Review Article

Electrical Characteristics of Nanofluid based Transformer Oil: A Review

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Abstract:

The mineral oil or synthetic oil is mainly being used as an insulating and heat transfer medium in conjunction with paper for the high voltage apparatuses. The incessant growth of high voltage network has provoked the researchers to draw their attention on to propose new insulation system which can abide the intensifying levels of high voltage to make electrical transmission and distribution network more efficient and reliable. The transformer oil modified by nanomaterials has the potential to overcome the limitation of mineral oil based products available at present due to superior insulating and thermal properties. This paper presents the comprehensive review in the area of nanofluids which addresses its electrical properties such as AC/DC/impulse breakdown strength, partial discharge characteristic and other critical properties.

Keywords: Transformer, Mineral oil, Nanofluid, Nanoparticle, Electrical Properties.

INTRODUCTION

The expansion of forthcoming high voltage network and smart grid has upraised the desires on reliability and performance of insulating materials used in electrical power system to deal with more vigorous and volatile operating conditions. Power transformers, the most important electric apparatus for providing the reliable energy flow are critical and costly assets in electric power system beginning with the grid, transmission, and down to the plant. As an asset class, transformers constitute one of the largest investments in a utility's system or in an industrial complex [1]. The political and media attention has remarkably addressed the surrounding blackouts at various locations around the world was due to the potential consequences of transformer failure [2]. The functioning consistency and lifespan of transformers predominantly rely on characteristics and grade of dielectric material [3].

One of the potential issues with existing liquid-solid insulation system in power transformer that limits the compactness in design of a transformer is the incompatibility in permittivities between them. Because of inferior properties of liquid insulation, it was stressed much more than the solids at ac and/or impulse voltages which might results in explosive operation of transformers. [4]. Apart from the key functions such as protecting solid insulation, arc quenching media and dissipating heat, liquid insulations can also act as acoustic dampening media in transformers [5]. So, to survive with the increasing demand of high voltage rate with compact design for transformers, the advancement of transformer oil with promising dielectric and thermal characteristics is extensively required [3].

After the first conceptual introduction of nanotechnology, the Nano dielectrics gained the notable devotion in improving the service life of insulations. Nowadays in dielectric society, the term nanofluid becomes renowned and prominent term that brings the challenges and opportunities to the investigators over the past decades. The terms “nanofluids” and “nano-liquids” are used mutually to refer to transformer oil/nanoparticle combination for insulating and cooling interest [3]. Nano structured particles dispersed homogeneously within the liquid with a few concentration forms the nanofluid. The term 'nanofluids – a two-phase mixture' was introduced by researchers at the Argonne National Laboratory containing a matrix liquid, and dispersed nanoparticles in suspension [6].

In recent years, nanofluids have concerned more attention because of their outstanding and exceptional characteristics [3]. Majority of the review articles are published based on the thermal properties of nanofluids [6-10]. Only a few of the researchers till date have examined the electrical properties. This review provides insight of electrical characteristics of transformer oil-based nanofluids examined by the researchers.

MANUFACTURING OF NANOFLUIDS

Nanoparticles

One of the most significant concerns in preparation of the nanofluid is the selection of the nanoparticle. With the aim of enhancing the dielectric properties of liquid insulations, several nanoparticle additives have been examined till date [11-41]. According to the conductivity and permittivity, these additives can be categorized into three major groups:

- Conducting Nanoparticles: Fe_3O_4, Fe_2O_3, ZnO, SiC
- Semiconducting Nanoparticles: TiO_2, CuO, Cu_2O, CdS
- Insulating Nanoparticles: Al_2O_3, SiO_2, BN

Dispersion processes of Nanofluids

One of the priliminary task is the preparation of the sample to make it ready for the experimentaion once the nanoparicle is selected. Ideally, the methods of dispersion can be classified as one-step or two-step methods.

One step Method: In this technique, the nanoparticles are dispersed traditionally into a host fluid all together to avoid drying, storage and transmission of nanoparticles to minimize the chances of agglomeration with enhanced stability [3, 11]. One of the key weaknesses of this procedure is the formation of clusters during mass production. The difficulty of grouping can be squeezed by using evaporation-condensation method.

Two-step Method: The extensively used technique for formulating the nanofluids is two-step method. In first step of formulation, the particles, tubes, fibers or any other non-metals of nano scale are primarily fashioned as dry powders via physical and chemical processes. In second step, these powders will be spread in the carrier fluid by magnetic stirrer or ultrasonic bath to get stable dispersion. Nonetheless, grouping of nanoparticles occurs during both the stages due to massive surface area and the large surface activity of the nanoparticles [3, 11]. The inert gas condensation process is used for mass production of nanoparticles which makes this technique more expensive to generate nanofluids in a big scale.

ELECTRICAL PROPERTIES OF NANOFLUIDS

The quality of high voltage electrical equipment mainly governs by the superiority of the insulating materials. Because of excellent electrical and physical properties, mineral oils are the most preferred coolant and insulators in transformers. In present days research, major focus rests on enhancing electrical characteristics of liquids without compromising its cooling and anti–corrosion properties, an avenue where seeding with dielectric nanostructures has emerged as a potential solution. This section deliberates the results gained by the different researchers.

AC Breakdown Strength

AC breakdown voltage is the most essential and significant perquisite for the insulation liquid which governs the harmless operation of transformers which are cooled by such liquids [3]. Generally, a numerous procedures suggested by the standards are employed to test the dielectric strength of the insulating liquid by exposing them to almost homogenous electric filed [3]. The AC breakdown strength essentially concludes the quality of the oil rather than its property.

The presence of the impurities and chemical agents dissolved for achieving superior properties significantly influences the dielectric strength of the insulating liquid [3]. Consequently, in modern times, researchers have started looking for substitutes to such chemical flavours in the form of nanostructures. The following section discusses the results of AC breakdown voltage investigated by the researchers by considering the above mentioned influential parameters. Table 1 shows the enhancement reported by different researchers.

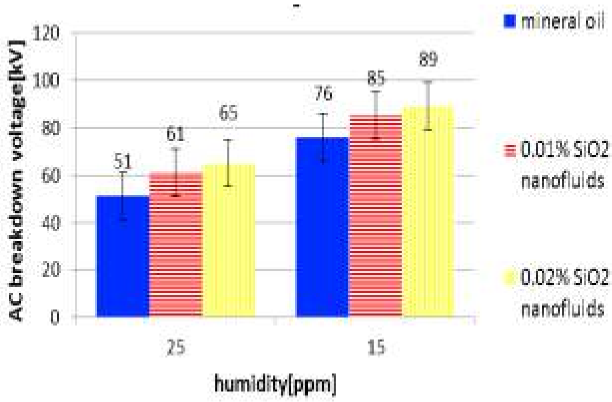
AC breakdown strength of SiO_2 based mineral oil was investigated by the group of Jin et al. [15] at two different moisture levels with the concentrations of 0.01% and 0.02% of silica nanofluid (Fig. 1).

The results demonstrated that at relatively high moisture content, a silica nanoparticle improves the AC breakdown strength of mineral oil at low probability of breakdown. The authors credited this

Table 1. Transformer-oil based Nanofluidsv

Nanoparticle /Oil	Avg. Particle size (nm)	Nanoparticle Loading (%)	% increase in BD Strength	Ref
TiO_2/MO	20	0.6	13 (AC)	12
Al_2O_3/MO	20	5	90.5 (AC)	12
CuO/MO	500	0.1	46.87 (AC)	13
Fe_3O_4/MO	20	0.1	120 (DC)	14
	20	0.1	100 (AC)	
BN/MO	50	0.1	100 (DC)	14
	50	0.1	80 (AC)	

Fig. 1. Average AC BDV of mineral oil, 0.01% and 0.02% silica [15]

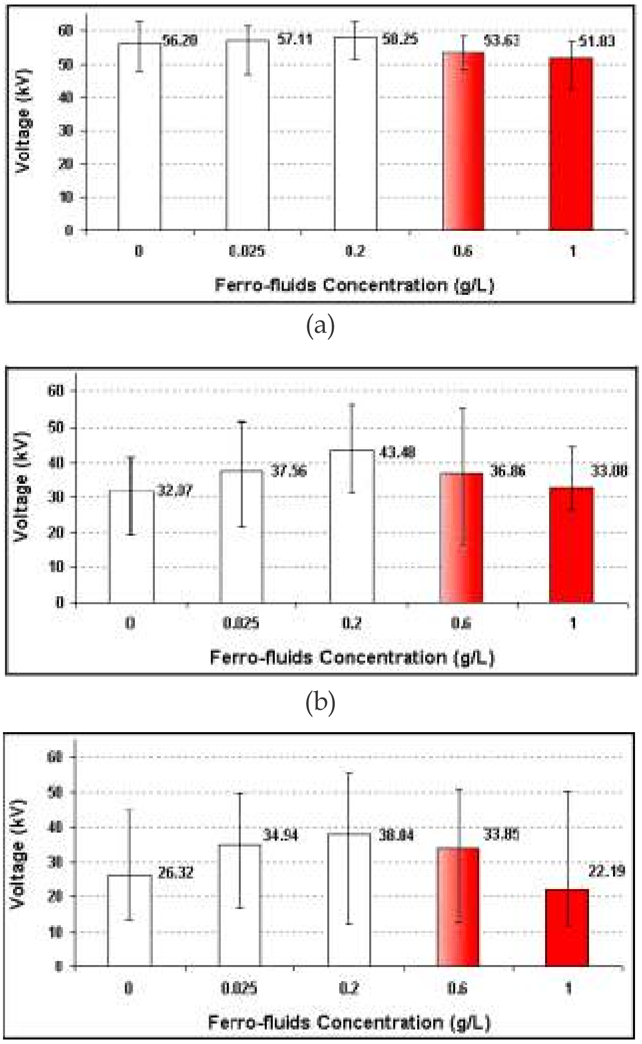


enhancement by offering that the surface of SiO_2 is hydrophilic, so it binds the water dispersed in oil on its surface and hence shows less impact on dielectric strength.

Irwanto et al. [16] have measured the dielectric strength of mineral oil and ferrofluid at different moisture level. They observed remarkable improvement in breakdown voltage with increasing the moisture level upto 0.2 g/l concentration and shows worst performance as the concentration increases (Fig. 2). They suggested that, a conductive nanoparticles acts as an electron scavengers and traps the electrons on low mobility particles and thus enhance the dielectric strength.

Lee at al. [17] have executed investigation on magnetic nanoparticle based transformer oil with volume concentration of 0.08% to 0.39% to evaluate the behaviour of breakdown voltage as shown in Fig. 3. They conclude this improvement on the platform of electron scavenging behaviour of magnetic nanoparticles which slowing down the motion of the free electrons by converting them to negative ions.

Fig. 2. BDV mean values as a function of ferrofluid concentrations at (a) 10 ppm, (b) 33 ppm and (c) 45 ppm [16]



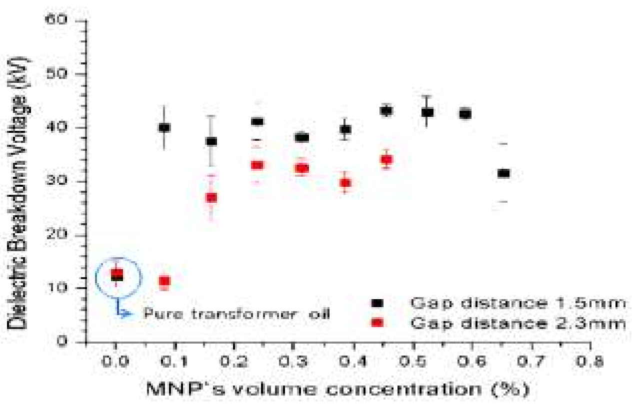
(a)

(b)

(c)

Atiya et al. [18] have prepared TiO_2 based nanofluid using cationic surfactant Cetyl Trimethyl Ammonium Bromide (CTAB). They noticed the improvement in breakdown voltage was due to the

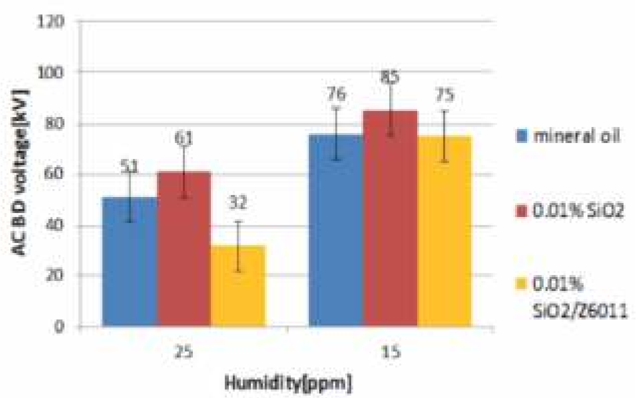
Fig. 3. Breakdown voltage with different MNP's concentration [17]



presence of suitable concentration of the surfactants which can effectively prevent the Van der Waals attraction force between the nanoparticles to stabilize them. Furthermore, the modified surface effectively influence on trapping and detrapping process of electrons.

Jin et al. [19] have studied the effect of surface treatment on breakdown voltage of silica nanoparticles. The change observed is shown in Fig. 4. Their results indicate the decrement in the AC dielectric strength of modified nanofluids as compared with the mineral oil and unmodified silica nanofluid.

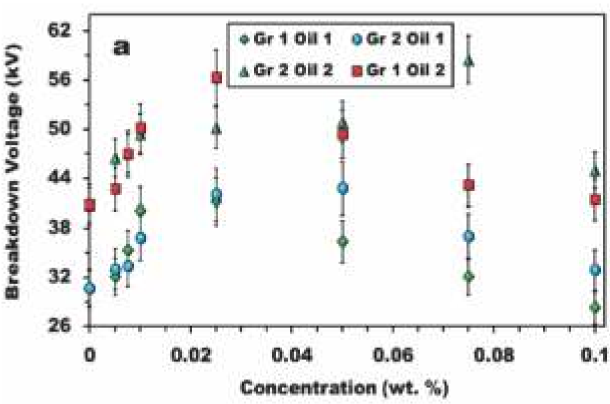
Fig. 4. AC breakdown strength of mineral oil, modified and unmodified silica nanofluids [19]



The reason in achieving the high dielectric strength by unmodified silica nanofluid was its hydrophilic surface which can bind the water particles.

Dhar et al. [20] have studied the effect of graphene and carbon nanotube on dielectric strength. The corresponding change in dielectric strength with respect to the nanoparticle types are presented in Fig. 5.

They conclude that the enhancement of the dielectric strength may occur due to: (1) the dispersed nanostructures alter the state of electrodynamics within the host oil and (2) the higher values of the electrical conductivities reduce the charge relaxation time constant.



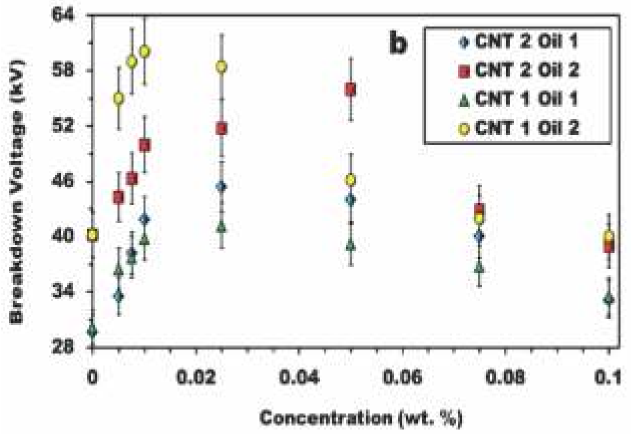


Fig. 5. Breakdown voltage of (a) Graphene & (b) CNT based nano-oils [20]

Karthik et al. [21] have examined the effect of aging on dielectric strength of silicon dioxide, tin oxide and magnetic nanofluid based transformer oil. Fig. 6 illustrates the dielectric strength of mineral oil and corresponding nanofluids.

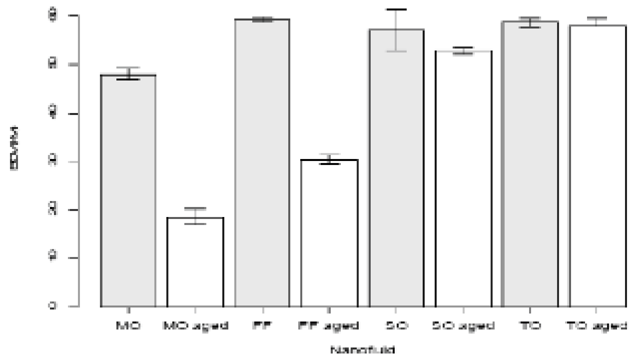


Fig. 6. Breakdown voltage of mineral oil and three different nanofluids [21]

They determined that, the breakdown voltage for the ferrofluid and mineral oil reduces with aging but the dielectric strength of insulating and semiconductive nanoparticles shows less dependency over the thermal aging.

DC Breakdown Strength

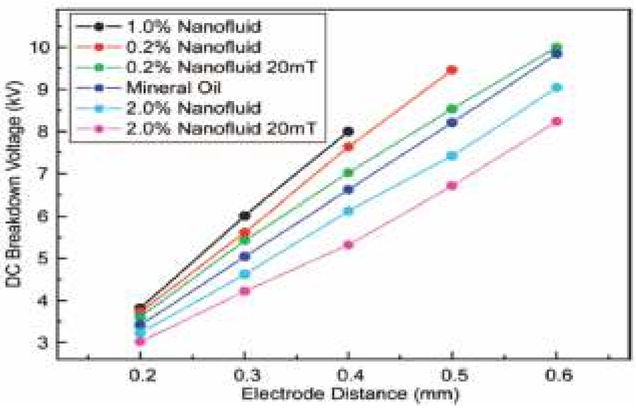
Du et al. [22] have illustrated that the addition of nanoparticles can improve 28% value of negative DC breakdown strength. However, the positive DC breakdown voltage was lower than the host oil. The results obtained are shown in Table 2.

Table 2. DC breakdown voltage of pure oil and nanofluid [22]

Samples	(+) DC Breakdown Voltage (kV)	(-) DC Breakdown Voltage (kV)
Mineral Oil	49.1	66.3
Nanofluid	45.1	84.6

Rafiq et al. [23] have observed that the trapping and detrapping nature of semiconductive nanoparticles enhances the breakdown strength of nanofluid under applied dc voltage. They observed the augmentation of dc dielectric strength of nanofluid was 1.27 times more than the host oil. Kudelcik et al. [24] have investigated the influence of summing Fe_3O_4 nanoparticles as a function of gap length (Fig. 7).

Fig. 7. DC breakdown voltage versus electrode distance at various concentrations of nanoparticles with and without magnetic field of 20 mT [11, 24]



The authors suggested that due to the formation of bubbles as a result of localized heating and the injection of field emitted electrons with and without magnetic field can reduce DC breakdown voltage at 2% concentration [24].

Impulse Breakdown Strength

Lv et al. [25] have investigated the effect of TiO_2 nanoparticles on the impulse breakdown strength. Table 3 & 4 indicates the results obtained by them for different polarities.

Table 3. Positive breakdown strength of pure oil and NF [25]

Samples	Breakdown Voltage (kV)	Time to breakdown (µs)
Mineral Oil	74.27	13.18
Nanofluid	97.16	97.16

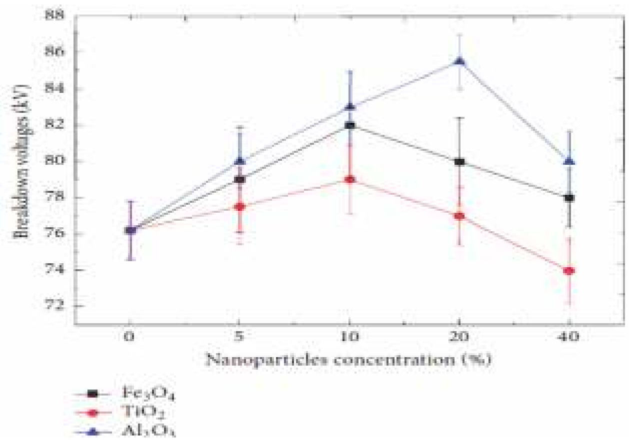
Table 4. Negative breakdown strength of pure oil and NF [25]

Samples	Breakdown Voltage (kV)	Time to breakdown (µs)
Mineral Oil	-116.42	49.58
Nanofluid	-108.46	11.39

They have noticed that the breakdown voltage and time to breakdown for nanofluid was raised by 30.8% and 94.6% with positive polarity respectively. On contradictory, both the parameters reduced by 6.8% and 77% with negative polarity. They conclude that the presence of semiconductive nanofluids alters the streamer propagation characteristics.

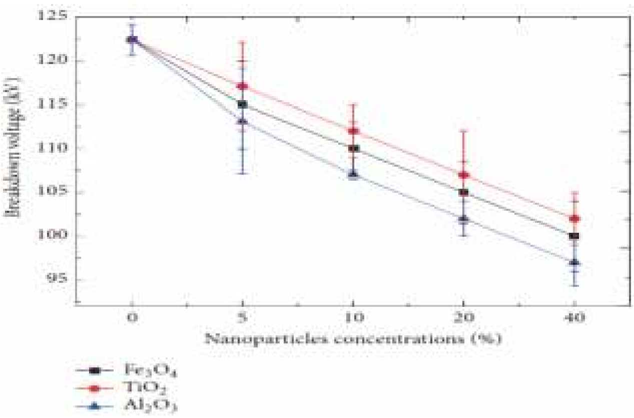
Wang et al. [26] have deliberated the effect of three types of nanoparticles on impulse breakdown strength at different concentrations. The results obtained by them are shown in Figs. 8 and 9.

Fig. 8. Positive impulse breakdown voltage of different nanofluids [26]



They have observed that the dielectric strength improves due to the alteration of space charge activity until the critical value of concentration is achieved. The agglomeration will be the reason for reduction observed in breakdown voltage at higher concentrations.

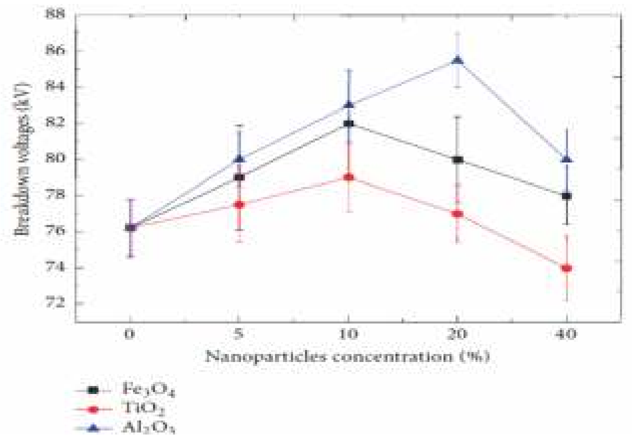
Fig. 9. Negative impulse breakdown voltage of different nanofluids [26]



Partial Discharge Characteristics

Partial discharge inception voltage characteristics before and after aging of mineral oil and corresponding nanofluids were studied by Karthik et al. [21]. The results obtained for mineral oil and nanofluids are shown in Fig. 10 (a) and (b) respectively.

Fig. 10. PDIV for mineral oil and nanofluids at (a) Fresh condition and (b) aged condition [21]



They have analyzed that before aging the ferrofluids does not modify the PDIV significantly as compared to tin oxide and SiO_2 based nanofluids. For both AC and DC voltages, silicone dioxide based nanofluids shows the improvement. Additionally, aged SiO_2 shows the better response as compared to aged mineral oil and rest of the nanofluids. They claimed that, the enhancement shown by silicon dioxide based nanofluid is due to its hydrophilic property.

Jin et al. [27] have studied the partial discharge behaviour of fullerene and silica based nanofluid with a volume fraction of 0.01%. They have observed 20% enhancement in PD inception voltage of silica nanofluid as compared o mineral oil under (+) ve DC voltage. The reduction in discharge magnitudes for silica and fullerene nanofluids was 63% and 33% respectively. They proposed that the reaction of the nanoparticle's surface with acid in mineral oil leads less effect on partial discharge behavior.

Critical Parameters

Critical characteristics include the electrical conductivity, permittivity, dissipation factor, resistivity, flash point and fire point. Several researchers have contributed to identify the effect of nanoparticles on such unavoidable parameters. Abd-Elhady et al. [28] have investigated the influence of semiconductive Cadmium sulfide (CdS) quantum dots on relative permittivity and dissipation factor by preparing the fluid at various concentrations. The obtained results are shown in Fig. 11 and Fig. 12.

They observed the slight increment in dielectric constant of nanofluid was because of the contribution to the net amount of dipoles in mineral oil. Regarding to the dissipation factor, enhancement occurred at small concentrations due to rise in real part of permittivity but it shows bad results at higher concentrations because of increase in imaginary part of permittivity due to increase in conductivity.

Fig. 11. Relative permittivity of host oil [28]

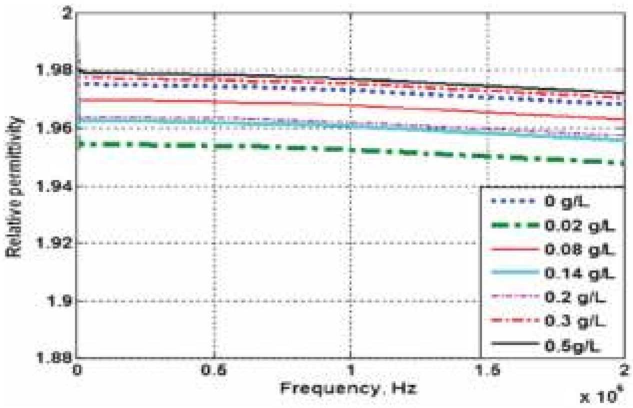
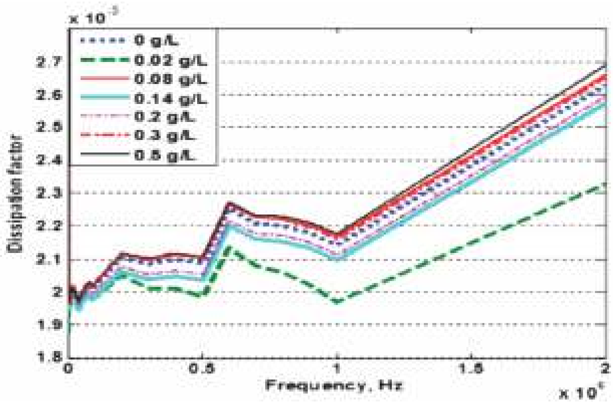
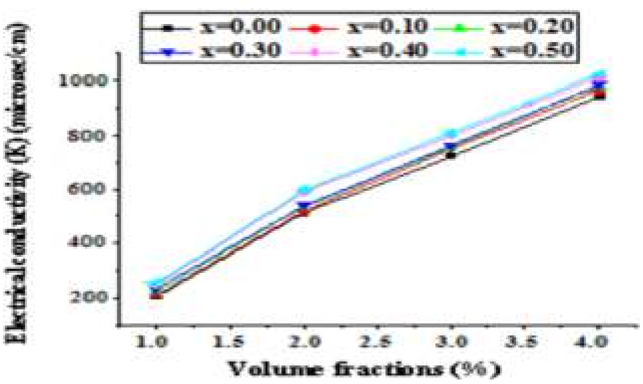


Fig. 12. Dissipation factor of host fluid [28]



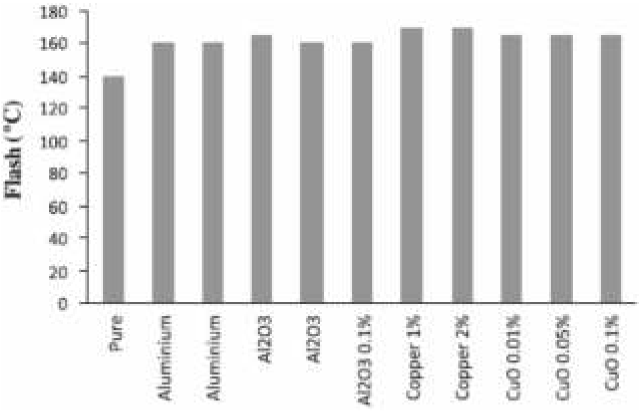
Chitra et al. [29] have carried out the research on MgMnNi/transformer oil based nanofluid and observed the performance of electrical conductivity with respect to different volume fraction of nanoparticles. The dependence of electrical conductivity and volume fractions is shown in Fig. 13. They have observed the linear increase in electrical conductivity with increase in concentrations.

Fig. 13. Electrical conductivity values for $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ ($0.00 \le x \le 0.60$) nanofluid at different volume fractions [29]



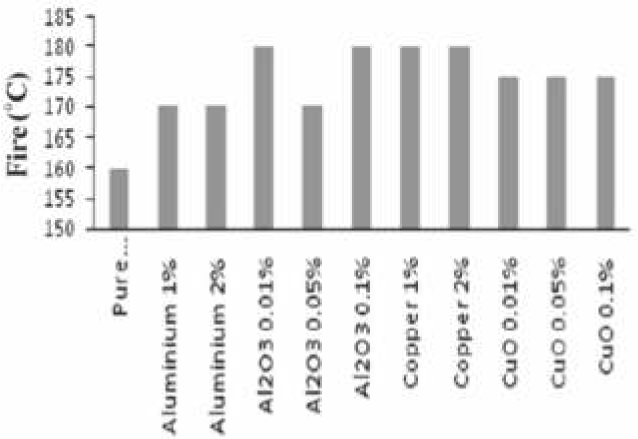
Karthik et al. [13] have also investigated the influence of nanoparticles on flash point and fire point. The results are shown in Figs. 14 and 15.

Fig. 14. Flash point of different nanofluids [13]



They have observed that the copper based nanofluid shows excellent improvement than the other types of nanofluids.

Fig. 15. Fire point of different nanofluids [13]

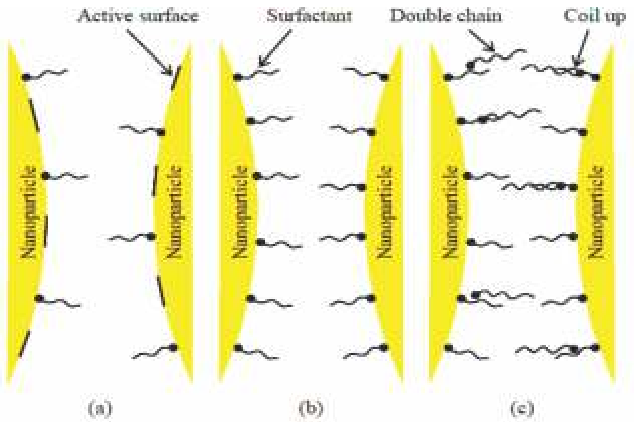


MODIFICATION MECHANISMS

The mechanisms by which the nanoparticles can affect the electrical properties of host oil are still not fully revealed [3]. Atiya et al. [18] have proposed a double layer model to validate the augmentation of the dielectric properties of nanofluids modified by surfactant. The surfactant plays a vital role in the stabilization of nanoparticles through two different mechanisms: (1) Steric stabilization and (2) Electrostatic stabilization. Steric stabilization is attained by capping the active surface of nanoparticles with surfactant to the degree that reduces surface activity and prevents agglomeration. Fig. 16 shows the steric stabilization and role of surfactant.

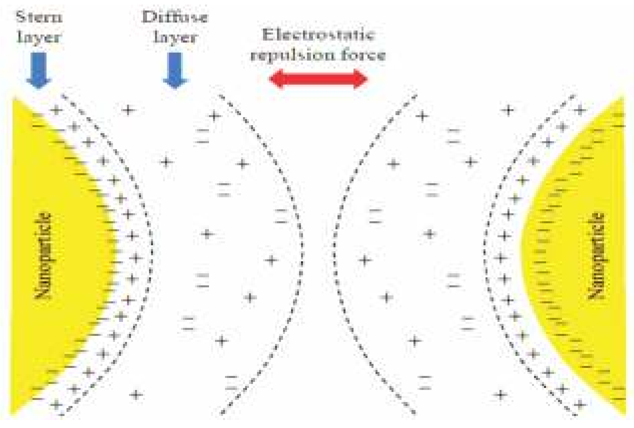
The surface coverage of nanoparticles by adsorption is low and not sufficient to fully cap the active surface of nanoparticles at no surfactant or low surfactant concentration. So, agglomeration of nanoparticles occurs. On the other hand, with excess amount of surfactant, adsorption sites on nanoparticle surface will be rare. Hence, surfactant will form a double chain around the surface of nanoparticles, resulting in a reverse effect.

Fig. 16. Steric stabilization and role of surfactant: (a) low coverage, (b) Full coverage and (c) Excess amount of surfactant [18]



The electrostatic stabilization is achieved by charging the particles with the same polarity as shown in Fig. 17. In this model the charges are counter balanced by a layer of oppositely charged ions, called counter ions or co-ions. The co-ions exist in two distinct layers.

Fig. 17. Electrostatic stabilization and double layer model [18]



The inner layer stuck to the nanoparticle surface and is called stern layer which is characterized by high concentration of co-ions. The other layer extends from the stern layer to the zero charging region of the oil and is called the diffuse layer.

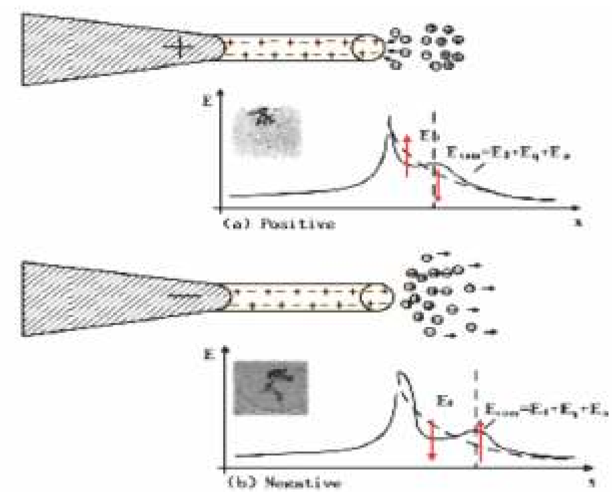
According to Derjaguin-Landau-Verwey-Overbeek (DLVO) theory [32, 18], the total interaction between two nanoparticles is the mixture of van der

Waals attraction force and electrostatic repulsion force. When nanoparticles are separated by a distance larger than the combined thickness of their electric double layers, there would be no interaction between the nanoparticles. The repulsion takes place when the nanoparticles moves closer and overlaps the double layer. Stabilization is maintained when the repulsion force becomes equal or exceeds van der Waals attraction force otherwise agglomeration occurs. The addition of surfactant will increases the number of co-ions and hence increases in electrostatic repulsion force which in turn enhance the dielectric property of nanofluid.

Lv et al. [25] have proposed a mechanism to explain the significant change occurred in the streamer propagation due to change in space charge distribution when TiO_2 nanoparticles were dispersed in transformer oil.

The presence of TiO_2 nanoparticles increases the shallow trap density in nanofluid which reduces the ionization probability by the trapping and de-trapping charge transportation in oil. The superposition of space charge field created by these negative ions modifies the electric field at the streamer tip and towards ground electrode.

Fig. 18. The electric field distribution in nanofluid [25]



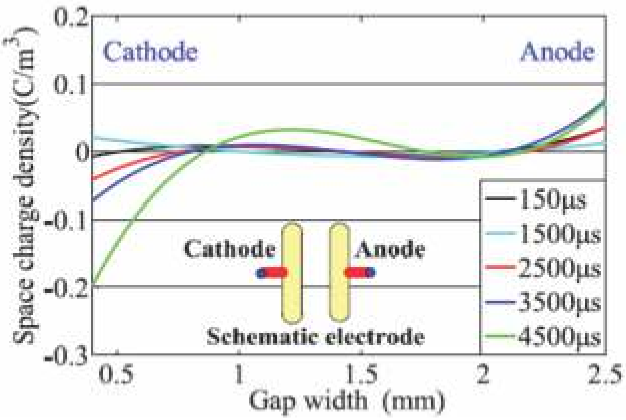
For positive polarity (Fig. 18 (a)), the electric field at the streamer tip is enhanced while at ground electrode it is weakened. Thus, it is tough for positive streamers in nanofluid to expand which results in increase in positive breakdown voltage. Contradictory, for negative polarity (Fig. 18 (b)), the electric field at the negative streamer tip is weakened as compared to ground electrode. As an effect, the streamers will propagate to the ground electrode at high velocity.

Abd-Elhady et al. [28] have proposed that the quantum dots of smaller size can increases the surface area and allow more trapping to the electrons which helps in improvement of dielectric properties. Bin et al. [30] have explained that the presence of appropriate content of surfactant can improve the morphology of nanoparticles and hinder the physical agglomeration of them.

Yang et al. [31] have projected a model based on space charge inhibition on improvement of breakdown voltage. Fig. 19 shows the space charge distribution characteristics in modified transformer oil.

They explained that the adsorption of free charge by nanoparticles can improve the dielectric strength by (1) hindering movement of electrons, (2) blocking charge injection from the electrodes in transformer oil, (3) lowering the space charge density and (4) augmenting the uniformity of the electric field.

Fig. 19. Space charge density in modified transformer oil [31]



Most of the researchers have also proposed the enhancement in dielectric properties based on the relaxation time constant and polarization characteristics [26].

CONCLUSION

Emerging nanofluid research brings the ample opportunities to the researchers in developing the nanoparticle based high voltage electrical insulation fluids with superior properties as compared to existing mineral oils. This paper gives the glimps of the research carried out in past years over the augmentaion in electrical characteristics of transformer oil-based nanofluids. Although many significant features related to nanofluids have been reported, there are many facts still need to be revealed. In this article, an effort was made to demonstrate how nanoparticles can affect the electrical properties of nanofluids. In-depth experimentation and multidisciplinarly research is required for better understanding of mechanisms and behavior of nanofluids to resolve the prevailing chanllenges.

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REFERENCES

[1] Paul G. Gill (1998) '*Electrical Power Equipment Maintenance and Testing*', 2nd edition, CRC Press.

[2] M. Chiesa and Sarit K. Das (2009) 'Experimental investigation of dielectric and cooling performance of colloidal suspensions in insulating media', Colloids and Surfaces A: Physicochemical and Engineering Aspects [Electronic], Vol. 335, Issue 1-3, pp. 88-97, Available: Elsevier/ScienceDirect/ j.colsurfa.2008.10.044, [5 March, 2009].

[3] Muhammad Rafiq, Yuzhen Lv and Chengrong Li (2016) 'A Review on Properties, Opportunities, and Challenges of Transformer Oil-Based Nanofluids', *Journal of Nanomaterials*, Vol. 2016, May 2016, pp. 1-23.

[4] Rongsheng Liu, Leif A.A. Pettersson, Tommaso Auletta and Olof Hjortstam (2011) 'Fundamental Research on the Application of Nano Dielectrics to Transformers', *IEEE Annual report Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, pp. 423-427.

[5] I Fofana (2013) '50 Years in the Development of Insulating Liquids', *IEEE Insulation Magazine*, Vol. 29, September/October 2013, pp. 13-25.

[6] Mandeep Singh and Lal Kundan (2013) 'Experimental study on Thermal Conductivity and Viscosity of Al_2O_3-Nanotransformer Oil', *International Journal on Theoretical and Applied Research in Mechanical Engineering (IJTARME)*, Vol. 2, pp. 125-130.

[7] Dan Li, Wenjie Xie and Wenjun Fang (2011) 'Preparation and properties of copper-oil-based nanofluids', *Nanoscale Research Letter* [Electronic], Spriger/ 1556-276X-6-373, [5 May, 2011].

[8] H. Jin, T. Andritsch, I. A. Tsekmes, R. Kochetov, P.H.F. Morshuis and J.J. Smit (2013) 'Thermal Conductivity of Fullerene and TiO_2 Nanofluids', *IEEE Annual report Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, pp. 711-714.

[9] Haibin Cheng, Pan Zhang, Qingjie Zhang, Jianfeng Wu, Yawen Dai, Wei Hu, and Norman M. Wereley (2014) 'Effects of Surface Modification on the Stability of Suspension and Thermal Conductivity Enhancement of Composite Fe Nanofluids', *IEEE Transactions on Magnetics*, Vol. 50, November 2014.

[10] B. X. Du, X. L. Li and M. Xiao (2015) 'High Thermal Conductivity Transformer Oil Filled with BN Nanoparticles', *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 22, April 2015, pp. 851-858.

[11] Y. Z. Lv, Y. Zhou, C. R. Li, Q. Wang and B. Qi (2014) 'Recent Progress in Nanofluids Based on Transformer Oil: Preparation and Electrical Insulation Properties', *IEEE Insulation Magazine*, Vol. 30, September/October 2014, pp. 23-32.

[12] Yu-zhen Lv, Le-feng Wang, Xiao-xin Li, Yue-fan Du, Jian-quan Zhou, Cheng-rong Li (2011) 'Experimental Investigation of Breakdown Strength of Mineral Oil-based Nanofluids', *IEEE International Conference on Dielectric Liquids*, SINTEF Energy Research and Norwegian University of Science and Technology, Norway, pp. 1-3.

[13] R. Karthik, T. Sree Renga Raja and R. Madavan (2013) 'Enhancement of Critical Characteristics of Transformer Oil Using Nanomaterials', *Arabian Journal of Science and Engineering*, Vol. 38, October 2013, pp. 2725-2733.

[14] B. X. Du, X. L. Li and J. Li (2015) 'Thermal Conductivity and Dielectric Characteristics of Transformer Oil Filled with BN and Fe_3O_4 Nanoparticles', *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 22, October 2015, pp. 2530-2536.

[15] Huifei Jin, Thomas Andritsch, Ioannis A. Tsekmes, Roman Kochetov, Peter H.F. Morshuis and Johan J. Smit (2014) 'Properties of Mineral Oil based Silica Nanofluids', *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 21, June 2014, pp. 1100-1108.

[16] rwanto, C. G. Azcarraga, Suwarno, A. Cavallini and F. Negri (2014) 'Ferrofluid Effect in Mineral Oil: PDIV, Streamer, and Breakdown Voltage', *International Conference on High Voltage Engineering and Application (ICHVE)*, Mississippi State University-USA, Poznan University of Technology-Poland and Chongqing University-China, pp. 1-4.

[17] Jong-Chul Lee and Woo-Young Kim (2010) 'Experimental study on the dielectric breakdown voltage of the insulating oil mixed with magnetic nanoparticles', *18th International Vacuum Congress*, Beijing, pp. 327-334.

[18] Eman G. Atiya, Diaa-Eldin A. Mansour, Reham M. Khattab and Ahmed M. Azmy (2015) 'Dispersion Behavior and Breakdown Strength of Transformer Oil Filled with TiO_2 Nanoparticles', *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 22, October 2015, pp. 2463-2472.

[19] Huifei Jin, Peter H.F. Morshuis, Johan J. Smit and Thomas Andritsch (2014) 'The effect of surface treatment of silica nanoparticles on the breakdown strength of mineral oil', *International Conference on Liquid Dielectrics*, Slovenia, pp. 1-4.

[20] Purbarun Dhar, Ajay Katiyar, Lakshmi Sirisha Maganti, Arvind Pattamatta and Sarit K Das (2016) 'Superior Dielectric Breakdown Strength of Graphene and Carbon Nanotube Infused Nano–oils', *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 23, April 2016, pp. 943-956.

[21] R.Karthik, F. Negri and A. Cavallini (2016) 'Influence of Ageing on Dielectric characteristics of silicone di oxide, tin oxide and ferro nanofluids based mineral oil', *2nd International Conference on Advances in Electrical, Electronics, Information, Communication and Bio-Informatics (AEEICB16)*, Prathyusha Institute of Technology and Management, Tamilnadu, pp. 40-43.

[22] Yuefan Du, Yuzhen Lv, Chengrong Li, Mutian Chen, Yuxiang Zhong, Jianquan Zhou, Xiaoxin Li and You Zhou (2012) 'Effect of Semiconductive Nanoparticles on Insulating Performances of Transformer Oil', *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 19, June 2012, pp. 770-776.

[23] Muhammad Rafiq, Wei Wang, Kaibo Ma, You Zhou, Qi Wang, Chengrong Li and Yuzhen Lv (2014) 'Insulating and Aging Properties of Transformer Oil-Based TiO_2 Nanofluids', *IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, IEEE Dielectrics and Electrical Insulation Society, USA, pp. 457-461.

[24]J. Kudelcik, P. Bury, P. Kopcansky and M. Timko (2010) 'Dielectric breakdown in mineral oil ITO 100 based magnetic fluid', *12th International Conference on Magnetic Fluids*, Japan, pp. 78-81.

[25] Yuzhen Lv, Yang Ge, Chengrong Li, Qi Wang, You Zhou, Bo Qi, Kai Yi, Xin Chen and Jinsha Yuan (2016) 'Effect of TiO_2 Nanoparticles on Streamer Propagation in Transformer Oil under Lightning Impulse Voltage', *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 23, August 2016, pp. 2110-2115.

[26] Qi Wang, Muhammad Rafiq, Yuzhen Lv, Chengrong Li and Kai Yi (2016) 'Preparation of Three Types of Transformer Oil-Based Nanofluids and Comparative Study on the Effect of Nanoparticle Concentrations on Insulating Property of Transformer Oil', *Journal of Nanotechnology*, Vol. 2016, pp. 1-6.

[27] Huifei Jin, Peter Morshuis, Armando Rodrigo Mor and Johan J. Smit (2015) 'Partial Discharge Behavior of Mineral Oil based Nanofluids', *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 22, October 2015, pp. 2747-2753.

[28] Amr M. Abd-Elhady, Mohamed E. Ibrahim, T.A. Taha and Mohamed A. Izzularab (2016) 'Dielectric and Thermal Properties of Transformer Oil Modified by Semiconductive CdS Quantum Dots', *Journal of Electronic Materials*, Vol. 45, October 2016, pp. 4755-4761.

[29] Subbiah Rammohan Chitra and Sechasalom Sendhilnathan (2016) 'Experimental Investigations on Dielectric fluids Behavior in High-power Transformers', *International Journal of Applied Ceramic Technology*, Vol. 13, August 2016, pp. 1096-1103.

[30] Bin Du, Jian Li, Bai-Mei Wang and Zhao-Tao Zhang (2012) 'Preparation and Breakdown Strength of Fe_3O_4 Nanofluid Based on Transformer Oil', *International Conference on High Voltage Engineering and Application (ICHVE)*, China, pp. 311-313.

[31] Qing Yang, Fei Yu, Wenxia Sima and Markus Zahn (2015) 'Space charge inhibition effect of nano-Fe_3O_4 on improvement of impulse breakdown voltage of transformer oil based on improved Kerr optic measurements', *AIP Advances*, Vol. 5, September 2015, pp. 097207-1-097207-8.

[32] N. Ise and I. S. Sogami (2005) '*Structure formation in solution: ionic polymers and colloidal particles*', Springer-Verlag, 2005.

[33] John A. Mergos, Maria D. Athanassopoulou, Theodore G. Argyropoulos and Constantine T. Dervos (2012) 'Dielectric Properties of Nanopowder Dispersions in Paraffin Oil', *IEEE*

Transactions on Dielectrics and Electrical Insulation, Vol. 19, October 2012, pp. 1502-1507.

[34] Jian Li, Zhaotao Zhang, Ping Zou and Stanislaw Grzybowski (2012) 'Preparation of a Vegetable Oil-Based Nanofluid and Investigation of Its Breakdown and Dielectric Properties', *IEEE Insulation Magazine*, Vol. 28, September/October 2012, pp. 43-50.

[35] Lucian Pîslaru-Dănescu , Alexandru M. Morega, Gabriela Telipan , Mihaela Morega, Jean Bogdan Dumitru and Virgil Marinescu (2013) 'Magnetic Nanofluid Applications in Electrical Engineering' *IEEE Transactions on Magnetics*, Vol. 49, November 2013, pp. 5389-5497.

[36] Yuzhen Lv, Wei Wang, Kaibo Ma, Shengnan Zhang , You Zhou, Chengrong Li, Qi Wang (2013) 'Nanoparticle Effect on Dielectric Breakdown Strength of Transformer Oil-Based Nanofluids', *IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, IEEE Dielectrics and Electrical Insulation Society, China, pp. 680-682.

[37] Huifei Jin, Peter H.F. Morshuis, Armando Rodrigo Mor and Thomas Andritsch (2014) 'An investigation into the dynamics of partial discharge propagation in mineral oil based nanofluids', *IEEE International Conference on Liquid Dielectrics*, Slovenia, pp. 1-4.

[38] Wenxia Sima, Jian Shi, Qing Yang, Sisi Huang and Xuefei Cao (2015) 'Effects of Conductivity and Permittivity of Nanoparticle on Transformer Oil Insulation Performance: Experiment and Theory', *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 22, February 2015, pp. 380-390.

[39] Raja Sekhar Dondapati, Vishnu Saini, Niraj Kishore and Vicky Prasad (2015) 'Enhancement of Performance Parameters Of Transformer Using Nanofluids', *International Journal of Scientific Engineering and Technology*, Vol. 4, June 2015, pp. 383-386.

[40] Andrea Cavallini, R. Karthik and Fabrizio Negri (2015) 'The Effect of Magnetite, Graphene Oxide and Silicone Oxide Nanoparticles on Dielectric Withstand Characteristics of Mineral Oil', *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 22, October 2015, pp. 2592-2600.

[41] Jacek Fal, Adriana Barylyak, Khrystyna Besaha, Yaroslav V. Bobitski, Marian Cholewa, Izabela Zawlik, Kamil Szmuc, Józef Cebulski and Gaweł Zyła (2016) 'Experimental Investigation of Electrical Conductivity and Permittivity of SC-TiO_2-EG Nanofluids', *Nanoscale Research Letter* [Electronic], Spriger/ s11671-016-1590-7, [24 August, 2016].