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RESEARCH ARTICLE

EXPERIMENTAL STUDIES ON BREAKDOWN STRENGTH OF TRANSFORMER OIL BASED NANOFLUIDS: AN OVERVIEW

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Abstract

The advent of nanotechnology opens up several research avenues. One of the promising outcomes of it is nanofluids. Remarkable research progress has been evidenced in recent years in this arena. Recently scientists have used nanoparticles as additives in transformer oils due to its enhanced thermophysical and excellent dielectric properties. This article portrays an overview of recent experimental studies on the potentials of nanofluids as transformer oils. The effect of particle type and particle concentrations on the dielectric break down voltage and heat transfer characteristics is summarized. It has been observed that use of nanofluids could improve the efficiency of existing high voltage infrastructures with a low financial cost.

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Introduction:-

The development of future high voltage network and smart grid has elevated high demands on the reliability and performance of insulating materials used in electric power system to deal with more dynamic and volatile operating conditions [1]. A transformer, which transforms voltage and transfer energy, is the most critical part of an electric power network. Transformers are one of the most important components of the generation and distribution electricity networks. Any fault in this system will affect the reliability of system. It is known to be high-cost component and has a direct effect on network operation, location, oil contents and toxic material where any interruption on the transformer would reduce the reliability of the power system [2–4].

The wide spread use of transformer oils for high voltage insulation and power apparatus cooling has led to the extensive research works aimed at enhancing both its dielectric and thermal characteristics. A particular innovative example of such extensive works is the development of dielectric nanofluids. The material can be manufactured by adding the magnetic nanoparticles to transformer oil with the aim of enhancing the insulating and thermal characteristics. Because of these advantages, many studies have been carried out to develop the nano insulation oil.[5]. Transformer oil (TO), apart from providing electrical insulation, also serves the vital function of conducting heat away from the solid insulation and lowers its operating temperature.

The design of superior insulating oil and maintenance of adequate cooling is a direct mode of energy saving process for the power and distribution transformers. A major portion of energy drops in the transformer is due to the ineffective heat transfer inside the transformer. Any improvement in thermal conductivity of the TO without adversely affecting insulation properties will enhance the life of the cellulose and hence that of the transformer. Alternately, it will permit the operation of the transformer at higher loads without the reduction in life and energy,

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thus increasing the capital utilisation [6]. Several reasons are identified for an energy deficient transformer performance, in which substandard insulating mineral oil (MO) is the front-runner [7]. Efficient insulating oil in the transformer is a key medium to maintain the effective insulation and cooling, which further is responsible for the energy saving. The dielectric strength of transformer oil based nanofluids should be studied because of the fact that transformer oil is designed to be an electrical insulator in transformer devices work under high electrical fields. Transformer oils will be failed, if the dielectric strength of oil is not able to prevent reaching the maximum electric field strength. So, having a high dielectric strength is a main factor of good quality transformer oil.

Types of nanoparticles used in transformer oil

The nanoparticles are selected for the improvement of dielectric properties of transformer oil by looking at their basic properties such as conductivity and permittivity. Nanoparticles can be categorized as conductive nanoparticles (Fe_3O_4 , ZnO and SiC), insulative nanoparticles (SiO_2 , Al_2O_3) and semi conductive nanoparticles (TiO_2 , CuO and Cu_2O). The carrier oils are normally mineral or vegetable oils. The basic properties of some of the nanoparticles are listed in Table1.

Table1:- Basic properties of conducting, insulating and semiconducting nanoparticles [8].

Properties	Magnetite (Fe_3O_4)	Zinc oxide (ZnO)	Alumina (Al_2O_3)	Silica (SiO_2)	Titania (TiO_2)
Density (g/cm^3)	5.17	5.61	3.96	2.20	4.3
Electrical conductivity (S/m)	$1 \times 10^4 - 1 \times 10^5$	$10 - 1 \times 10^3$	1×10^{-12}	1.4×10^{-9}	1×10^{-11}
Relative dielectric constant	80	7.4 – 8.9	9.9	3.8	100
Relaxation time constant (s)	7.47×10^{-14}	1.05×10^{-11}	12.2	5.12×10^{-2}	77
Thermal conductivity (W/mK)	4-8	23.4	30	1.4	4.8
Thermal expansion coefficient ($\mu\text{m/mK}$)	9.2	2.9	8	30	-
Specific heat (J/kgK)	-	494	850	670	683

Preparation of transformer oil based nanofluid

The first step for experimentation is the preparation of nanofluids. The two methods of preparation are one-step method or single -step method and two-step method.

Single-step method: In this method, the nano particles are developed and suspended in the base liquid at the same time, the course of drying, storage and conveyance of nanoparticles is by-passed with the intention to diminish the agglomeration and the stability of nanoparticles suspension is enhanced. The disadvantage of this method is its high cost and problems with a large-scale production.

Two-step method: In this method, the nanoparticles are prepared by physical or chemical methods and then dispersed in the carrier oil by ultrasonic route and magnetic stirring. The most commonly using two-step process is illustrated in Figure1.

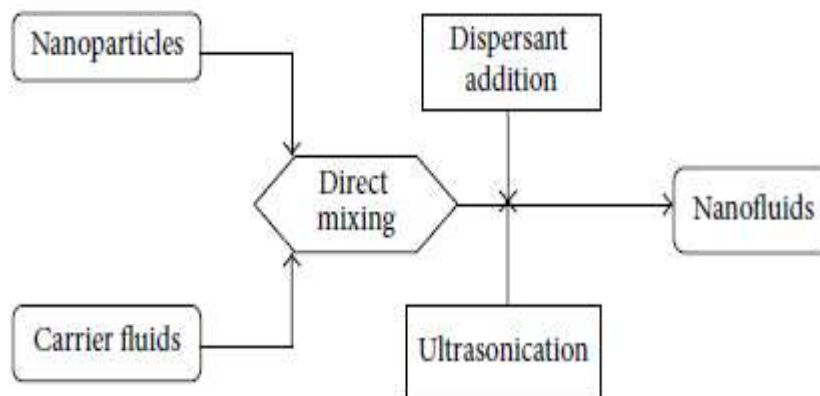


Figure1:- Two step method for the preparation of nanoparticles [9].

Experimental studies on transformer oil- nanofluid.

The recent experimental studies on transformer oil based nanofluids are described in the following sections.

Many researchers in literature reported that, adding nanoparticles into transformer oil leads to enhancement of dielectric strength by increasing the breakdown voltage. Thermal characteristics in transformer oil by dispersing nano sized solid particles, and its effects on transformer cooling needs to be extensively studied. The basic principles of transformers and transformer oil specifications with nanofluids are presented in many researches in literature.

Qi Wang [10] considered three different types of nanoparticles and transformer oil-based nanofluids were prepared with multiple nanoparticles volume concentration. The impulse breakdown strength of prepared nanofluids was tested and analyzed and concluded that the positive lightning impulse breakdown voltages of three nanofluids modified by Al_2O_3 , TiO_2 , and Fe_3O_4 showed improvement as the concentration is increased until a critical value of concentration after which it starts decreasing. Due to the presence of these nanoparticles, higher breakdown corresponds to longer time to breakdown. The study also concluded that the suspension of nanoparticles improves the breakdown performance of oil until a critical value of nanoparticle concentration after which the breakdown voltage tends to decrease. This decrease in breakdown voltages is mainly attributed to agglomeration of nanoparticles at higher volume concentration.

Yuzhen.Lvet al.[11] prepared three types of transformer oil based nanofluids by dispersing nanoparticles into mineral oil by ultrasonic treatment. Insulating metal oxide nanoparticles (INPS), semi-conductive metal oxide nanoparticles (SNPS) and conductive metal oxide nanoparticles (CNPS) were selected to add into the base oil at the concentration of 0.05 g/L, respectively. They observed that all kinds of nanofluids possess a higher AC breakdown voltage at both 1% and 50% probabilities. It is also observed that the impulse breakdown voltage of nanofluids is higher than that of pure oil. The impulse breakdown voltage of the transformer oil adding conductive nanoparticles have no significant increase compared with pure oil, while the breakdown voltage of INPS/oil and SNPS/oil is increased upto 7~8%. All the test results indicate that conductive nanoparticles, semi-conductive nanoparticles and insulating nanoparticles can improve the dielectric strength of mineral oil. The direct relation between the dielectric properties of nanofluid and the conductivity of nanoparticles is not found.

Du Yuefan et al. [12] formulated new type of colloidal dielectric fluids by mixing TiO_2 nanoparticle with transformer oil. They found that, the mean value and 1% probability breakdown voltage of nanofluid increased by 1.15 and 1.43 times compared with pure transformer oil respectively. Also, for lightning breakdown voltage, nanofluid was 13.3KV higher than that of transformer oil. Their results confirmed that transformer oil mixed with TiO_2 nanoparticles hold a promise to improve its insulating properties.

George Hwang et al. [13] studied the effects of transformer oil-based nanofluids on the electrical properties of oil and its breakdown voltage. They found that, the mixing of nanoparticles with transformer oil have substantially higher positive voltage breakdown levels than that of pure transformer oil. They explained this electrical breakdown performance compared to that of pure oil due to the electron charging of the nanoparticles to convert fast electrons from field ionization to slow negatively charged nanoparticle charge carriers with effective mobility reduction.

Yuefan Du et al. [14] studied the effects of semi conductive nanofluids prepared by adding TiO_2 nanoparticles on the transformer oil on the insulating characteristics, AC, DC and lightning impulse breakdown voltage and partial discharge (PD) characteristics of oil. They found that, semi conductive nanofluids have AC, DC and lightning impulse breakdown voltage up to 1.2 times compared with pure oil. Meanwhile, the partial discharge resistance was also dramatically improved. Srinivasan [15] proposed a new semi-physical model comprising of the environmental variables for the estimation of hot spot temperature and loss of insulation life in transformer. The winding hot-spot temperature was calculated as a function of the top-oil temperature that can be estimated using the transformer loading data, ambient temperature, wind velocity and solar heat radiation effect. The proposed model has been validated using real data gathered from a 100 MVA power transformer.

Dong et al. [16] prepared Aluminum-nitride-(AlN)-transformer oil based nanofluid and investigated its effects on the composition-dependent electrical conductivity at different ambient temperatures. They found that, the electrical conductivity has nonlinear dependences on the volumetric fraction and temperature. In comparison to the pure transformer oil, the electrical conductivity of nanofluid containing 0.5% AlN nanoparticles has increased by 1.57 times at 60 °C.

Murtaza [17] performed a steady-state calculation using IEC guidelines to determine the hot spot temperatures of distribution and power transformers. In this paper a transformer oil-based nanofluid is studied as a cooling medium in distribution transformer instead of pure transformer oil and the cooling modification is investigated by analyzing and modelling a complete transformer with pure oil and with four types of nanofluids (Cu-oil, Al_2O_3 -oil, TiO_2 -oil, and SiC-oil). Moreover, the effect of increase in winding resistance due to increase in ambient temperatures has been taken into account. They found that, the power and distribution transformers should be progressively de-rated under such circumstances for their safe operations, which will not only prove cost-effective for utilities but also improve the reliability of the power supply to their valued customers in the challenging future smart grid environment.

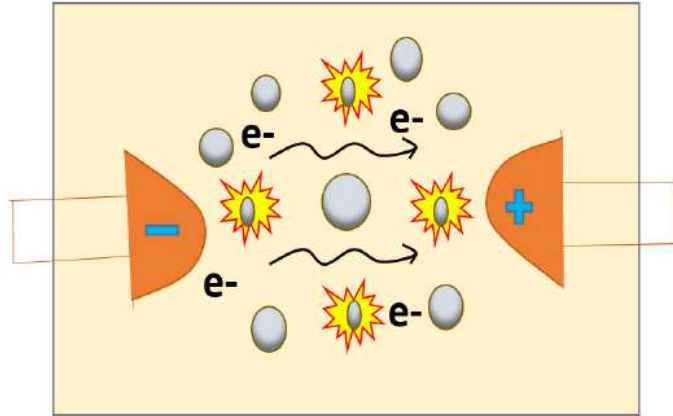


Figure 2:- Schematic representation of enhanced breakdown voltage of transformer oil after the addition of nanoparticles [18].

Researchers observed that the addition of nanoparticles enhanced the breakdown voltage of transformer oil. The nanoparticles acted as scattering obstacles and trap sites in the charge carrier paths, limiting the electrons' mobility (shown in Fig 2). Size of nanoparticles plays a role in enhancing the breakdown voltage of transformer oil nanofluid. Smaller nanoparticle size ensures a greater density of the nanoparticle in the nanofluid than nanoparticle with the larger size for the same concentration. This increases the nanoparticle population to trap free electrons from streamers at a higher rate, leading to higher breakdown strength [18].

Jian Li [19] presents some of the results of a study of the breakdown voltages and dielectric properties of a vegetable oil-based nanofluid. The nanofluid was prepared by dispersing Fe_3O_4 nanoparticles in a vegetable insulation oil obtained from a laboratory at Chongqing University. Oleic acid was used for surface modification of the nanoparticles. The attenuated total reflection-Fourier transform infrared spectroscopy, TGA, and DTA data indicate that physical adsorption and chemical bonding occur at the oleic acid/ Fe_3O_4 nanoparticle interface. The power frequency breakdown voltages of the oil based nanofluids are 20% greater than those of the oil itself. The positive lightning impulse breakdown voltages of the nanofluids are greater than the corresponding negative voltages. The volume resistivities of the nanofluids and the oil are almost equal at frequencies exceeding 100 Hz, and their dissipation factors are very similar at frequencies exceeding 10 Hz. However, the relative permittivity of the nanofluids is greater than that of the oil at all frequencies between 10–2 and 107 Hz, probably because of the much higher relative permittivity of the Fe_3O_4 nanoparticles. A lot of other researchers have also measured impulse breakdown strength of prepared nanofluids and pure oil. The summary of breakdown voltages with time to breakdown and streamer velocity is presented in Table 2.

Table2:- Comparison of Breakdown characteristics.

Material	Breakdown voltage (kV)		Time to breakdown (μs)		Average streamer velocity (km/s)	Enhancement of breakdown voltage (%)
	Average	SD	Average	SD		
Pure oil	51.84	0.48	4.44	0.33	1.126	0
Fe_3O_4 nanofluid	62.86	0.88	5.24	0.83	0.954	21.3
TiO_2 nanofluid	65.72	1.10	5.40	0.65	0.926	26.8
Al_2O_3 nanofluid	66.24	1.14	6.12	0.68	0.817	27.8

Thabet et al. [20] investigates on the impacts of individual and multi-nanoparticles on effective conductivity of transformer oils. Also, it has been investigated on the main effective factors of effective electrical conductivity for transformer oil nanofluids like; concentration of nanoparticles, applied electric field, and thermal conditions. A simulation study has been performed for using individual and multiple nanoparticles (SiO_2 , ZnO , TiO_2 , and Graphite). An experimental work has been carried out for verifying the importance of using multiple nanoparticles for controlling in conductivity of power transformers nanofluids. Experimental work verified that the effective electrical conductivity of multi-transformer oils nanofluids is better than electric conductivity of individual nanofluid. Different types of nanoparticles significantly influence the breakdown strength of transformer oil. The AC breakdown voltages measurement by different researchers are summarized in Table 3.

Sadegh Aberoumand [21] prepared Tungsten (III) oxide (WO_3)- Silver/Transformer Oil Hybrid Nanofluid in three weight fractions of 1%, 2% and 4% via Electrical Explosion of Wire and its stability was evaluated by measuring zeta potential. In addition, thermal conductivity of hybrid nanofluids has been experimentally studied. An enhancement of 41% was observed in 4% wt and the thermal conductivity increased in an increasing way in contrast to pure transformer oil which behaves in a decreasing way. Finally, dielectric strength of hybrid nanofluids has been measured and in comparison, with pure oil, a reduction has been observed which was probably due to the electrical conductivity of silver nanoparticles, because, WO_3 nanoparticles have a low electrical conductivity in all known nanoparticles till now.

Table 3:-Enhancement in AC breakdown voltage of transformer oil based nanofluids reported in literature.

Author/year	Nanofluid	Average Particle size(nm)	Concentration (Volume%)	Enhancement ratio
Segal et al./1998[22]	Fe_3O_4 /Mineral Oil	10	-	42.8%
Sartoratto et al./2005[23]	Fe_2O_3 /Mineral Oil	7.4	0.016	12.8%
Du et al./2005[24]	TiO_2 /Mineral oil	20	0.075	19%
Y.-F. Du et al./2010[24]	TiO_2 /Mineral oil	<20	0.00075	15%
Liu et al./2012[25]	SiO_2 /Mineral oil	15	0.0074	17%
Li et al./2012[26]	Fe_3O_4 /Vegetable Oil	30	-	19.8%
Hanai et al./2013[27]	ZnO /Mineral oil	34	0.0005	8.3%
Jian et al./2014[19]	SiO_2 /Mineral oil	15	0.01	29%
Sima et al./2015[28]	Al_2O_3 /Mineral oil	10	-	35.5%
Prasath et al./2017[29]	$\text{CaCu}_3\text{Ti}_4\text{O}_{12}$ /Synthetic Esther	-	0.005	41.6%
Fan Xu et al./2020[30]	Co_3O_4 /Mineral Oil	16	0.0008	61.6%

Conclusions:-

Research works on nanofluid based transformer oil provides great opportunities for researchers for future research. This paper reviews literature regarding electrical properties of transformer oil- based nanofluids. This review paper leads to a few conclusions about the factors affecting the values of breakdown voltage (BDV) and the lightning impulse breakdown voltage (LI BDV). The concentration of nanoparticles in transformer oils has a strong effect on BDV values. As many researchers have revealed that the increase in nanoparticles in the base fluid causes an increase in BDV. On the other hand, there are nanofluids that exhibit an increase in BDV only up to some concentration, above which a decrease in BDV is observed. In some cases, the addition of nanoparticles causes the completely opposite effect: decreasing BDV below a pure base fluid. The development of transformer oil could potentially improve the operation of the transformer itself and perhaps reduced machine size or volume overall. Unfortunately, the mechanisms occurring in transformer oils containing nanoparticles during breakdown voltage tests are not fully understood. Also, a lack of a unified method of preparation and testing of the BDV of nanofluids and concentration representation cause problems with the comparison of the results obtained by different researcher. So more in-depth experimental work on nanofluids is required, and multidisciplinary research collaboration in dealing the challenges is imminent taking into account standardized rules of sample preparation, measurement methods and data representation.

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