https://doi.org/10.48048/tis.2021.21

Effect of Concentration of Al_2O_3 Nanoparticles on Electrical Properties of Mineral Oil

Pichai Muangpratoom[1,*], Noppharit Chaipanha[1], Kanchanok Sangduan[1] and Issaraporn Khonchaiyaphum[2]

[1]*Department of Electrical Engineering, Faculty of Engineering, Rajamangala University of Technology Isan, Khon Kaen Campus, Khon Kaen 40000, Thailand*
[2]*Department of Mathematics, Faculty of Engineering, Rajamangala University of Technology Isan, Khon Kaen Campus, Khon Kaen 40000, Thailand*

([*]Corresponding author's e-mail: pichai.mu@rmuti.ac.th)

Received: 8 March 2021, Revised: 30 May 2021, Accepted: 8 June 2021

Abstract

This study aimed to compare the electrical characteristics of mineral oil-based nanoparticles to those of pure mineral oil. Mineral oil used in distribution transformers was mixed with aluminum oxide (Al_2O_3) nanoparticles, which serve as an insulator, with 0.01, 0.03, and 0.05 % mineral oil volume concentrations. The moisture content in mineral oil was measured beforehand, and the electrical tests were subsequently conducted in accordance with international standards. The moisture content test revealed that the combination of nanoparticles and mineral oil resulted in an increase in moisture content. As regards the test of AC withstanding voltage and negative polarity lightning impulse voltage, it was found that the mineral oil mixed with the nanoparticles had higher dielectric strength than the original mineral oil. In addition, the test results of positive polarity lightning impulse voltage demonstrated that with a mixture of mineral oil and the nanoparticles at a 0.01 % concentration, the positive polarity lightning impulse dielectric strength of the mineral oil increased. However, at concentrations of 0.03 and 0.05 %, it did not rise, regardless of the increasing volume of nanoparticles. The results, thus, showed promising directions for applications of nanoparticles in the development of electrical properties of mineral oil.

Keywords: Mineral oil, Nanoparticles, AC breakdown voltage, Lightning impulse voltage

Introduction

Electric power usage constantly increases, so the power transmission and generation increase accordingly. For this reason, the voltage breakdown strength of dielectric is needed for the transmission and distribution system since such systems are the bulk distribution of power at a low rate of energy loss. The most popular transmission system is the high voltage alternating current system. However, the problem with such a system is the insulator of the high voltage (HV) units, such as transformer oil or mineral oil, electric insulator, and high voltage transmission cable. Mineral oil (MO), in particular, is the liquid insulator of the electric transformer that can withstand the voltage and ventilate heat very well [1]. When the heat increases, the insulating strength is compromised, leading to the deterioration or damage of the electric transformer. Transformers are the most important component of a modern power generating and distribution network. Typically, cellulose and MO are utilized as insulating materials in power transformers. Cellulose is a kind of cellulose that is used for mechanical and electrical insulation. Electrical insulation and cooling qualities are the most common uses for MO [2-4]. Since the first commercially oiled transformers were utilized in the past, MO has been employed. On the other hand, MO continues to play an important role in high-voltage equipment insulation, notably transformers and instrument transformers [5,6]. By focusing on advancements in nanotechnology and applications, nanoparticles have promised that they can be used with MO to enhance properties that enable more compact designs and lower production costs [2,3,7-11].

Choi pioneered thermal conductivity in 1993 [12,13], which is one of the concepts for employing nanoparticles (NPs) to enhance the thermal characteristics of liquids. Since 1995, with an average of 32 % per year, the number of publications involving nano-liquids has grown [6]. In 1998, Vladimir *et al.* [14] began research into MO-based nanocomposite liquids' dielectric properties. They added magnesite NPs to improve the dielectric properties of MO. Other research tested the alternating current (AC) degradation ability of nanofluid samples under different moisture levels. They used MO based on Silicon dioxide (SiO_2) compared to base oil [15]. In conclusion, in the nano-fluid sample, the decaying pressure increased. The dissolution pressure of MO and SiO_2 nanofluids increased with the decrease in water content. It is consistent with the finding [16] that MO-based SiO_2 NPs outperformed original MO under various field direct current conditions. They also looked at how interstitial zones impact the dielectric characteristics of MO-based alumina (Al_2O_3) and titanium dioxide (TiO_2), as described in [17]. The studies showed that increasing insulating properties of MO may be achieved through the use of different types of NPs [18,19]. However, the relative permittivity and conductivity differed from the host oil, including the prepared nano-fluid loss factor [20,21]. In transformer units designed with pure oil properties, applications of these NFs to these specific properties may have different stress distributions. This may result in structural difficulties for the transformer. There should be revisions to standard testing and maintenance procedures. A number of other issues related to fluid nanofabrication should be addressed, such as precipitation, oxidation stability, and moisture absorption issues. The use of nano-fluid in existing transformers is highly complex due to the difference in electrical properties. Therefore, further research is needed to find NPs in MO suspensions that do not affect the insulating properties to a great extent and can improve the dielectric properties of MO.

The above review of the literature showed that different nanoparticles showed an enhancement in the degradation of MO. The research lacks extensive analyses on the influence of Al_2O_3 NPs on MO degrading efficiency in terms of shape, concentration, and surface modification factors. A novel nanofluid was created by dispersing Al_2O_3 nanoparticles into MO to boost insulating properties. The effect of these parameters of NPs on the degradation efficiency of MO was studied. The lightning impulse decay voltage was measured with different shapes for the prepared nano fluids (nanorod, nanoplate). The higher dissolution efficiency was demonstrated by the nanofluid prepared with the nanopod. The effect of several surface modifications (C2, C18, Oleic acid) on the breakdown efficiency of MO was then investigated. The higher decomposition efficiency was seen from the nanofluid prepared with the nanopod modified by oleic acid. Nano fluids with effect concentrations of 0, 0.6, 0.8 and 1.2 g/L were made using nanorods modified with oleic acid (OA). Nano fluids were prepared with nano-shapes to survive. The surface modification of oleic acid including the 0.8 g/L concentration demonstrated the best decomposition efficiency. For this reason, they were used to study the effect of electrode spacing on the alternating current degradation efficiency of MO. The electron trap theory has dramatically improved the dielectric strength of nanoscale fluids [18].

This research studied the insulation efficiency enhancement of MO by mixing with the nanoparticles (NPs). Aluminium oxide (Al_2O_3) is a fascinating nanoparticle that has been mentioned in conference papers and journals as an excellent insulating material for nano dielectric applications. In general, most research papers did not compare different concentrations of Al_2O_3 NPs (0.01, 0.03 and 0.05 %). As a result, the goal of this study was to compare the features of MO-based nanofluids with varied NP concentrations. Furthermore, during the production of MO combined with Al_2O_3 NPs, this research focuses on a specific circumstance. The findings and conclusions of this study will contribute to a better understanding of Al_2O_3 NPs' utilization in dielectric materials. In addition, this study used Al_2O_3 NPs, which were smaller than 50 nanometers [22]. They were used in this research at 0.01, 0.03 and 0.05 % of the volume of MO in order to compare the insulation of the original MO and that mixed with NPs by testing the electric properties. The study results would lead to the improvement of MO quality.

Materials and methods

Preparation of MO-based nanofluids

Pure MO was prepared for mixing NPs at 60 °C for 24 h in a vacuum oven. The Al_2O_3 nanopowders were weighted and mixed with Al_2O_3 at 0.01, 0.03 and 0.05 % of the volume of MO, as well as the surfactant before stirring well in a stirrer at 60 °C for 30 min. After that, all the mixtures were mixed in a shaker with high frequency ultrasonic at 60 °C for 2 h. Lastly, the nanofluids were put at 60 °C for 24 h using a vacuum oven. Well-dispersed nanofluids as shown in **Figure 1** [1,6].

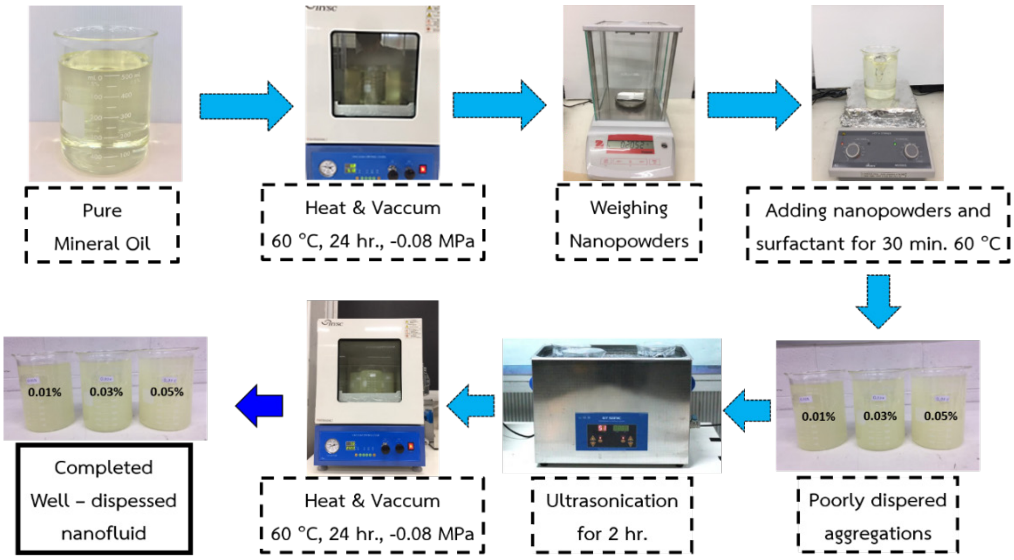


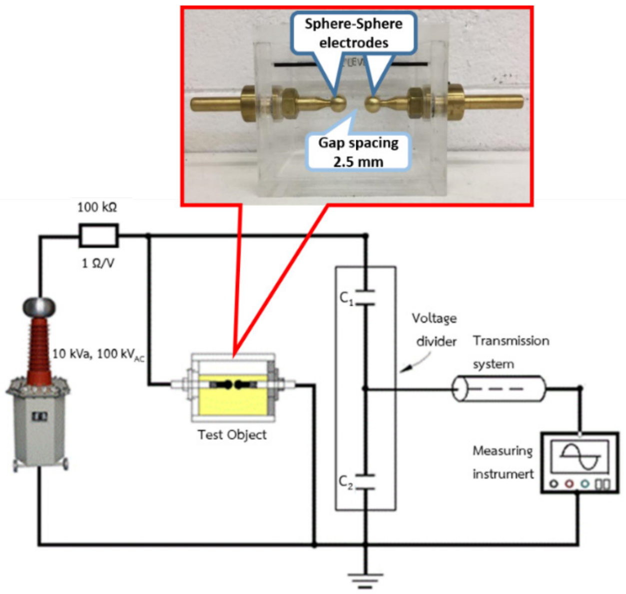
Figure 1 Preparation of MO-based nanofluids.

Experimental measurement methods

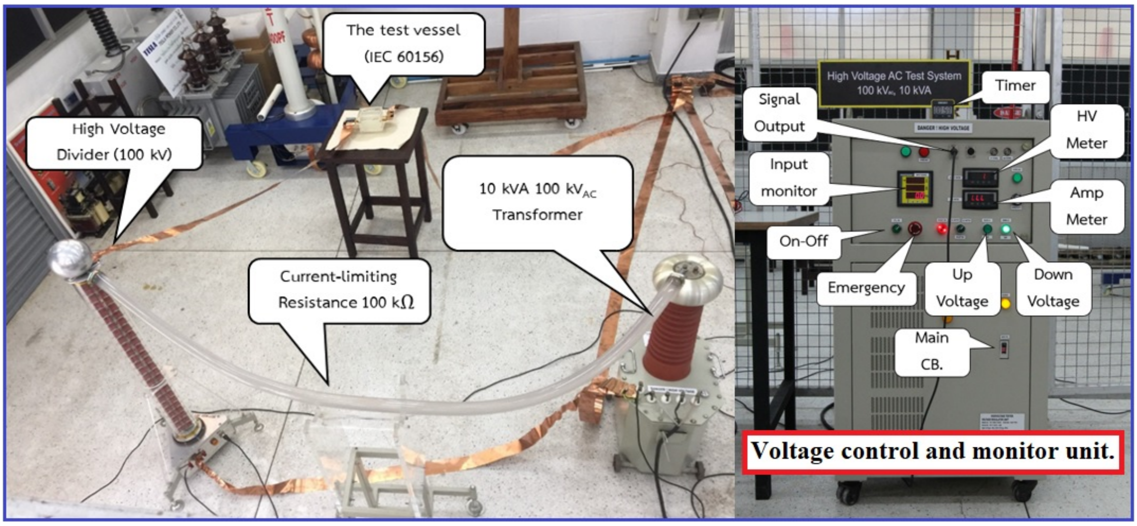
Prior to the electric testing, the MO moisture test was mixed with and without NPs. Moisture analyzer model: CA-310 MITSUBISHI as Karl Fischer Titration, a technique for determining moisture content, was used in the MO in accordance with ASTM-D1533 [23], and the test was repeated 3 times to find the average.

The current voltage breakdowns test (AC Breakdowns) was alternated with the original MO and the MO was mixed with Al_2O_3 using an AC breakdown test kit of 10 kVA, 100 kV_{AC} with AC breakdown based on the IEC 60156 [24]. The gap between the sphere-sphere electrodes, both 13 mm in diameter, with a fixed length of 2.5 mm, was tested at room temperature. The test was repeated 6 times to find the average. The test circuit is shown in **Figure 2**.

The tests of positive and negative polarity lightning impulse breakdown voltages of the original MO and the MO mixed with Al_2O_3 with the Lightning Impulse Voltage test kit 400 kV, 40 kJ were performed in accordance with IEC 60897 [25]. With a gap separation of 10 mm, the electrode (needle-sphere) arrangement was established. A tungsten needle with a tip radius of 40 μm and a spherical electrode with a diameter of 13 mm were tested at room temperature. The test was carried out 6 times. **Figure 3** depicts the test circuit.

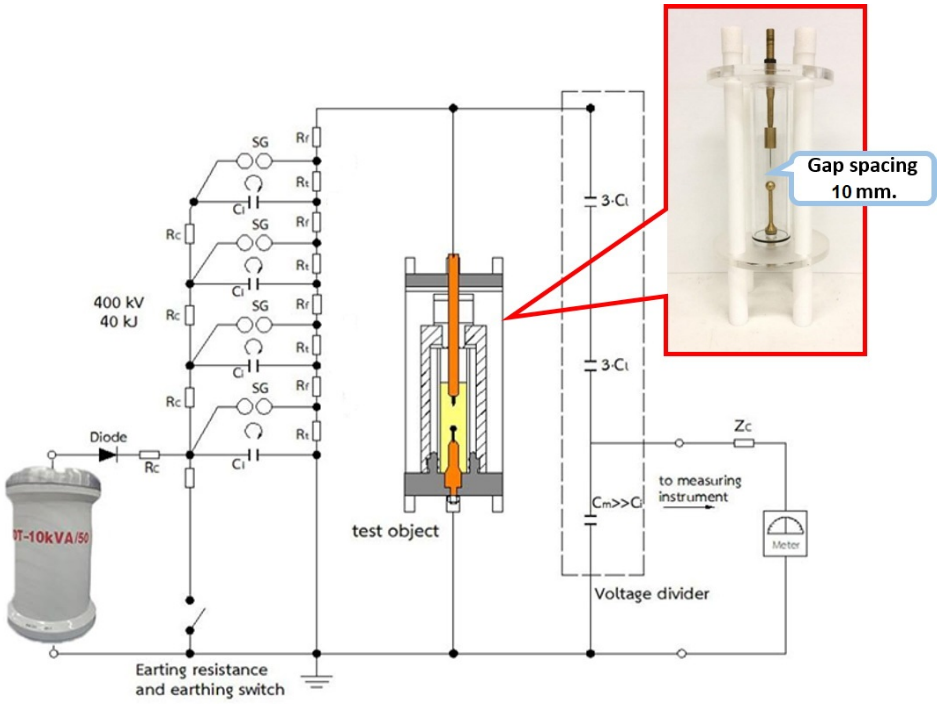


(a)

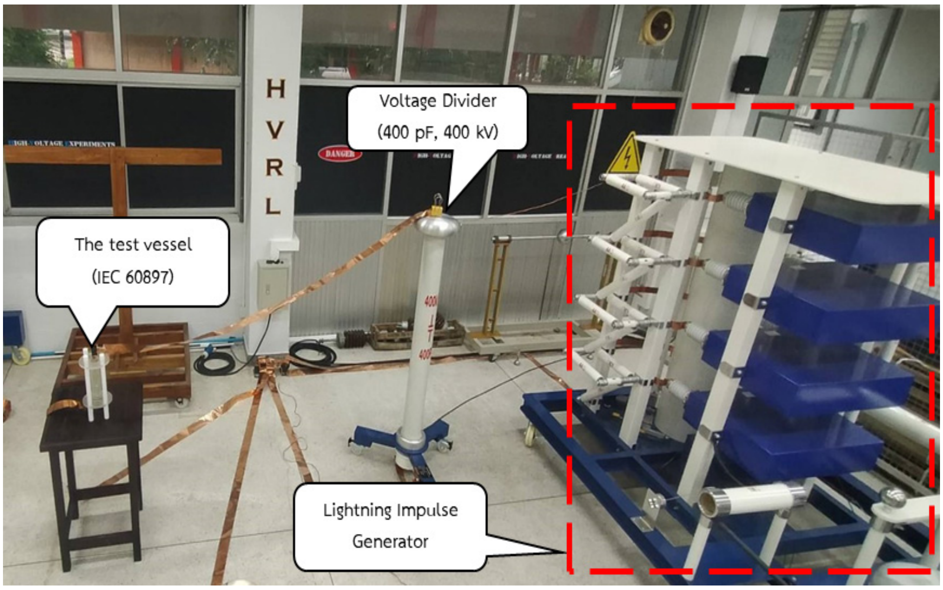


(b)

Figure 2 Circuit for testing the AC breakdowns voltage of MO-based nanofluids (a) Diagram of the AC breakdowns voltage test circuit. (b) The test circuit set-up used for the AC breakdowns voltage.



(a)



(b)

Figure 3 Circuit of lightning impulse breakdowns voltage test; (a) diagram of the lightning impulse test circuit, (b) the test circuit set-up used for lightning impulse voltage.

Results and discussion

Test results of moisture content in MO

From the moisture analysis of the original MO and the MO mixed with NPs at 0.01, 0.03 and 0.05 %, it showed that the average moisture content level in the MO mixed with Al_2O_3 was higher than that in the original MO. However, it was likely to decrease due to the increasing NPs as they penetrated into water in the mineral water. Meanwhile, the NPs contained the moisture on the surface, so when 0.05 % of the NPs were added, it also penetrated into water in the MO. Consequently, the moisture of the MO dropped. In any case, the moisture content of the MO mixed with Al_2O_3 was greater than that of the original MO, as shown in **Figure 4**, while 1st, 2nd and 3rd symbols mean the number of times a measurement is executed in the test results, i.e. the test was repeated 3 times to find the average.

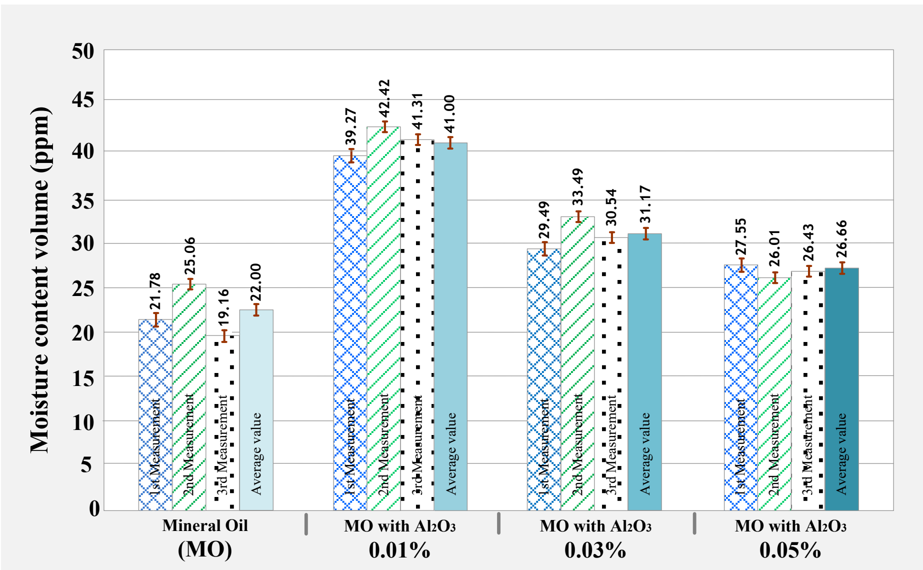


Figure 4 The test results of moisture content in the original MO and the MO mixed with Al_2O_3 NPs.

Test results of alternating current voltage breakdowns

The test results of AC breakdowns between the original MO and the MO mixed with Al_2O_3 indicated that the MO mixed with 0.05 % of Al_2O_3 had increasing breakdowns at every volume and higher than that of the original MO. Moreover, the increase in breakdown strength is the result of the suspension of different concentrations of nanomaterials into MO effects. As a result of the spacing between NPs being smaller, the cause of the electrons becoming trapped in more oil gap [19]. The comparison of increasing breakdown voltage as shown in **Table 1** and **Figure 5**. The error of test results could be determined from the standard deviation in the Eq. (1) [26].

$$\text{S.D.} = \sqrt{\frac{n\Sigma X^2 - (\Sigma X)^2}{n(n-1)}} \tag{1}$$

where S.D. represented standard deviation
X represented data (1, 2, 3..., n)
n represented all data

Table 1 Test results of AC breakdowns.

Liquid Types	AC breakdowns voltage (kV)							
	1^{st}	2^{nd}	3^{rd}	4^{th}	5^{th}	6^{th}	Average	S.D.
Mineral Oil (MO)	40.6	41.7	44.1	44.4	44.9	41.2	42.82	1.86
MO+Al_2O_3 0.01 %	53.7	56.3	55.4	54.1	57.6	56.5	55.60	1.50
MO+Al_2O_3 0.03 %	60.5	58	56.5	57.2	57.9	56.9	57.83	1.43
MO+Al_2O_3 0.05 %	60.5	60.6	59.5	59.1	62.7	59.8	60.37	1.28

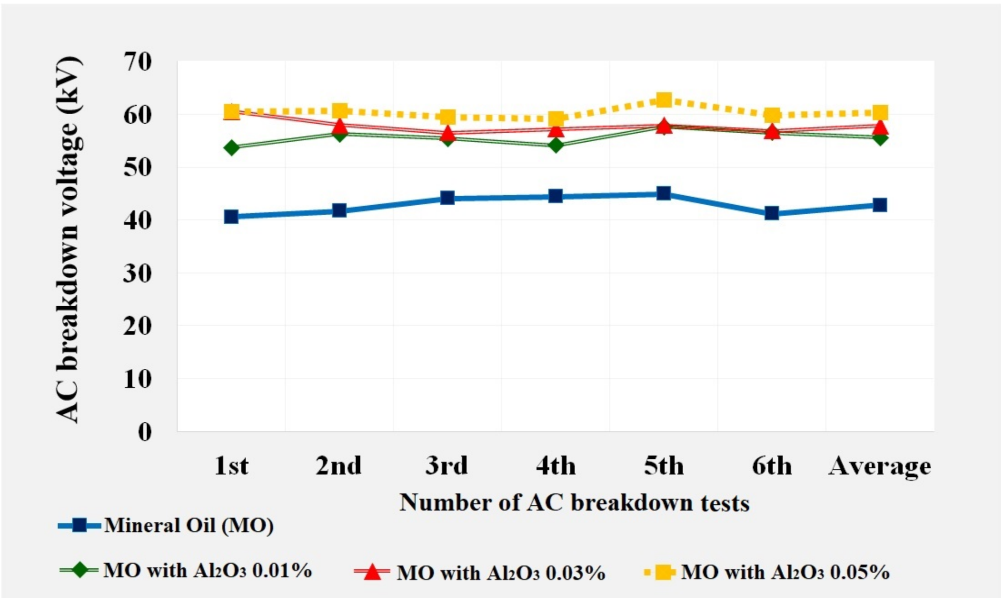


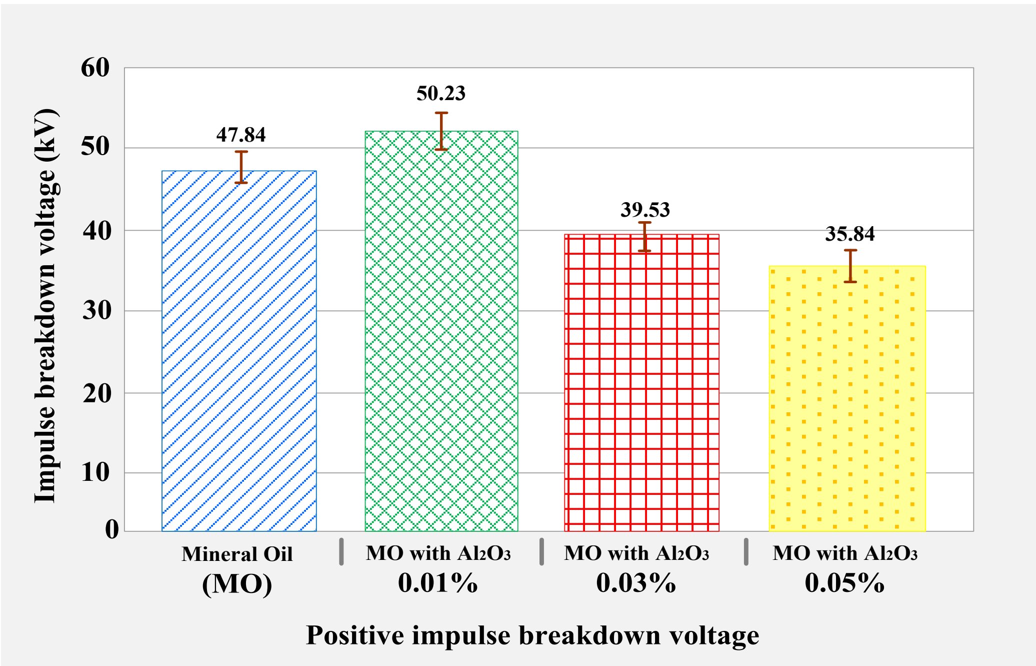
Figure 5 Comparison of test results of alternating current voltage breakdowns.

The data was evaluated and a comparison of the alternating current breakdown voltage characteristics of original MO and MO-based nanocomposite liquids was made at room temperature. First and foremost, when the alternating current breakdown strength of MO mixed with Al_2O_3 NPs was compared to original MO, a favorable association was found. The presence of Al_2O_3 NPs in MO, which were introduced to prevent streamer rise and hinder beam diffusion, resulted in an increase in the alternating current decay voltage of MO-based nanofluids. Therefore, it can be explained by the influence of the nano-fluid concentration. **Figure 5** shows that the nanofluid at 0.01 %, a very low concentration, has a slightly increased decay strength because the oil molecules and electrons were ionized before the NPs were trapped. Besides, **Figure 5** showed that the alternating current decomposition was significantly increased at 0.03 and 0.05 % concentrations because there was a greater likelihood of particles with less distance in the oil gap being the cause of electrons being trapped in those gaps. In the presence of an external electric field, each NP has a polarization effect, which can initiate the trapping process [27].

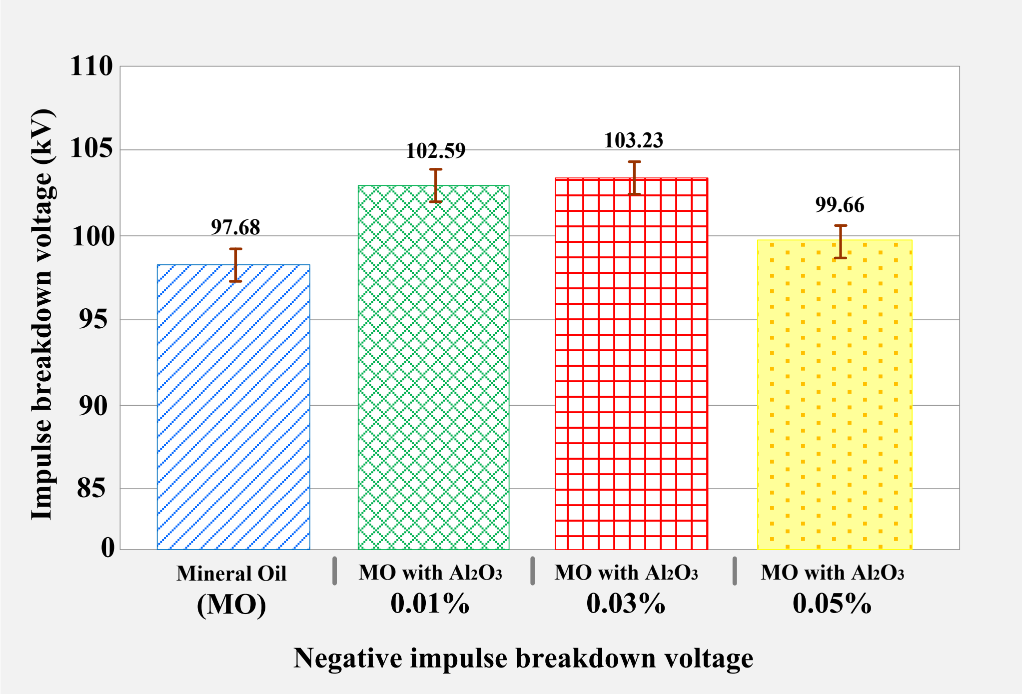
Test results of lightning impulse breakdowns voltage

The lightning impulse breakdown voltage was measured at room temperature with both positive and negative polarities using the original MO and the MO mixed with Al_2O_3. It was discovered that NPs had a significant impact on impulse breakdowns. The comparison of the increasing breakdowns of the Al_2O_3 at 0.01, 0.03 and 0.05 % of the MO volume. Furthermore, the test results of lightning impulse voltage on positive polarity demonstrated that with a mixture of MO and NPs at a 0.01 % concentration, the lightning impulse dielectric strength on the positive polarity of the MO increased, but not at concentrations of 0.03 and 0.05 %, despite the increasing volume of NPs, as shown in **Figure 6**.

Figure 6 showed the results of testing the effect of Al_2O_3 NPs on the impulse decomposition pressure properties of MO. The data analysis showed that the type of Al_2O_3 NPs added to MO had a great influence on the impulse decay pressure of MO-based nanofluids. In **Figure 6(a)** showing the anode of the impulse decay voltage, when adding Al_2O_3 NPs at a fraction concentration of 0.01 % to MO, the impulse decay pressure slightly increased ascending with the anode. However, when Al_2O_3 NPs were added to MO at a concentration of 0.03 % and a volume fraction of 0.05 %, no benefits were found. The results showed that Al_2O_3, a NP that was added to MO, all of the nanofluid samples tested, among the 3 volumetric fractions of the NPs, could increase the impulse decay voltage with the negative polarity as shown in **Figure 6(b)**.



(a)



(b)

Figure 6 Effect of NPs on the lightning impulse breakdowns voltage; (a) the test results of lightning impulse breakdowns voltage on positive polarity, (b) the test results of lightning impulse breakdowns voltage on negative polarity.

Conclusions

The results of the tests showed that the MO mixed with Al_2O_3 increased the moisture content. However, when Al_2O_3 was added, the increased volume resulted in a small drop in moisture content. Furthermore, the test results of AC voltage breakdowns indicated that the value of the MO mixed with Al_2O_3 was higher than that of the original MO, especially when the Al_2O_3 concentration increases at 0.01, 0.03 and 0.05 % of the volume of MO, the AC breakdown voltage increases are 55.60, 57.83 and 94.61 kV respectively. Besides, the test results of positive polarity lightning impulse voltage demonstrated that with a mixture of MO and the Al_2O_3 NPs at a 0.01 % concentration, the positive polarity lightning impulse dielectric strength of the MO increased. However, at the Al_2O_3 concentrations of 0.03 and 0.05 %, it did not rise, regardless of the increasing volume of NPs. Meanwhile, it was found that the negative polarity lightning impulse voltage that was mixed with the MO and with the Al_2O_3 NPs at all concentrations had a higher dielectric strength than the original MO.

Acknowledgements

The authors gratefully acknowledge the support by the Faculty of Engineering, Rajamangala University of Technology Isan, Khon Kaen Campus, Thailand.

References

[1] M Pichai and P Norasage. Dielectric breakdown strength of mineral oil based nanofluids. *In*: Proceedings of the International Conference on Condition Monitoring and Diagnosis, Xi'an, China. 2016, p. 261-4.

[2] CL Jong and YK Woo. Experimental study on the dielectric breakdown voltage of the insulating oil mixed with magnetic nanoparticles. *Phys. Proc.* 2012; **32**: 327-34.

[3] R Liu, LAA Petterson, T Auletta and O Hjortstam. Fundamental research on the application of nano dielectrics to transformers. *In:* Proceeding of the 2011 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, Cancun, Mexico. 2011, p. 423-7.

[4] M Rafiq, Y Lv and C Li. A review on properties, opportunities, and challenges of transformer oil-based nanofluids. *J. Nanomater.* 2016; **2016**, 8371560.
[5] N Pattanadech. 2013, Partial discharge inception voltage characteristics of mineral oil. Ph. D. Dissertation. Graz University of Technology, Graz, Austria.
[6] H Jin. 2015, Dielectric strength and thermal conductivity of mineral oil based nanofluids. Ph.D. Dissertation. Delft University of Technology, Amsterdam, the Netherlands.
[7] SC Pugazhendhi. Experimental evaluation on dielectric and thermal characteristics of nano filler added transformer oil. *In*: Proceedings of the International Conference on High Voltage Engineering and Application, Shanghai, China. 2012, p. 207-10.
[8] DA Mansour, EG Atiya, RM Khattab and AM Azmy. Effect of titania nanoparticles on the dielectric properties of transformer oil-based nanofluids. *In*: Proceedings of the 2012 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, Montreal QC, Canada. 2012, p. 295-8.
[9] M Nazari, MH Rasoulifard and H Hosseini. Dielectric breakdown strength of magnetic nanofluid based on insulation oil after impulse test. *J. Magn. Magn. Mater.* 2016; **399**: 1-4.
[10] Y Du, Y Lv, C Li, M Chen, Y Zhong, J Zhou, X Li, Y Zhou. 2012. Effect of semiconductive nanoparticles on insulating performances of transformer oil. *IEEE Trans. Dielectr. Electr. Insul.* 2012; **19**, 770-6.
[11] Y Lv, W Wang, K Ma, S Zhang, Y Zhou, C Li and Q Wang. Nanoparticle effect on dielectric breakdown strength of transformer oil-based nanofluids. *In*: Proceedings of the 2013 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, Chenzhen, China. 2013, p. 680-2.
[12] SK Das, SU Choi, W Yu and T Pradeep. *Nanofluids: Science and technology*. John Wiley & Sons, New Jersey, 2007.
[13] SUS Choi and JA Eastman. Enhancing thermal conductivity of fluids with nanoparticles. *In*: Proceedings of the 1995 International Mechanical Engineering Congress and Exhibition, San Francisco, CA. 1995, p. 99-105.
[14] V Segal, K Linsley, A Hjortsberg and A Rabinovich. AC (60 Hz) and impulse breakdown strength of a colloidal fluid based on transformer oil and magnetite nanoparticles. *In*: Proceedings of the 1998 IEEE International Symposium on Electrical Insulation, Arlington VA, USA. 1998, p. 619-22.
[15] H Jin, T Andritsch, IA Tsekmes, R Kochetov, PHF Morshuis and JJ Smit. Properties of mineral oil based silica nanofluids. *IEEE Trans. Dielectr. Electr. Insul.* 2014; **21**, 1100-8.
[16] A Cavallini, R Karthik and F Negri. The effect of magnetite, graphene oxide and silicone oxide nanoparticles on dielectric withstand characteristics of mineral oil. *IEEE Trans. Dielectr. Electr. Insul.* 2005; **22**, 2592-600.
[17] DEA Mansour, AM Elsaeed and MA Izzularab. The role of interfacial zone in dielectric properties of transformer oil-based nanofluids. *IEEE Trans. Dielectr. Electr. Insul.* 2016; **23**, 3364-72.
[18] M Rafiq, Y Lv and C Li. Effect of shape, surface modification and concentration of Al_2O_3 nanoparticles on breakdown performance of transformer oil. *J. Electr. Eng. Tech.* 2019; **15**, 457-68.
[19] Q Wang, M Rafiq, Y Lv, C Li and K Yi. Preparation of three types of transformer oil-based nanofluids and comparative study on the effect of nanoparticle concentrations on insulating property of transformer oil. *J. Nanotechnol*. 2016; **2016**, 5802753.
[20] JA Mergos, MD Athanassopoulou, TG Argyropoulos and CT Dervos. 2012. Dielectric properties of nanopowder dispersions in paraffin oil. *IEEE Trans. Dielectr. Electr. Insul.* 2012; **19**, 1502-7.
[21] F Herchl, K Marton, L Tomčo, P Kopčanský, M Timko, M Koneracká and I Kolcunová. Breakdown and partial discharges in magnetic liquids. *J. Phys. Condens. Matter*. 2008; **20**, 204110.
[22] Inframat Advanced Materials LLC, Availble at: http://www.advancedmaterials.us/26N-0802A.htm, accessed May 2020.
[23] ASTM D1533. *Standard test method for water in insulating liquids by coulometric Karl Fischer titration.* ASTM International, 2013.
[24] IEC 60156. *Insulating liquids determination of the breakdown voltage at power frequency test method*. 2nd ed. International Standard, 1995.
[25] IEC 60897. *Methods for the determination of the lightning impulse breakdown voltage of insulating liquids.* 1st ed. International Electrotechnical Commission, 1987.
[26] G Smith. *Essential statistics, regression, and econometrics*. Academic Press, USA, 2012.
[27] P Muangpratoom and N Pattanadech. Dielectric properties of mineral oil-based nanofluids under temperature variations. *IET Sci. Meas. Tech.* 2019; **13**, 1318-25.