Comparison of Potential of Natural and Synthetic Multifunctional Additives with Natural Ester and Mineral Oil for Transformer Applications

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Abstract: *Transformers are meticulously used in power system and for century the mineral oil is used as dielectric, which performs superior function such as insulation and heat dissipation (cooling). The availability of petroleum resource and disposal methods (incineration) may introduce panic threads to human life and environment. On the other hand the deterioration of transformer insulation system will affect the life and stability of power system. This work envisages the optimality of critical characteristics enhancement of mineral oil and natural ester with high performance antioxidants (natural and synthetic) and lubricating oil additives. The enhancement percentages were calculated 2 % compositions of antioxidants and lubricating oil additives. The electrical, physical and thermal properties like breakdown voltage, viscosity, flash point and fire point are calculated for the samples before and after addition of antioxidants and lubricating oil additives. The enhancement of fresh transformer oil is carried by adding multiple combinations of antioxidants with different mechanisms like free radical scavenging, metal chelating and synergism. The critical parameters like breakdown voltage, viscosity, flash point, fire point acid value of the samples are calculated using before and after additives according to IEC and ASTM standards. The recorded parameters prove that the performance characteristics of natural ester oil shows superiority against mineral oil when used with multifunctional additives.*

Key words: *breakdown voltage, viscosity, flashpoint, firepoint, acidity, additives, antioxidant.*

1. Introduction

Power transformer is the vital equipment in power system, where its years depend on the properties of insulating mediums. In power sectors we commonly use solid and liquid mediums in transformer for the optimal function of the total system [1]. The probability of transformer failure is due to the unsympathetic properties of dielectric mediums. The odds of consistent fault are majorly due to the life of liquid insulation, which is prone to be affected by solid insulation too [2, 3].

The nature of power transformer and its increasing population from the time of its invention uses mineral oil as a default substitute of liquid insulation. Since the life transformer insulation being affected by ageing has pessimistic effects on the oil dielectric properties [1]. The intensified researches carried by researchers suggest the use of alternative insulation fluid, which is of natural way of existence and superior performance. Another prime fact is that, 75 % of transformer failure is chiefly reported on the liquid insulation [2, 3] and 50 % is defined by its tensile strength of solid insulation [4]-[6].

Moreover the relentless use of naphthalene and paraffin based mineral oil, synthetic oils like silicone and perchloroethylene; when disposed cause panic threads to terrestrial and ecosystem [7]. Many restrictions were imposed on special purpose transformer system using synthetic oils and improved versions of natural based insulating oils were being a landmark of transformer fluid revolution. Such high grade insulating fluids like R-Temp®, Envirotemp® FR3™ and Beta fluid® triumph over the negative possessions of existing mineral like petroleum based mineral oil [8]-[10]. Further the mineral oil and regenerative additives such as conductive, semiconductive and magnetic nano particles were integrated to obtain a superior performance of dielectric properties of the oil [11]. But due to annoying cost of nanoparticles and its environmentally hazardous nature (non-biodegradable) impose descending statements in implementing this technology.

The efforts taken by integrating natural esters like sunflower oil, rice bran oil, corn oil and soy bean oil and antioxidants (natural and synthetic) sympathetically positive results. The superior performance of transformed natural esters using antioxidants and its combinations exhibit parallel mechanisms like free electron scavenging, quenching, metal chelating and synergist [12]. In this work, α-tocopherol is used in place of natural antioxidant, synthetic antioxidants like propyl gallate and pyro gallol and synergists like carnosic acid and rosemary extracts were used due to its excellent performance reported in various research works [12]-[14].

The investigation of lubricating oil additives such as zinc dialkly dithiophosphates and Barium dinonylnapthelene Sulfonate polymethacrylates exhibit multiple mechanisms like antiwear, potent oxidation, corrosion inhibitors, detergents, rust and corrosion inhibitors, viscosity modifiers, dispersants and pour point depressants [15], which are the obligatory mechanisms of liquid insulation used in power transformer, but its complicacy is its nature of non-biodegradability and higher cost. To define the oxidation stability for insulating oils, it is mandatory to ensure the acidity and viscosity increase with oxidation during testing.

The present work envisages the use of high performance antioxidant additives and lube oil additives in mineral oil and natural ester oil. The selection of natural ester oil is based on the tropical climatic condition and proficient availability in India. For comparison traditional petroleum based mineral oil and natural ester oils like coconut oil is integrated with antioxidant and lubricating oil additives. This invokes the use of such additives in petroleum based mineral oil and natural ester oil.

2. Drive of the work

The extent of this investigation is based on common objective such as, to improve the present technologies which are currently under followed to enhance the properties of liquid insulation and to toss an alternative insulating fluid using natural esters and additives. Moreover tedious comparisons were imparted on the critical characteristics of the samples of mineral oil and natural ester oil before and after adding additives. The demonstrated method is an effervescent fixation for economically enhancing the fresh transformer oil and natural ester oils for the enhanced role of power transformer.

3. Materials

A. Multifunctional Additives

Antioxidants are compounds that delays or suppress the oxidation reaction. According to ASTM standard these antioxidants are designated as oxidation inhibitors and are used in least quantities such as 0.08 % for Type-I and 0.3 % for Type-II mineral oil. These oxidation inhibitors should be greater than 0.03 % for operating units [16]. In order to ensure this quantity, periodic testing is carried on the operating units and vanished level is supplemented to the operating units [16]. Based on its nature, it is generally classified into natural and synthetic type; on the mechanisms exhibited it is classified into primary antioxidants, secondary antioxidants and synergists [13]. Traditionally antioxidants like Butylated Hydroxy Toluene (BHT), Butylated Hydroxy Anisole (BHA) and Propyl Gallate (PG) are used by petroleum industries for manufacturing mineral oil [12]. Based on the careful investigation of antioxidants their mechanisms are categorized as follows; free radical

Table1
Nature and mechanisms of multifunctional additives used for investigations

	Antioxidant Name	Origin	Mechanism Exhibited	Risk on disposal	Melting Point (°C)
Antioxidants Additives	α- Tocopherol	Natural	Quenchers of singlet oxygen	Nil	62
	Propyl Gallate	Synthetic	Free radical scavengers + Metal chelators	Minimum	95
	PyroGallol	Synthetic	Free radical scavengers + Metal chelators	Minimum	130–135
	Carnosic Acid	Natural	Free radical scavengers + Synergists	Nil	120-125
	Rosemary Extracts	Natural	Free radical scavengers + Synergists	Nil	196-198
Lubricating Oil Additives	Zinc Dialklydithiophosphates	Synthetic	Antiwear + Potent oxidation + Corrosion inhibitors	High	72 to 74
	Barium dinonylnaphthalene Sulfonate	Synthetic	Detergents + Rust and corrosion inhibitors	High	Not available

scavenging, quenching, metal chelation and regeneration of primary antioxidants [13]. The Table1 shows the nature and mechanisms of antioxidants used in this investigation.

During the oxidation process, the formation of aldehydes, polymers and ketones reported which are panic to environment and human health. The use of carnosic acid obtained by natural origin is a potent antioxidant to suppress the activity of free radicals during oxidation and exhibit synergist mechanism.

Carnosic acid is found in high levels in rosemary extracts, in particular the carnosic acid is responsible for the high anti-oxidant levels of rosemary extract.

It scavenges free radicals and hydrogen peroxide. Similarly to adhere the qualities of antioxidants, the rosemary extracts reveal synergistic and suppress the formation of peroxide formed due to oxidation. Rosemary extracts contain several compounds belonging to groups like phenolic acids, flavonoids, diterpenoids and triterpe nes, which have proven antioxidative functions.

In addition to that, the α-tocopherol shows very good inhibition in addition with other antioxidants. Moreover the synthetic antioxidants like propyl gallate and pyrogallol are very good metal chelators (deactivators), that typically deactivates the catalyst metals which are harmfully present in the transformer. Owing to the mechanisms of lubricating oil additives, the selected additives like zinc dialkly dithiophosphates and barium dinonylnapthelene sulfonate performs multiple mechanisms.

4. Standards Used

In this work the following standards given in Table2 are used in determining the critical properties of the samples.

Table2
Critical properties and associated standards

Critical Parameters	Standard Used
Breakdown Voltage (kV)	IEC 60156
Flash Point (^{O}C)	ASTM D93
Fire Point (^{O}C)	ASTM D93
Viscosity (cSt)	ASTM D445
Acid Value (mg KOH/g)	ASTM D974

5. Sample Descriptions

Natural ester like coconut oil contains variety of highly sensitive fatty acids that ultimately affects the oil's stability under difference stressing provision. The presence of free radicals in unsaturated fatty acids undergoes oxidation. The samples are prepared by taking 500 ml of base fluids and antioxidants and lubricating oil additives in minimum and maximum compositions such as 0.3 % of sample volume. In this work, fresh mineral oil and coconut oil are designated as base fluid 1 and 2 respectively. For consistency the sample numbers 1-8 is prepared by combining the base fluid 1 and 2 and antioxidants mixtures A1-A8 and sample number 9-12 is prepared by combining the base fluid 1 and 2 and lubricating oil additives mixtures L1-L4. The samples are heated to the melting temperature of antioxidants and lubricating oil additives and finely stirred using magnetic stirrer arrangement for 30 to 60 minutes until complete dispersion of solute and solvent take place. Then the critical properties like breakdown voltage, viscosity, flash point, fire point and acid value are predetermined for qualitative comparison with base fluid 1, and 2. The critical properties of base fluids are depicted in Table3.

Table3
Critical properties of base fluids

Critical Parameters	Base Fluid 1 Mineral Oil	Base Fluid 2 Coconut Oil
Breakdown Voltage (kV)	29	31
Flash Point (^{O}C)	152	210
Fire Point (^{O}C)	165	232
Viscosity (cSt)	23	45
Acid Value (mg KOH/g)	≈ 0	≈ 0

6. Critical Properties

The samples prepared using base fluids 1 and 2 with multifunctional additives are tested as per the standards of IEC and ASTM. The properties of the oil samples are categorized into electrical, physical, thermal and chemical properties.

A. Electrical Property

The breakdown voltage is an important property in determining the strength of the insulating oil. It is majorly affected by the degree of moisture, acid and impurities present in the oil. The test is conducted as per IEC60156 standard [17] in a breakdown voltage test kit with spherical electrodes of standard diameter and inter spacing is 2.5 mm. The samples are tested successively for 4 to 5 times and the average value is taken as the breakdown strength of the oil.

B. Physical Property

The effective dissipation of heat is associated with flow rate of insulating fluid in other words the shear stress. Higher viscosity leads to the formation of bubbles and voids, which are dangerous to the transformer system and lower viscosity also initiates the formation of bubbles. Hence moderate viscosity is optimal to neglect the stray charges produced on the surfaces of the metals and pipes during flow of oil. The test is carried out as per ASTM D445 [18] standard in redwood apparatus containing test cup with 20 ml capacity and a orifice at the bottom to measure the time taken to collect the sample at the other end. The viscosity of oil decreases as the temperature and increases as the temperature drops.

C. Thermal Property

In operating units the temperature of the oil increases abruptly and it initiates the formation of gases inside the transformer tank. Such fumes when contacts the atmospheric oxygen forms ignition mixture and generate a temperature flash on the oil surface, which is termed as flash point. If the flashing condition prevails successively then oil begins to burn and the condition is termed as fire point; explosion of transformer unit may happen. Hence the thermal properties of the insulating fluid are essential in evaluating the oil grade. The flash point and fire point of the samples are measured as per ASTM D93 and ASTM D92 [19] and are depicted in Table 4.

D. Chemical Property

Atmospheric condition is the important source of acid formation in the insulating fluid. The formed organic acids detoriates the insulation system and be capable of stimulating corrosion in the presence of water. Increase in the acidity also increases the sludge content in transformer oil and hence detriments the oil strength. By the picture of transformer analysis guide, acidity of insulating fluid in a transformer system should never be allowed to surpass 0.25mg KOH/g of oil. Here the samples are tested for acidity as per ASTM D974 [20] and are illustrated in Table 6.

7. Results and Discussion

The comparison is made between the antioxidants and lubricating oil additives behavior in natural ester and the mineral oil in 2 g composition. The existing demand of natural resources and depletion strategy of petroleum based resources bring another outrage in the field of transformer cooling medium development. The recorded characteristics proves that, the addition of environmentally less harmful antioxidants (A1, A2, A3 and A4) in coconut oil and mineral oil than lubricating oil additives (L1 and L2).

The electrical characteristics of base fluid 1 and 2 before and after adding multifunctional additives shows a good percentage of enhancement in the category of antioxidants and lubricating oil additives. But another interesting finding is on repeated breakdown voltage testing of base fluids 1 and 2 with antioxidants composition (A1 – A4) in a time gap of 2 minutes between each test, the samples exhibit a constant value of breakdown. But for samples containing base fluids 1 and 2 with lubricating oil additives shows constant increase in voltage with increase in oil temperature, which is displayed in Figure 1. This could account in the formation of different gas mixtures on the top (Headspace) of transformer tank. Further the oil exhibit higher breakdown voltage at high temperature, because at high temperature the partial pressure of the gases built up on the headspace of transformer will increase the net pressure on the tank. The temperature in turn increases the space between liquid molecules and gases begin to occupy the space between molecules. Hence increasing the breakdown voltage of oil at higher temperature and decreases the life of oil due to rapid ageing.

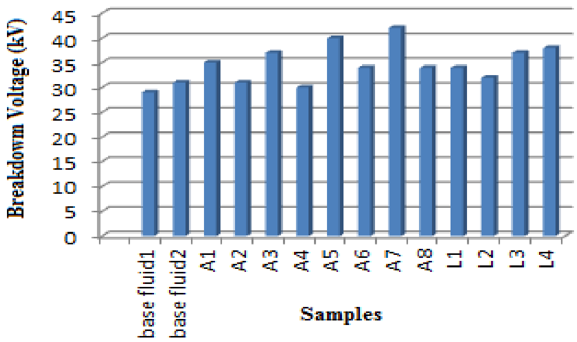

Figure 1. Breakdown voltage characteristics of samples treated with antioxidants (A1-L4).

Similarly the physical properties like viscosity from Table4 shows, the value of samples treated with antioxidants remains more or less same. But to the view point the samples containing the composition of base fluids 1 and 2 with lubricating oil additives shows better enhancement. Further the viscosity value of sample decreases for the

Table4
Critical properties of samples

Sample No.	Antioxidant Mixture	Additive Mixture and Oil Mixture		Breakdown Voltage (kV)	Viscosity (cSt)	Flash Point (°C)	Fire Point (°C)	Acidity (mg KOH/g)
		Antioxidant Mixture (2 g)	Base Fluid					
1	A1	Propyl Gallate + α-Tocopherol	1	35	25	154	170	< 0.02
2	A2	Pyrogallol + α-Tocopherol	1	31	24	155	167	< 0.02
3	A3	Rosemary Extracts + α-Tocopherol	1	37	24	152	167	< 0.02
4	A4	Carnosic Acid + α-Tocopherol	1	30	23	150	165	< 0.02
5	A5	Propyl Gallate + α-Tocopherol	2	40	48	215	240	< 0.02
6	A6	Pyrogallol + α-Tocopherol	2	34	46	212	237	< 0.02
7	A7	Rosemary Extracts + α-Tocopherol	2	42	48	215	234	< 0.02
8	A8	Carnosic Acid + α-Tocopherol	2	34	46	207	228	< 0.02
9	L1	Zinc dialkly dithiophosphates	1	34	21	156	166	< 0.02
10	L2	Barium dinonylnapthelene sulfonate	1	32	20	155	168	< 0.02
11	L3	Zinc dialkly dithiophosphates	2	37	40	218	235	< 0.02
12	L4	Barium dinonylnapthelene sulfonate	2	38	38	215	238	< 0.02

displayed in Figure 2.

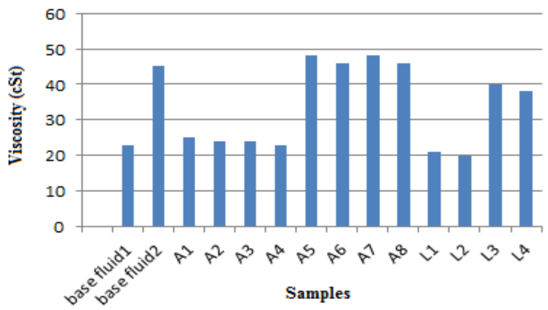

Figure 2. Viscosity characteristics of samples treated with antioxidants (A1- L4).

Furthermore the physical characteristics such as flash point and fire point of samples from Table IV shows the percentage enhancement of thermal characteristics of samples containing base fluid 1 and 2 with antioxidants is smaller compared to samples containing base fluids 1 and 2 with lubricating oil additives. The characteristics are given in Figure 3.

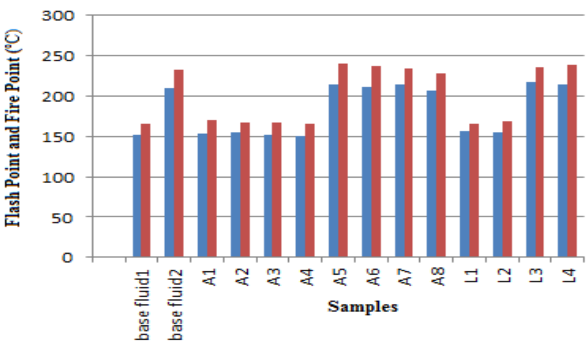

Figure 3. Flash Point and Fire Point characteristics of samples treated with antioxidants (A1- L4).

Since the same parallel mechanisms can be observed on natural and synthetic antioxidants. Much likely the lubricating oil additives can be qualitatively used in systems with higher mechanical stresses (wear and tear). In accessing the chemical property of samples from Table IV and its characteristics are given in Figure 4, the percentage increase in acidity is much likely remains same for all samples due to oxidation.

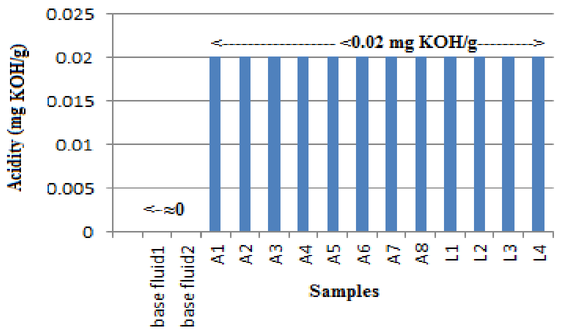

Figure 4. Acidity characteristics of samples treated with antioxidants (A1-L4).

With the addition of antioxidants and lubricating oil additives to base fluids 1 and 2, no prominent increase of acidity is determined. The acidity could be greatly inferred when the samples gets in contact with paper insulation, which is made up of cellulose material and highly prone to polymerization.

8. Conclusion

The analysis is used to establish a technology to transform natural ester like coconut oil, which is ample in tropical countries like India. Moreover the multifunctional additives like antioxidants (combination of antioxidants) and lubricating oil additives is a proven technique for enhancing the natural ester oil and mineral oil. The inclusion of natural and synthetic antioxidants (A1 – A4) and lubricating oil additives (L1 – L2) with natural ester oil (base fluid 2) and petroleum oil (base fluid 1) enhances the critical properties of oils. More specifically the performance of enhanced base fluid 1 and 2 with multifunctional additives is stable at normal and elevated temperature for antioxidants. The significant facet with antioxidants combination during experimentation is very less carbon content is observed during breakdown and this constitutes least percentage of dissolved gases formation.

From inspection, combinatorial effect of high performance antioxidants is effective and less prone to chemical effects than lubricating oil additives. Result offers a different dimension in estimating the performance of transformer oil and fresh transformer oil with antioxidants. This technique of enhancement of mineral oil and natural ester oils helps to overcome oil shortages expected in the near future. This approach is also useful in avoiding harmful disposal of used transformer oil to environment. On the whole the coconut oil and mineral oil enhanced using multifunctional additives is an appropriate solution for potential use in power transformer.

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