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INVESTIGATION OF ELECTRO-PHYSICAL CHARACTERISTICS OF ECO-FRIENDLY FLUIDS FOR PROMISING REPLACEMENT OF PETROLEUM OIL IN POWER TRANSFORMER APPLICATIONS

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Abstract:

Transformer is generally considered to be the heart of the power system. For the continuous flow of power, the key element in the transmission and distribution network to be monitored is transformer. The insulating fluid plays a vital role in the proper functioning of transformer which serves as an effective coolant and insulation and it determines the lifetime of transformers. Thus, the reliability of a transformer is largely determined by its insulation condition.The globally used insulating fluid is mineral oil which is the derivative of petroleum. However, the exploitation of petroleum oil is running out of demand and in the near future, oil scarcity exists. Also during its use and disposition, mineral oil is potentially hazardous to aquatic/human life due to its non-biodegradability and hence it is not environment friendly. This has given rise to a new class of natural esters based alternative biodegradable dielectric fluid. Furthermore, the efforts have been put up in this work to improve the critical characteristics of this biodegradable fluid by the addition of additives such as Nanoparticles and anti-oxidants.

Index Terms: Mineral Oil, Dielectric Fluid, Natural Esters, Nanoparticles & Anti-Oxidants

1. Introduction:

Electrical energy is generated at places where it is easier to get the water head, oil or coal for hydro-electric, diesel or thermal power stations respectively. The energy is then to be transmitted at considerable distances for use in villages, towns and cities located at distant places. The transmission of electrical energy at high voltages is economical, therefore some means are required for stepping up the voltage at generating stations and stepping down the same at the places where it is been used. Electric machine used for this purpose is transformer. A transformer is a static ac machine that transfers electrical energy from one electric circuit to another without a change of frequency but with a change of voltage. Transformer is generally considered to be one of the most important power system equipments. The critical part of a modern power system is the transformer life management and the transformer life primarily depends on the insulating mediums used. The basic insulating materials used in transformer system are categorized into solid, liquid and gas. Among them solid (press board, Kraft paper) and liquid (mineral oil) insulations are essentially used. The first oil cooled, oil–insulated transformer was constructed by Brown in the year 1890 [1].Transformer oil serves two purposes (i) it provides liquid insulation (ii) it acts as coolant and dissipates heat of the transformer. In addition to these, it also serves two other purposes, it helps to preserve the core and winding as these are fully immersed inside oil and it prevents direct contact of atmospheric oxygen with cellulose made paper insulation of windings, which is susceptible to oxidation. Petroleum based oils (mineral oil) have been used as liquid dielectrics [2] for transformers. Such oils possess high dielectric strength, but poor in flash point and fire point characteristics. The major limitations of mineral oil are low biodegradation and panic threats to human beings and ecosystem. Due to their poor performance at high temperature, the use of mineral oil is restricted in ecologically sensitive locations. Also, mineral oil is poorly biodegradable and it could contaminate our soil and waterways. Petroleum products are eventually going to run out, and there could be serious shortages in the mid-twenty-first century. The aim of this paper is to highlight the effort in finding an alternate natural source of insulating fluids to the existing mineral oil. The research efforts were started in the mid 1990s to develop a fully biodegradable insulating fluid and further the natural esters (vegetable oil) were considered the most likely candidate [3]. Vegetable oil [4, 5] is a natural resource available in plenty which is a fairly good insulator and is fully biodegradable [6]. In order to use natural esters in transformer, its properties like dielectric dissipation factor, dielectric strength, viscosity and flash/fire point should be satisfied as per IEC (International Electrotechnical Commission) and ASTM (American Society for Testing and Materials) standards.

2. Need for an Alternate Source of Insulating Fluid:

Mineral oil is poorly biodegradable [7] and contaminate our soil and waterways to the greater extent. Mineral oil filled transformer explosions and fires causing heavy collateral damage have raised major safety concerns. There have also been major environmental concerns over the toxic effects of uncontained mineral oil spills. This has given rise to a new class of alternate natural sources of dielectric insulating fluids which have better biodegradability and higher fire point when compared to mineral oil. Merits and Demerits over conventional mineral oils

A. Merits:

- ✓ Readily biodegradable and non-toxic – thus mitigating soil and water contamination during transformer oil spillage.
- ✓ High fire point (K class) and explosive limits thus reducing the risk of transformer fire and explosion.
- ✓ Higher Thermal Conductivity.
- ✓ Lower aging rate.
- ✓ High water saturation limit which improves the life performance of cellulose insulation [9] and allows higher temperature rise limits.

B. Demerits:

- ✓ Faster streamer propagation over longer distances and higher viscosity.
- ✓ Lower oxidation stability [10].

3. Properties of Transformer Oil:

The properties of transformer oil are 1. Electrical - Dielectric Strength, Specific Resistance, Dielectric Dissipation Factor (tan δ). 2. Chemical - Water Content, Acidity, Sludge Content. 3. Physical - Inter Facial Tension, Viscosity, Flash/Fire Point, Pour Point. Out of the above, the critical properties are Breakdown voltage, Dielectric dissipation factor, Viscosity, Flash point/Fire point.

A. Breakdown Voltage (BDV):

The BDV of an insulating oil is a measure of the oils ability to withstand electrical stress without failure. The transformer oil offers the insulation upto a certain voltage level after which an insulation breakdown occurs. This voltage at which the breakdown occurs is called breakdown voltage or dielectric strength of transformer oil.

B. Flash Point/Fire Point:

When the transformer is energised, there will be a rise in temperature. As the conventional mineral oil based transformer oil is a derived product of crude petroleum, it starts evaporating at higher temperature. After a certain temperature, the mixture of this oil vapour and atmospheric air produces a highly combustible product which is easily ignitable by any kind of spark. Thus flash point of an oil is the temperature at which the oil ignites spontaneously. The temperature at which the oil starts firing continuously is called fire point. The flash/fire point can be measured using Cleveland open cup apparatus or Pensky Martens closed cup apparatus [11].

C. Pour Point:

The pour point of transformer oil refers to that lowest temperature at which the transformer oil just start to flow or pour freely, when tested under specific conditions. Determination of pour point is very important and rarely it creates a problem, especially in cold countries and hence is an important property mainly at the places where climate is extremely cold. If the oil temperature falls below the pour point, transformer oil stops convection flowing and obstruct cooling in transformer. Paraffin based oil has higher value of pour point compared to Naphtha based oil since it has more wax content. Higher the wax content, higher will be the pour point. But in tropical country like India, it does not affect the use of Paraffin oil due to its warm climate condition. The transformer oil is required to have low pour point and its maximum value should be of -6°C.

D. Viscosity:

Viscosity is the resistance of transformer oil to flow under normal conditions. A good oil should have low viscosity so that it offers less resistance to its convectional flow thereby not affecting the cooling of transformer. Low viscosity of transformer oil is essential and it is equally important that the viscosity of oil should increase as less as possible with decrease in temperature. Every liquid becomes more viscous if temperature decreases [12].

4. Characteristics of Transformer Oil:

- ✓ High Breakdown Voltage
- ✓ Low Viscosity
- ✓ High Flash/Fire Points
- ✓ Low Dielectric Dissipation Factor
- ✓ Environmental Acceptability
- ✓ Low Flammability

5. Enhancement of Critical Parameters of Natural Esters Dielectric Insulating Fluid:

Nanoparticles and Antioxidants were added to the base fluids (natural esters) to enhance its critical parameters.

A. Nanoparticles and Its Types:

Nanoparticles modifying technology [13] is one of the newest and effective way of improving the performance of oil-paper insulation system. Nanoparticles have recently attracted significant attention from the materials science community. Ultrafine particle or nanoparticle is a microscopic particle with diameter in the range between 1 and 100 nm. Nanoparticles find applications in variety of fields such as biomedical, optical, electronic and energy [14]. The value of the critical parameters [15] of natural esters, for its potential to be used as insulating fluid can be improved by adding nanoparticles. Several researches are being going on for the application of nanoparticles in the domain of liquid dielectrics. Various types of nanoparticles of metallic oxides such as conductive, semi-conductive [16] and insulating nanoparticles with various electrical conductivities can be used to modify the dielectric insulating fluid. Any of the above types of nanoparticles can be added based on the requirement. For this proposed work, semiconducting nanoparticles such as ZnO was added and its mechanism behind the improvement of critical parameters [17] were analysed and presented.

B. Antioxidants and its Types:

Oxidation [18] is any chemical reaction in which an atom of an element loses one or more of its electrons to an atom of a different element. Originally, the term was applied only to a reaction in which oxygen combines with another element or group of elements to form a compound called an oxide. Antioxidants [19] by making the free radicals stable, avoids the movement of electrons between the neighbouring atoms, which thus decreases the conductivity of the fluid. Thus it paves the way for improving the breakdown voltage. The viscosity and thermal characteristics of the base fluids with antioxidants are greatly influenced by the degree of unsaturation. The degree of unsaturation is measured by finding the iodine value of the oil samples. Higher the degree of unsaturation, higher is the iodine value and the convection property will be dominant which in turn thus lowers the value of viscosity and improves the flash/fire point. Types of antioxidants include natural and synthetic antioxidants. Natural antioxidants [20] are mainly found in fruits and vegetables, marine plants and some seafood that eat marine plants and Synthetic antioxidants are produced artificially and consumed in supplement form. Citric Acid (CA), L-ascorbic acid, Vitamin C, Vitamin E etc., are few of the natural antioxidants and Butylated Hydroxy Toluene, Butylated Hydroxy Anisole (BHA), Propyl Gallate etc., are few of the synthetic antioxidants. The natural and synthetic antioxidants are added in individual and combined proportion with minimum quantity of 1g, thus utilising the parallel mechanism of both the antioxidants.

6. Tests and Standards for Measurement of Critical Parameters:

S.No	Test Conducted	Testing Kit used	Standard
1	Breakdown Voltage (BDV) test	60 kV and 100 kV BDV test kit	IEC 60156
3	Viscosity test	Redwood Viscometer	ASTM D 445
4	Flash & Fire point test	Pensky Martens Apparatus	ASTM D 93

7. Quantity of Oil Samples for Measurement of Critical Parameters:

S.No	Critical Parameter	Quantity of Oil Required
1	BDV using 60 kV BDV Test Kit	500 ml
2	BDV using 100 kV BDV Test Kit	1000 ml
3	Lightning Impulse BDV	1000 ml
4	Viscosity and Flash/Fire Point	50 l

8. Samples and Methodology:

Commercially available oil such as Coconut oil is used as the base fluid for the proposed work. The base fluid is collected and the additives such as nanoparticles/nanofluids, antioxidants are added to the base fluids by means of Magnetic Stirring as shown in Figure 2. Nanoparticles are available in solid/liquid form. In liquid form, the nanoparticles are dispersed in other solvents like ethylene glycol, water etc.

Sample 1	Base Fluid 1 (Coconut Oil)
Sample 2	Base Fluid + 0.01% ZnO (Liquid)
Sample 3	Base Fluid + 0.01 % ZnO (Powder)
Sample 5	Base Fluid + 1g Citric Acid (CA)
Sample 6	Base Fluid + 1g Butylated Hydroxy Anisole (BHA)
Sample 7	Base Fluid + 0.5 g CA + 0.5 g BHA

9. Equipments Used For Preparation of Samples:

Equipments for Weighing Additives:

Nanoparticles: Electronic Weighing Machine (220g) with 0.0001 accuracy
Antioxidants: Digital Weighing Machine (300g) with 0.01 accuracy

Equipments for Mixing the Additives to Base Fluids:

Magnetic Stirrer

Sonicator

Figure 1: Magnetic Stirrer

The magnetic stirring as shown in Figure 2 was conducted at constant speed and room temperature for about 2 hours. The prepared nanofluids are then heated at 100°C to remove any moisture content that may be introduced during stirring process from the atmosphere.

Figure 2: Digital Ultrasonic Cleaner

The sonication process was done by Digital Ultrasonic Cleaner EQUITRON, 2500 ml Heater for a maximum time setting of 480 seconds as shown in Figure 4.3. In ultrasonicator setup, the oil contained in a beaker is placed in a water bath. The additives which are dispersed inside the oil sample already, starts getting mixed up with the oil due to the influence of ultrasonic waves. For an instant, the process can be done for 480 seconds i.e., 8 minutes to the maximum as per the rating of the equipment. The process is performed for around 30 minutes and the as prepared fluid will be mixed well further by Magnetic stirring.

10. Determination of Quantity of Nanoparticles to be Added to the Base Fluids:

Nanoparticles are available in solid and liquid form. For liquid form of ZnO, the quantity of ZnO nanosolution to be added to the insulating fluid is based on the particle volume fraction. The particle volume fraction chosen is 0.01%.

$$Particle\ Volume\ Fraction\ \left(\frac{v}{v}\%\right) = \frac{Volume\ of\ ZnO\ Nanosolution}{Volume\ of\ Insulating\ Fluid}$$

$$Volume\ of\ ZnO\ Nanosolution = \frac{0.01}{100} * 500\ ml = 0.05\ ml$$

For ZnO in solid form, the quantity of ZnO nanoparticles to be added to the insulating fluid is based on the weight percentage. Weight percentage chosen is 0.01% . The weight of ZnO nanoparticles to be added to the base fluids can be estimated using Gravimetric test. Gravimetric test was performed in Electronic Weighing Machine SHIMADZU (220g, 0.0001 accuracy). The weight of the empty vessel is calculated first and after which the nanoparticles will be placed in the vessel. The difference between the weight of empty vessel and the weight of nanoparticles gives the required weight of nanoparticles. The required quantity of antioxidants was weighed using Digital Weighing Machine (300g, 0.01 accuracy).

$$Weight\ Percentage\ \left(\frac{w}{w}\%\right) = \frac{Weight\ of\ nanoparticle\ (g)}{Weight\ of\ Insulating\ Fluid\ (g)}$$

$$Weight\ of\ ZnO\ Nanoparticle = \frac{0.01}{100} * Weight\ of\ insulating\ fluid$$

Weight of each vegetable oil sample will differ from the other. For the chosen base fluid (Coconut Oil), the quantity of ZnO nanoparticle to be added is calculated as follows.

Weight of 500 ml of RSO = 356.529 g

$$Weight\ of\ Nanoparticles\ (g) = \frac{0.01}{100} * 356.529 = 0.0357\ g$$

11. Results and Discussions:

A. Properties of Mineral Oil: The properties of conventional mineral oil [23] measured at room temperature as per ASTM and IEC standard are shown in below Table 2.

Table 1: Properties of Mineral Oil

Properties	Values
Breakdown Voltage	32 kV
Flash Point	140°C
Fire Point	160°C
Viscosity at RTP	21.5cSt

B. Electrical Parameter:

Breakdown Voltage*:* The breakdown voltage of the base fluid with and without adding additives are listed in Table II.

Using 100 kV BDV test kit with

Frequency = 50 Hz

Electrode : Mushroom type

Gap between electrodes : 2.5 mm

Table 2: Breakdown Voltage of Base Fluids with and Without Additives

Samples	Average BDV (kV)
Base Fluid (Coconut Oil)	36.8
Base Fluid + 0.01% ZnO (Liquid)	42.6
Base Fluid + 0.01 % ZnO (Powder)	59
Base Fluid + 1g Citric Acid (CA)	47.6
Base Fluid + 1g Butylated Hydroxy Anisole (BHA)	56
Base Fluid + 0.5 g CA + 0.5 g BHA	58.6

The oil sample is subjected to steadily increasing alternating voltage until breakdown occurs in a BDV test kit [21]. The Breakdown voltage is the voltage reached at the time of spark appears between the electrodes. The test is carried out six times on the same oil sample with a time gap of 5 minutes. Sufficient time gap should be given between successive readings so that the carbon formed due to breakdown of oil will settle at the bottom. The BDV of the oil is the arithmetic mean of the six result obtained. The Electrodes are mounted on the horizontal axis with the test spacing of 2.5 mm. Table II shows that the average BDV of the basefluids after adding nanoparticles and antioxidants are found to be greater when compared to that of the respective base fluid. Nanoparticles after adding to the coconut oil thus has improved its breakdown voltage by electron scavenging mechanism. Furthermore, the reason for the improvement in breakdown voltage of the base fluids with antioxidants is that it eliminates or keeps the free radicals to minimum quantity which reduces sludge formation (Acid Value).

Table 3: Increment Percentage In BDV Of Base Fluids

Samples	Increment Percentage
Base Fluid + 0.01% ZnO (Liquid)	15.76
Base Fluid + 0.01 % ZnO (Solid)	60.32
Base Fluid + 1g Citric Acid (CA)	29.34
Base Fluid + 1g Butylated Hydroxy Anisole (BHA)	52.17
Base Fluid + 0.5 g CA + 0.5 g BHA	59.23

Figure 3 and Figure 4 shows the comparison results for BDV of the base fluids with and without additives to highlight the percentage improvement in BDV after adding additives.

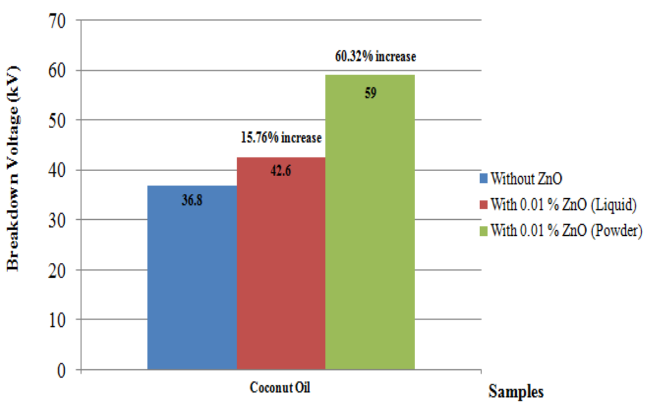

Figure 3: Increment percentage in BDV of base fluids after adding Nanoparticles

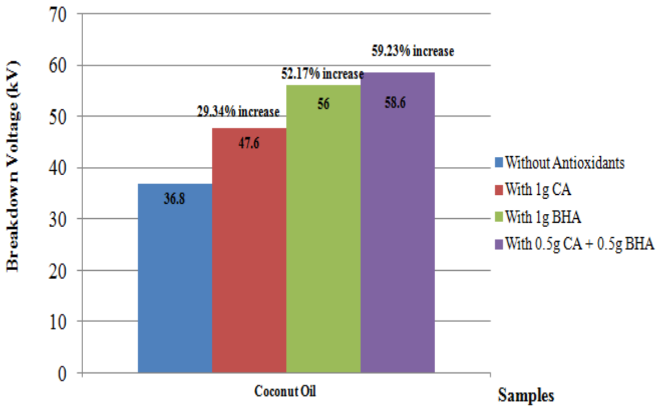

Figure 4: Increment percentage in BDV of base fluids after adding antioxidants

C. Physical Parameters:

Viscosity: The kinematic viscosities of the oil samples are measured at 60°C and 90°C because the transformer is expected to have a temperature rise of 30°C during its operation from the room temperature and further the maximum temperature rise that can be allowed can be till 90°C.

Table 4: Kinematic Viscosity of Base Fluids With and Without Additives

Samples	**Viscosity at RTP (cSt)**	**Viscosity at 60°C (cSt)**	**Viscosity at 90°C (cSt)**
Base Fluid (Coconut Oil)	86.47	40.89	20.29
Base Fluid + 0.01% ZnO (Liquid)	84.25	38.65	19.09
Base Fluid + 0.01% ZnO (Powder)	83.15	35.48	17.89
Base Fluid + 1g Citric Acid (CA)	86.02	33.9	15.94
Base Fluid + 1g Butylated Hydroxy Anisole (BHA)	85.36	31.40	13.45
Base Fluid + 0.5g CA + 0.5g BHA	84.47	28.88	16.19

Table 5: Decrement Percentage in Kinematic Viscosity of Base Fluids

Samples	**Decrement Percentage in viscosity (in cSt)**		
	At RTP	**At 60°C**	**At 90°C**
Base Fluid + 0.01% ZnO (Liquid)	2.56	5.47	5.92
Base Fluid + 0.01 % ZnO (Powder)	3.85	13.2	11.8
Base Fluid + 1g Citric Acid (CA)	0.52	17.06	21.4
Base Fluid + 1g Butylated Hydroxy Anisole (BHA)	1.28	23.16	33.65
Base Fluid + 0.5 g CA + 0.5 g BHA	2.32	29.3	20.17

From tables IV and V, it is observed that there is a decrease in viscosity values after adding nanoparticles and antioxidants for all the three operating temperature. Confinement and surface effects provided by nanoparticles produce changes in polymer molecules affecting their macroscopic viscosity. Nanoparticles may induce rearrangements in polymer conformation with an increase in free volume significantly lowering the viscosity.

Flash/ Fire Point: The flash/fire point of the base fluid with and without adding additives are listed in Table II.

Table 6: Flash/Fire Point Of Base Fluids With and Without Additives

Samples	**Flash Point (°C)**	**Fire Point (°C)**
Base Fluid (Coconut Oil)	235	270
Base Fluid + 0.01% ZnO (Liquid)	235	285
Base Fluid + 0.01 % ZnO (Powder)	290	315
Base Fluid + 1g Citric Acid (CA)	250	270
Base Fluid + 1g Butylated Hydroxy Anisole (BHA)	243	275
Base Fluid + 0.5 g CA + 0.5 g BHA	248	278

Table 7: Change in Flash/Fire Point of Base Fluids with and Without Additives

Samples	**Increment in percentage of**	
	Flash Point	**Fire Point**
Base Fluid + 0.01% ZnO (Liquid)	0	5.55
Base Fluid + 0.01 % ZnO (Powder)	23.1	16.65
Base Fluid + 1g Citric Acid (CA)	6.3	0
Base Fluid + 1g Butylated Hydroxy Anisole (BHA)	3.36	1.85
Base Fluid + 0.5 g CA + 0.5 g BHA	5.46	2.96

From tables VI and VII, it is observed that there is an increment in flash and fire point of the base fluid after adding nanoparticles and antioxidants for all the three operating temperature. It is inferred that there is no change in flash point of the sample prepared from base fluid with 0.01% ZnO liquid and fire point of the sample prepared from base fluid + 1g citric acid. Hence it does not affect the thermal stability of these fluids for using in transformer. However the values remains greater than that of the mineral oil. Thus, it is evident that the addition of nanoparticles and antioxidants to the dielectric fluid derived from natural esters has the potential to improve the thermal property of the fluids by Brownian motion of nanoparticles and degree of unsaturation respectively.

12. Conclusion and Future Scope:

From the results of the work, it is observed that the Breakdown voltage and Flash/Fire point of the base fluid had shown improvement and the values are higher than the mineral oil and viscosity of the base fluid had a decrement in its value due to the addition of nanoparticles and antioxidants. Thus the additives to the natural esters resulted in constructive outcomes. The research can be extended in performing the oil analysis test to understand the further effects of additives at the chemical structure of the insulating fluids. Overall investigation concludes that the the natural ester transformed using nanoparticles and antioxidants is an appropriate substitute of mineral oil for power transformer applications.

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