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A study on transformer fluids & effects of nano particles on it-review

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Abstract
Transformer fluids play a critical role in the operation and longevity of electrical transformers. Recent advancements in nanotechnology have shown that incorporating nanomaterials can significantly enhance the properties of transformer fluids, leading to improved thermal performance, electrical breakdown strength, and chemical stability. This review explores the influence of various nanomaterials on transformer fluids, highlighting key findings from latest recent studies. Challenges and future research directions are also discussed to pave the way for innovative solutions in transformer fluid technology.

Keywords : Transformer Fluids, nano fluids , mineral oils , natural esters, silicon dioxide (SiO_2), titanium dioxide (TiO_2), aluminum oxide (Al_2O_3), and carbon nanotubes (CNTs)

1. Introduction

As the key component of the power grid, power transformer is vital in delivering and distributing energy, and its reliability is a significant guarantee for safe and stable operation of the power system [1]. Insulating oil plays a vital role in oil-filled transformers alike blood in the human body: first, it eliminates the air gap in the transformer by impregnation and filling, thereby improving the electrical insulation strength and helping heat dissipation for the transformer and second, it acts as an arc extinguishing medium to reduce the chance of equipment failure as well as an information carrier of the transformer performance [2,3].Transformer fluids are essential for cooling and insulating transformers, ensuring optimal performance and safety. Traditional fluids such as mineral oil have served the industry well but face limitations in terms of thermal conductivity, aging, and oxidation stability. Nanotechnology offers promising solutions by incorporating nanoparticles into transformer fluids to enhance their properties. This review aims to provide an overview of recent advancements in transformer nanofluids, highlighting the impact of nanomaterials on their physical, electrical, and chemical properties. Although numerous studies that provide a guideline for the continually evolving competition space for plant-based insulating fluids, many state-of-the-art strategies and techniques, such as nanotechnology, newly emerging methods for fault diagnosis and investigations of pre/breakdown phenomena, etc., as well as constantly updated international standards, are rarely comprehensively and systematically summarized. Encouraged by this motivation, this paper critically reviews the research progress over the past three decades with the help of the "science mapping" literature review technique [16] and prospects for plant-based insulating fluids. First, we touch briefly on the evolution of insulation fluids for transformer and summarize the latest international standards on plant-based oil. Second, some physicochemical properties of plant-based oil are presented. Next, plant-based insulating fluids will be analyzed in terms of aging properties and followed by streamer development and breakdown phenomena. Then we will discuss the application of nanotechnology and molecular design in plant-based insulating oil. Lastly, the conclusions and general outlook circa 2019 will be provided. We intend that this review will help academia and industry toward the next set of research and development actions for renewable and sustainable insulating fluids.

2. Traditional Transformer Fluids [1-3]

More than a century ago, the power industry's rise pushed the search for proper liquid insulating materials. MOs, due to their low cost, good thermal conductivity, and insulation properties, quickly became the preferred dielectric fluid, and they enabled the massive application of oil-filled electrical equipment. However, originally from petroleum, MOs carried on the characteristics of high volatility and low flash point, being blamed for the fire or/and explosion accidents that happened.

Traditional transformer fluids include mineral oils, synthetic esters, and natural esters. Mineral oils are widely used due to their cost-effectiveness and dielectric properties but suffer from aging and environmental concerns. Synthetic and natural esters offer better biodegradability and higher flash points but are more expensive. [4] Each of these fluids has limitations that hinder the performance of transformers under extreme conditions. Table 1 shows typical property values of insulating oils and the appropriate ASTM test numbers and specification value. [*image taken with permission from ref 5*]

TABLE I
ASTM D-3487

Property	Specification Value	Typical Value	ASTM NO.
Color	0.5 max.	0.5	D-1500
Dielectric breakdown at 60 Hz			
0.100 in. gap	30 kV/min	35 kV	D-877
0.040 in. gap	28 kV/min	30 kV	D-1816
0.080 in. gap	56 kV/min	60 kV	D-1816
Neutralization number	0.03 mg max	0.01 mg	D-974
Free or corrosive sulphur	Noncorrosive	Noncorrosive	D-1275
Flash point	145°C (293°F) min	150°C	D-92
Pour point	−40°C (−40°F) max	−55°C	D-97
Viscosity			
max. cS @ 100°C	3 sec max	3 sec	D-88
max. cS @ 40°C	12 sec max	10 sec	D-88
max. cS @ 0°C	76 sec max	70 sec	
Moisture content	35 ppm max	20 ppm	D-1533
Specific gravity @ 60°F	0.910 max	0.890	D-1298
Inorganic chlorides or sulfates	None	None	D-878
Interfacial tension	40 dynes/min	45 dynes	D-971
Power factor, 60 Hz			
25°C (77°F)	0.05% max	0.01%	D-924
100°C (212°F)	0.30% max	0.10%	D-924
Oxidation stability			
Sludge after 72 hr	0.15%	0.1%	D-2440
Sludge after 164 hr	0.30%	0.2%	D-2440
Total acid after 72 hr	0.5 mg KOH	0.2 mg KOH	D-2440
Total acid after 164 hr	0.6 mg KOH	0.3 mg KOH	D-2440
Aniline point	63-83°C	75°C	D-611
Dielectric breakdown,			
Impulse, needle-negative	145 kV	105 kV	D-3300

3. Nanotechnology and Its Application in Transformer Fluids

Nanotechnology in transformer fluids involves the addition of nanoparticles to the base oil, creating "nanofluids," which can significantly enhance the fluid's thermal conductivity and dielectric strength, leading to improved cooling and insulation capabilities in transformers, allowing for higher loading and operational efficiency.This technology involves the manipulation of materials at the nanoscale, providing unique physical and chemical properties. [5-7] Nanomaterials such as silicon dioxide (SiO_2), titanium dioxide (TiO_2), aluminum oxide (Al_2O_3), and carbon nanotubes (CNTs) have shown significant potential in enhancing transformer fluids. These nanoparticles are typically dispersed in the base fluid to form nanofluids, which exhibit improved dielectric and thermal properties. [8-10].

4. Influence of Nanomaterials on Transformer Fluid Properties

Due to the increasing demand on developing good insulation, several researchers have performed experimental studies to prove the effectiveness and capabilities of transformer oil. This is done by suspending nanosized solid particles in the oil (nanofluid) for transformer applications.

Fig 1 : A detailed scientific illustration comparing traditional transformer fluids and nanofluids. The image should show two sections_ the left side depicting

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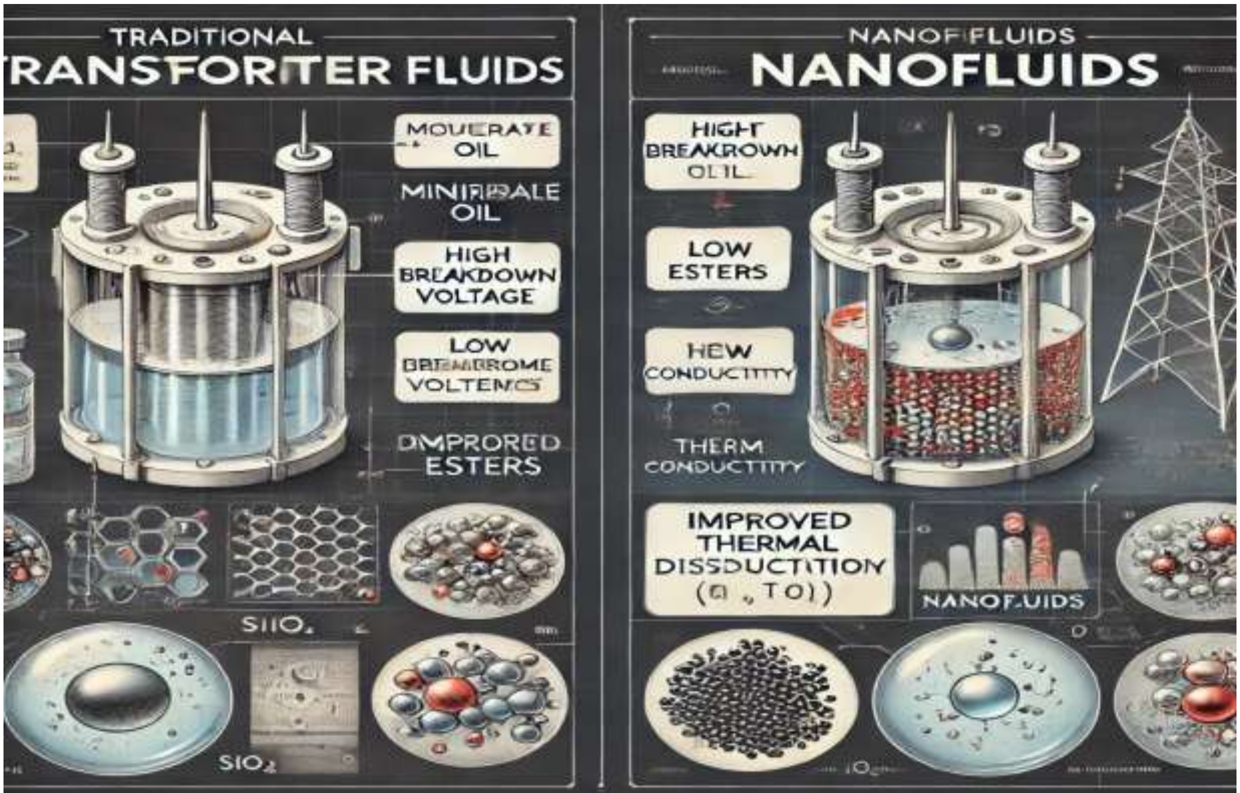
Fig:1

Table1: Comparison of Traditional and Nanofluids



Property	**Traditional Fluid**	**Nanofluid (with Nanoparticles)**
Breakdown Voltage	Moderate	High
Thermal Conductivity	Low	High
Oxidation Stability	Low	Improved
Dielectric Constant	Moderate	High

4.1 Electrical Properties

The addition of nanoparticles can enhance the breakdown voltage of transformer fluids, improving their insulating performance. Studies have shown that nanoparticles create charge traps that inhibit the formation of electrical discharge channels. [11-13]

Kaizheng Wang et al. investigated the impurity effect of iron and copper metal particles of different diameters on mineral oil and natural ester [20]. In their experimental study, they investigated the dielectric strength of these two liquid dielectrics under AC and impulse voltage. They revealed that the AC breakdown voltage decreased with the increase in the size of the metal particle and this effect was more visible in mineral oil. It is seen that the amount of metal particles under the impulse voltage reduces the breakdown voltage more, especially when copper particles are used, after a threshold value of 10% for positive impulse voltage and 20% for negative impulse voltage. However, in the related study, an analysis of harmonics, which is a clue about the partial discharges that occur before the oil is fully breakdown, has not been analysed. In addition, the breakdown behaviour of synthetic ester, which is used in transformers and has high dielectric strength, has not been investigated.

Ivanka Atanasova-Höhlein investigated the metal particle effects for mineral oil, synthetic ester, natural ester and silicone oil with the following methods [21].

insulating fluid only
insulating fluid + copper
insulating fluid + electrical steel
insulating fluid + copper + electrical steel
insulating liquid + copper + electrical steel + insulation paper

By analysing the gases dissolved in 4 different liquids with the above method, the differences between liquids behaviours' were revealed. Accordingly, hydrogen, ethane and methane gases were formed in liquids at higher concentrations than the other gases. Only hydrogen gas was found dissolved in the synthetic ester. The highest gas concentration value for this ester was measured under insulating liquid + copper condition. Even though, hydrogen gas in mineral oil was measured highest under insulating liquid + copper condition, methane and ethane gases were measured highest under insulating liquid + copper + electrical steel + insulation paper condition. In natural ester, hydrogen gas was dissolved at the highest concentration into liquid insulator by the effect of steel particles, while methane gas was measured in conditions other than pure liquid and paper insulation. In the related study, no increase in gas concentration value of silicone oil was detected. Although gases dissolved in liquids are an important criterion for early failure, the dielectric behaviour of liquids under sudden and high electric field stresses needs to be investigated. In addition, since transformers are generally made of iron core, the effect of iron particles rather than steel should be examined in order to make a more widespread assessment.

Although there are many studies examining the effect of metal nanoparticles in transformer liquids [18], [13], [19], [15] there are very few experimental studies evaluating mineral oil, natural ester and synthetic ester together. In addition, the lack of analyses evaluating partial discharges in these studies is striking. In addition, there is no study investigating harmonic leakage currents with the analysis of current data occurring after ionizations in a liquid insulator. Therefore, conducting research involving these analyses is very important in terms of examining a correct dielectric strength behaviour for different liquid dielectrics. This provides as comprehensive analysis as possible for the correct liquid dielectric selection for transformers.

4.2 Thermal Properties , Chemical Stability & Dielectric Properties

Nanoparticles improve the thermal conductivity and heat dissipation of transformer fluids. Enhanced heat transfer helps prevent transformer overheating and prolongs the lifespan of the equipment. [14-15]

Nanoparticles can improve the oxidation stability and aging characteristics of transformer fluids, reducing the formation of acids and sludge over time. This leads to longer maintenance intervals and improved operational efficiency. [16-18]

Nanofluids exhibit enhanced dielectric constant and loss tangent properties, making them more effective as insulating fluids. The uniform dispersion of nanoparticles is critical for achieving these improvements. [19]

5. Challenges and Limitations

Table 2 below shows the Challenges and Potential Solutions with description

 Table 2: Challenges and Potential Solutions

Challenge	Description	Potential Solution
Dispersion Stability	Nanoparticles settling over time	Use of surfactants
Compatibility Issues	Materials interaction concerns	Material testing protocols
Environmental Concerns	Nanoparticle toxicity	Biodegradable nanoparticles

6. **Future Trends and Opportunities**

Research is ongoing to develop hybrid nanofluids that combine multiple nanomaterials for synergistic effects. Smart fluids with adaptive or self-healing properties are also being explored to enhance transformer reliability. [18-19] Regulatory and standardization efforts are necessary to ensure the safe and effective use of nanofluids in the electrical industry. [19]

7. **Conclusion**

1. Enhanced Electrical Properties: Nanoparticles significantly improve the breakdown voltage and dielectric properties of transformer fluids, making them more effective insulators.
2. Improved Thermal Conductivity: The addition of nanomaterials enhances heat dissipation, reducing transformer overheating and extending equipment lifespan.
3. Increased Chemical Stability: Nanoparticles help improve oxidation stability, reducing aging effects and maintenance needs for transformer fluids.
4. Challenges Remain: Issues such as nanoparticle dispersion stability, material compatibility, and environmental safety need further research and development.
5. Future Potential: Continued research on hybrid nanofluids and smart transformer fluids will likely lead to advanced solutions for the electrical industry.
6. Collaboration is Essential: Industry collaboration is crucial for overcoming challenges and ensuring the safe and sustainable implementation of nanofluids in transformers.

Nanotechnology holds great promise for transforming traditional transformer fluids into high-performance insulating and cooling mediums. While significant progress has been made, further research is needed to overcome challenges and unlock the full potential of nanofluids. Collaborative efforts between researchers, manufacturers, and regulatory bodies will be crucial in advancing this field and ensuring the safe, efficient, and sustainable operation of electrical transformers in the future.

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