 2 shows the comparison of acidity between transformer oil and nanofluids-based transformer oil. The result shows that

Table 1. Dielectric strength measurement of transformer oil and nanofluids-based transformer oil (kV)

Transformer oil	TiO_2 with transformer oil	Al_2O_3 with transformer oil	MoS_2 with transformer oil
52.5	72.6	66.2	59.2

Table 2. Acidity measurement of transformer oil and nanofluids-based transformer oil (mg KOH/g)

Transformer oil	TiO_2 with transformer oil	Al_2O_3 with transformer oil	MoS_2 with transformer oil
0.25	0.12	0.21	0.18

nanofluids-based transformer oil has low acid content compared to normal transformer oil. So there will be no chance of corrosion occurring in the transformers. Figure 6 is a graphical comparison of the results.

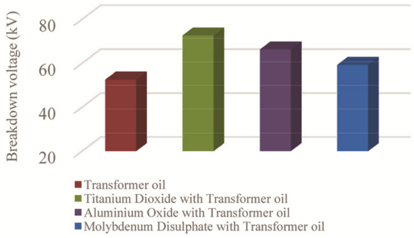

Figure 4. Graphical comparison of dielectric strength between transformer oil and nanofluid-based transformer oil (kV).

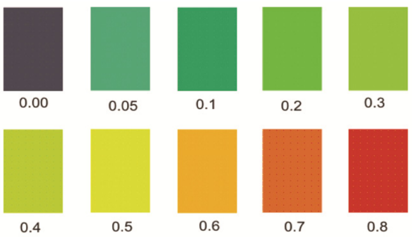

Figure 5. Colour chart for rapidly determining acid content of insulating oil.

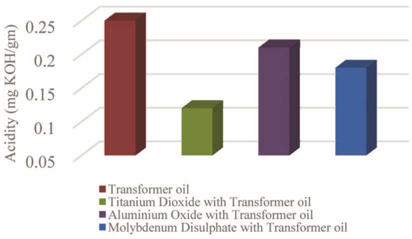

Figure 6. Graphical comparison of acidity between transformer oil and nanofluids-based transformer oil (mg KOH/g).

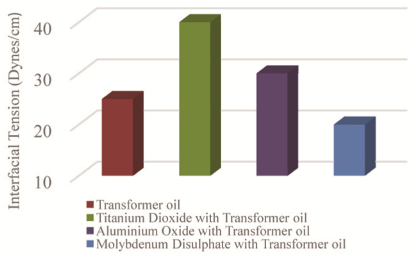

Figure 7. Graphical comparison of interfacial tension between transformer oil and nanofluids-based transformer oil (dyn/cm).

Interfacial tension

Interfacial tension is the measure of molecular attractive force between oil and water molecules at their interfacial level. Using interfacial tension test it is possible to determine the soluble polar contaminants present in the oil, which reduce the molecular attraction force between oil and water. The pure transformer oil should have a minimum value 18 dyn/cm and maximum 40 dyn/cm. The interfacial tension of transformer oil is measured using ASTM D971 standard[47]. A tensiometer is used to determine the interfacial tension of the transformer oil, which works on the basis of Du Nuoy principle.

Table 3 shows the experimental results of interfacial tension of transformer oil and nanofluids-based transformer oil. The results show that nanofluids-based TiO_2 and Al_2O_3 have higher interfacial tension. MoS_2-based transformer oil has low interfacial tension when compared to normal transformer oil. Figure 7 is a graphical comparison of the results.

Flash point

The flash point of a chemical or any volatile material is the lowest temperature at which it can evaporate to form an ignitable mixture or combustible concentration in air. A minimum flash point is specified in order to prevent the risk of fire that might be the result of accidental ignition. For a good transformer oil, the flash point should be higher than 140°C. Flash point of various nanomaterials-based transformer oil is measured by cleveland open cup flash point tester using ASTM D93 (Figure 8)[48].

Table 4 shows the test results of flash point of transformer oil and nanofluids-based transformer oil. It can be seen that

Table 3. Interfacial tension measurement of transformer oil and nanofluids-based transformer oil (dyn/cm)

Transformer oil	TiO_2 with transformer oil	Al_2O_3 with transformer oil	MoS_2 with transformer oil
25	40	30	20

Table 4. Flash point measurement of transformer oil and nanofluids-based transformer oil (°C)

Transformer oil	TiO_2 with transformer oil	Al_2O_3 with transformer oil	MoS_2 with transformer oil
142	157	152	148

Table 5. Fire point measurement of transformer oil and nanofluids-based transformer oil (°C)

Transformer oil	TiO_2 with transformer oil	Al_2O_3 with transformer oil	MoS_2 with transformer oil
150	164	155	152

Table 6. Viscosity measurement of transformer oil and nanofluids-based transformer oil

Temperature (°C)	Transformer oil	TiO_2 with transformer oil	Al_2O_3 with transformer oil	MoS_2 with transformer oil
50	73.26	79.61	118.29	98.21
60	65.80	58.58	106.29	87.62
70	51.25	53.04	96.95	79.47
80	44.22	47.35	89.58	73.92

nanofluids-based transformer oil has higher flash point compared to normal transformer oil. Figure 9 is a graphical comparison of the results.

Fire point

Fire point is the lowest temperature at which vapour of the oil burns continuously for at least 5 sec, when a tiny flame is brought near it.

Fire points are used to indicate the following:

- Fire hazard of petroleum products and evaporation losses under high temperature losses.
- Maximum temperature below which the oil can be used.
- A means of identification of a specific lubricating oil.
- For detection of contamination in the given lubricating oil.

For a good transformer oil, the fire point should be higher than 150°C. Cleveland open cup fire point tester measures the fire point of nanomaterials-based transformer oil. Table 5 shows that all nanofluids-based transformer oil has higher fire point compared to normal transformer oil. Figure 10 shows the blue flame of the transformer oil during fire point tests. Figure 11 is a graphical comparison of the results.

Figure 8. Schematic diagram of cleveland open cup flash point tester.

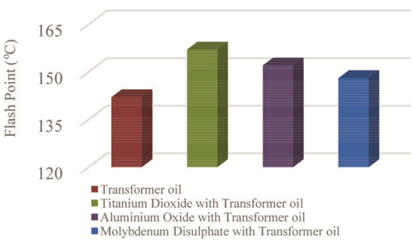

Figure 9. Graphical comparison of flash point between transformer oil and nanofluids-based transformer oil (°C).

Viscosity

Viscosity is the property of a fluid that determines its resistance to flow. It is an indicator of flow ability of a lubricating oil; lower the viscosity, greater is the flow ability. It is mainly due to the forces of cohesion between molecules of the lubricating oil[49]. Viscosity is measured using IS 1448(P-25):1976 standard[50].

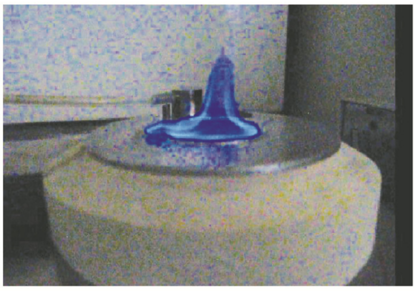

Figure 10. Blue flame produced in transformer oil.

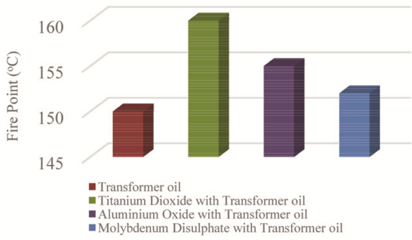

Figure 11. Graphical comparison of fire point between transformer oil and nanofluids-based transformer oil (°C).

Figure 12. Schematic diagram of red wood viscometer.

Viscosity values are used for the following:

- Evaluating load-carrying capacity.
- To determine the effect of temperature changes and the presence of contaminants in used oil during service.
- Absolute viscosity values are required for use in all bearing design calculations and other lubrication engineering technical design problems.

For a good transformer oil, the viscosity should be low. Viscosity is measured using red wood viscometer (Figure 12).

Table 6 shows the experimental results of transformer oil and nanofluids-based transformer oil. Figures 13–16 show a graphical comparison of viscosity at different temperatures. The results show that Al_2O_3-based transformer oil has high viscosity and TiO_2-based transformer oil has low viscosity compared to normal transformer oil.

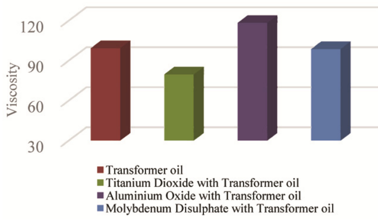

Figure 13. Graphical comparison of dynamic viscosity between transformer oil and nanofluids-based transformer oil at 50°C.

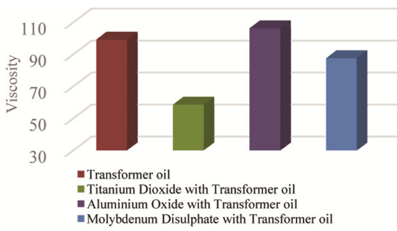

Figure 14. Graphical comparison of dynamic viscosity between transformer oil and nanofluids-based transformer oil at 60°C.

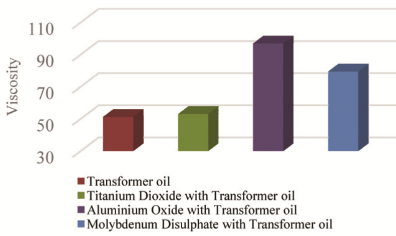

Figure 15. Graphical comparison of dynamic viscosity between transformer oil and nanofluids-based transformer oil at 70°C.

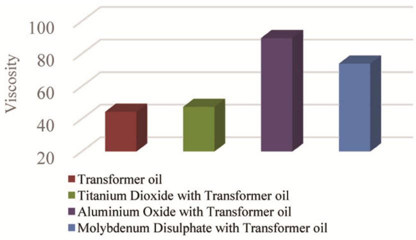

Figure 16. Graphical comparison of dynamic viscosity between transformer oil and nanofluids-based transformer oil at 80°C.

Conclusion

In order to enhance the properties of transformer oil, nanofluids-based transformer oil was prepared using semiconductor materials like TiO_2, MoS_2 and insulators like Al_2O_3. Nanomaterials were synthesized in the transformer oil with 0.025% concentration using magnetic stirrer. Measurements of breakdown voltage, acidity, interfacial tension, flash point, fire point, and viscosity were made according to the standards. TiO_2-based transformer oil gave better properties than MoS_2 and Al_2O_3-based transformer oil, since TiO_2 is stable against higher electric field and relatively high dielectric strength.

1. Liu, M. S., Lin, M. C. C., Huang, I. T. and Wang, C. C., *Chem. Eng. Technol.*, 2006, **29**(1), 72–77.
2. Jin, H., Andritsch, T., Tsekmes, I. A., Kochetov, R., Morshuis, P. H. F. and Smit, J. J., *IEEE Trans. Dielect. Electr. Insul.*, 2014, **21**(3), 1100–1108.
3. Thabet, A., Allam, M. and Shaaban, S. A., *IET Gener., Transm. Distrib.*, 2017, **12**(5), 1171–1176.
4. Oommen, T. V., Claiborne, C. C. and Mullen, J. T., In Proceedings of the Electrical Insulation Conference and Electrical Manufacturing and Coil Winding Conference, Rosemont, IL, USA, 1997, pp. 465–468.
5. Bartley, W. H., In Proceedings of the Weidmann-ACTI 5th Annual Technical Conference on New Diagnostic Concepts for Better Asset Management, Albuquerque, NM, USA, November 2006, pp. 1–7.
6. Okabe, S., Kaneko, S., Kohtoh, M. and Amimoto, T., *IEEE Trans. Dielectr. Electr. Insul.*, 2010, **17**(1), 302–311.
7. Choi, S. U. S., In The Proceedings of the 1995 ASME International Mechanical Engineering Congress and Exposition, San Francisco, USA, ASME, FED 231/MD 66, 1995, pp. 99–105.
8. Joshil, A. and Kumar, S., *NDT&E Inter.*, 2005, **38**, 459–461.
9. Rafiq, M., Lv, Y. Z., Zhou, Y., Ma, K. B., Wang, W., Li, C. R. and Wang, Q., *Renew. Sust. Energy Rev.*, 2015, **52**, 308–324.
10. Das, S. K., Choi, S., Yu, W. and Pradeep, T., *Nanofluids: Science and Technology*, John Wiley, 2008, vol. 21, pp. 5–8.
11. Jama, M., Singh, T., Gamaleldin, S. M., Koc, M., Samara, A., Isaifan, R. J. and Atieh, M. A., *J. Nanomater.*, 2016, **1**, 1–23.
12. Yu, W. and Xie, H., *J. Nanomater.*, 2012, **5**, 17.
13. Das, S. K., Choi, S. U. and Patel, H. E., *Heat Transfer Eng.*, 2006, **27**(10), 3–19.
14. Segal, V., Hjorstberg, A., Rabinovich, A., Nattrass, D. and Raj, K., IEEE International Symposium on Electrical Insulation, Arlington, VA, USA, 1998, pp. 619–622.
15. Okabe, S., Kaneko, S., Kohtoh, M. and Amimoto, T., *IEEE Trans. Dielectr. Electr. Insul.*, 2010, **17**(1), 302–311.
16. Sumathi, S. and Subburaj, P., *Asian J. Res. Soc. Sci. Hum.*, 2017, **7**(2), 678–690.
17. Lee, J. C., Seo, H. S. and Kim, Y. J., *Int. J. Therm. Sci.*, 2012, **62**, 29–33.
18. Du, B., Li, J., Wang, F., Yao, W. and Yao, S., *J. Nanomater.*, 2015, **4**, 1–9.
19. Segal, V., Rabinovich, A., Nattrass, D., Raj, K. and Nunes, A., *J. Magn. Magn. Mater.*, 2000, **215**, 513–515.
20. Kopcansky, P., Tomco, L., Marton, K., Koneracka, M., Potocova, I. and Timko, M., *J. Magn. Magn. Mater.*, 2004, **276**, 2377–2378.
21. Chiesa, M. and Das, S. K., *Colloids Surf. A*, 2009, **335**, 88–97.
22. Pfaff, G. and Reynders, P., *Chem. Rev.*, 1999, **99**, 1963–1981.
23. Yeh, Y. C., Tseng, T. T. and Chang, D. A., *J. Am. Ceram. Soc.*, 1989, **72**, 1472–1475.
24. Awati, P. S., Awate, S. V., Shah, P. P. and Ramaswamy, V., *Catal. Commun.*, 2003, **4**, 393–400.
25. Moafi, H. F., Shojaie, A. F. and Zanjanchi, M. A., *Appl. Surf. Sci.*, 2010, **256**, 4310–4316.
26. Tsevis, A., Spanos, N., Koutsoukos, P. G., Linde, A. J. and Lykleme, J., *J. Chem. Soc., Faraday Trans.*, 1998, **94**, 295–300.
27. Shojaie, A. F. and Loghmani, M. H., *Chem. Eng. J.*, 2010, **157**, 263–269.
28. Pourabbas, B. and Jamshidi, B., *Chem. Eng. J.*, 2008, **138**(1–3), 55–62.
29. Cotton, A. F., Wilkinson, G., Bochmann, M. and Murillo, C. A., *Advanced Inorganic Chemistry*, John Wiley, USA, 1999.
30. Choudhary, R., Khurana, D., Kumar, A. and Subudhi, S., *J. Exp. Nanosci.*, 2017, **12**(1), 140–151.
31. Yu, W. and Xie, H., *J. Nanomater.*, 2012, **4**, 1–17.
32. Wang, X.-Q. and Mujumdar, A. S., *Braz. J. Chem. Eng.*, 2008, **25**(4), 631–648.
33. Chiesa, M. and Das, S. K., *J. Colloids Surf. A*, 2009, **335**, 1–3.
34. Martin, D. and Wang, Z. D., *IEEE Trans. Dielectr. Electr. Insul.*, 2008, **15**(4), 1044–1050.
35. Dissado, La. and Fothergill, J. C., *IEEE Trans. Dielectr. Electr. Insul.*, 2004, **11**(5), 737–738.
36. Timko, M. and Marton, K., *Czech. J. Phys.*, 2004, **54**, 654–657.
37. Timko, M., Herchl, F. and Marton, K., In Proceedings of the CSMAG'07 Conference, 2008, vol. 113, no. 1, pp. 569–572.
38. Kopcanský, P., Tomco, L., Marton, K., Koneracka, M., Potocova, I. and Timko, M., *J. Magn. Magn. Mater.*, 2004, **272**, 2377–2378.
39. Segal, V., Hjortsberg, A., Rabinovich, A., Nattrass, D. and Raj, K., In Conference Record of the 1998 IEEE International Symposium on Electrical Insulation (Cat. No. 98CH36239), 1998, vol. 2, pp. 619–622.
40. IEC 156, Insulating Liquids – Determination of the Breakdown Voltage at Power Frequency – Test Method, 1995, 2nd edn.
41. Wadhwa, C. L., *High Voltage Engineering*, New Age International, 2007.
42. Du, Y. F., Lv, Y. Z., Wang, F. C., Li, X. X. and Li, C. R., In Electrical Insulation (ISEI), Conference Record of the 2010 IEEE International Symposium, San Diego, CA, USA, 2010, pp. 1–3.
43. Fallah-Shojaie, A., Tavakoli, A., Ghomashpasand, M. and Hoseinzadeh, S., In 21st Iranian Conference on Electrical Engineering, ICEE, 2013.
44. Pugazhendhi, S. C., In International Conference on High Voltage Engineering and Application, Shanghai, China, 2012, vol. 9, pp. 207–210.
45. Chandini, G. and Karthik, R., In International Conference on Circuits, Power and Computing Technologies, Nagercoil, India, ICCPCT, 2014, pp. 370–376.
46. ASTM D974. Standard test method for determining acidity of oil.
47. ASTM D971. Standard test method for determining inferential tension of oil.
48. ASTM D93. Standard test method for determining flash point of oil.
49. Kumar, T. A., Pradyumna, G. and Jahar, S., *J. Environ. Res. Dev.*, 2012, **7**, 768–777.
50. IS 1448 (P-25):1976. Standard for measuring viscosity of oil.

Received 19 February 2019; accepted 12 October 2019

S. Sumathi is in the Department of Electrical and Electronics Engineering, Anna University, Regional Campus, Coimbatore 641 046, India; R. Rajesh is in the Department of Instrumentation and Control Engineering, Sri Krishna College of Technology, Coimbatore 641 042, India.*
**e-mail: sumathime@gmail.com*