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Environmentally Friendly Fire Safe Superior Synthetic Ester Dielectric Fluids for Green Transformers

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ABSTRACT: Electricity is the engine powering the economic development and growth of any country. Transformer is the most vital equipment in the application of the electrical energy for diverse needs like domestic, indoor and outdoor distribution, high voltage, extra high voltage and ultra-high voltage applications. The transformers and reactors are critical links in the transmission and distribution systems. Over the period rapidly expanding power transmission systems involving HV, EHV & UHV equipments, have seen vast changes in the material concept and designs also. Today we have an installed capacity of electricity is 330.86 GW as of 22 December 2017, and we find thousands of transformers are ubiquitous in human environment. Added to it in today's overriding concerns about environment and fire safety compact transformers capable of taking higher loads, electrical & thermal stress and meeting environmental requirements are increasingly in use.

Distribution transformers are very crucial parts of transmission & distribution domain these units require dielectric fluids which ensure excellent performance and absolute safety. The synthetic ester based dielectric fluids having extraordinary properties are ideal for these power equipments.

In this paper we present the results of the study undertaken by us on a vastly superior synthetic ester dielectric fluid in accordance with IEC 61099, 61125 Method C, OECD 301B & IEEE C57.104

Keywords: *synthetic ester dielectric fluid; high fire point; high flash point; oxidation stability; biodegradability; total acidity; total sludge; ddf; compact dt; turbine transformer.*

1.0 INTRODUCTION

Majority of power transformers in use today utilize mineral insulating fluid and cellulose insulation system for the management of dielectric stresses. This system is reliable since past 125 years and this situation is likely to continue well into the future. Today the power sector has become very conscious about environmental considerations and is actively moving towards substituting with ecologically friendly solutions. The transformer industry and users have realized the limitations with regard to use of conventional naphthenic oil, silicone oil and PCBs in the light of the ecological demands.

Transformers and reactors are the most critical equipments all the way from generation, transmission, and distribution to millions of end users of all categories. In the last 125 years or more the demand for electrical energy has been registering exponential growth. One can hardly imagine any activity where dependence on electricity is not there. Further in the context of today's mega cities the fire safety and other environmental considerations have assumed major dimensions. Hence today all equipments in transmission and distribution systems have to be created bearing in mind this important factor.

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Dielectric fluids are critical for the efficient performance of electrical equipments. Primarily Dielectric Fluids have three critical functions - insulating the live parts, effectively conveying the heat from conductors to the radiators and extending diagnostic support to monitor the health of the equipments through regular checks. This is vital from the point of view of prolonged healthy life of the equipment. In the current scenario the synthetic ester & natural ester dielectric fluids are in use for specific applications, considering its overall fire safety advantage and environmental benefits.

In this paper we present the results of the study undertaken by us on our vastly environmentally fire safe synthetic ester dielectric fluid in accordance with IEC 61099, 61125 Method C, OECD 301B and IEEE C57.104

2.0 APPLICATION OF ALTERNATIVE DIELECTRIC FLUIDS

Alternative dielectric fluids are now being widely used in a variety of transformer applications for distribution, power and traction applications as shown in Table 1.

TABLE 1

APPLICATION OF ALTERNATIVE DIELECTRIC FLUIDS IN POWER EQUIPMENT [1]

Transformer Type	Mineral DF	Silicone DF	Synthetic Ester DF	Natural Ester DF
Distribution Transformer	√	√	√	√
Marine transformer	√	√	√	√
Mine Transformer	√	√	√	√
Power Transformer	√	X	√	√
Traction Transformer	√	√	√	√
Turbine Transformer	√	√	√	√
Instrument Transformer	√	X	X	X

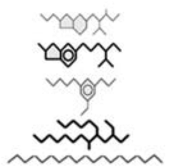
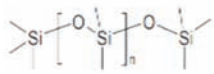
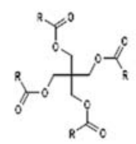
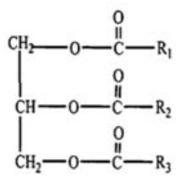
(√= largely used, X= currently Not used)

3.0 COMPARISION OF PROPERTIES OF ALTERNATIVE DIELECTRIC FLUIDS

An overview of comparison of properties of alternative dielectric fluids for designing transformers as shown in Table 2.

TABLE 2

OVERVIEW OF PROPERTIES OF ALTERNATIVE FLUIDS [2, 3, 4, 5]

Overview of Properties of Dielectric Fluids				
Characteristics	Mineral DF (Conventional Naphthenic Oil)	Silicone DF	Synthetic Ester DF	Natural Ester DF
Standards Governed	IEC 60296:12 ASTM D3487:16 IS:335	IEC 60836:15 ASTM D4652:05 (2012)	IEC 61099:13 ASTM D IS 16081:13	IEC:62770:13 ASTM D6871:17 IS 16659:17
Dielectric Fluid Type	Refined from Crude Oil	Synthetic	Synthetic	Refined from Vegetable Oil
Source	Petroleum Crude	Chemical Synthesis	Chemical Synthesis	Plant Seeds
Molecular Structure				

Flash Point, °C	160-170	>300	>250	>300
Fire Point, °C	170-180	>350	>300	>350
K. Viscosity, mm2/S, at 40°C	10	50	26.4	36
Pour Point, °C	<-40	-50	-55	-21
Fire Classification as per IEC 61100	O	K3	K3	K2
Net Calorific Value, MJ/kg	46	28-32	31.6	37.5
Specific Heat at 20 °C, J/kg K	1860	1510	1920	1848
Expansion Coefficient, °C	0.00075	0.00104	0.00075	0.00074
BDV, kV	>70	50	70	56
DDF @90°C	<0.005	<0.001	<0.03	<0.05
Permittivity	2.2	2.7	3.1	3.2
Negative Impulse, kV at 25.4mm gap	>250	<200	>200	<150
Bio-Degradability	Slow	Very Slow	Readily	Readily
UBA Ranking	NO	NO	NWG	NWG
Moisture Tolerance at Room Temperature, ppm	55	220	2600	1100
Oxidation Stability	Excellent Stability	Excellent Stability	Excellent Stability	Poor Stability
Miscibility	Synthetic Ester & Veg Ester	Not Miscible with other DFs	Min Oil & Veg Ester	Min Oil & Synth. Ester

4.0 EXPERIMENTAL RESULTS & DISCUSSIONS

A. Synthetic Ester Dielectric Fluid - Risk Of Fire Assessment

Fire safety risk is a vital factor in choosing a dielectric fluid which is used in specially designed special transformers such as distribution transformers in distribution applications in highly urbanized areas like shopping malls, mega towers, hospitals, traction transformer in metro trains, high speed trains, tunnel transformer in railway tunnels, mine transformers in coal mines, marine transformers in cruise, ships, offshore transformer in wind turbines and high rise off shore substations, etc., synthetic ester dielectric fluid is the best solution to address the fires safety requirement as shown in Fig 1.

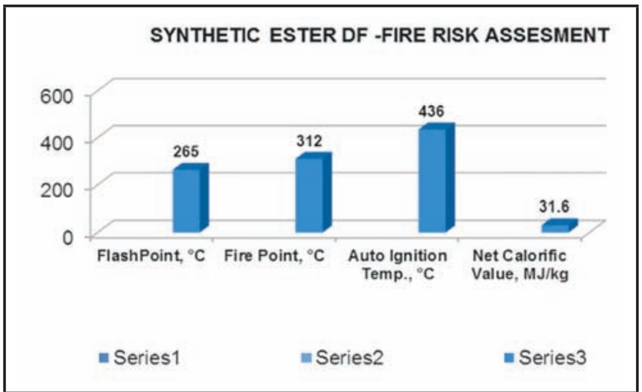


FIG. 1 RESULT OF FIRE RISK PARAMETER

B. Synthetic Ester Dielectric Fluid - Risk Of Ecological Assessment

Synthetic ester dielectric fluid filled in specially designed special transformers will not pollute the surroundings such as water pollution, air pollution and land pollution. Both natural and synthetic ester fluids are officially classified as 'readily biodegradable'. They pass strictly controlled degradation tests carried out according to OECD methods. These test methods are internationally established and recognized. Their behaviour contrasts markedly with silicone fluids and conventional naphthenic fluids. These fluids are tested for biodegradability as per OECD methods for aquatic toxicity - such as 203 for fish, 202 for daphnia and 201 for algae. To further support the environmental credentials of synthetic ester dielectric fluids they are also officially classed as 'non water hazardous' according to Umweltbundesamt (UBA) ranking as shown in Fig 2.

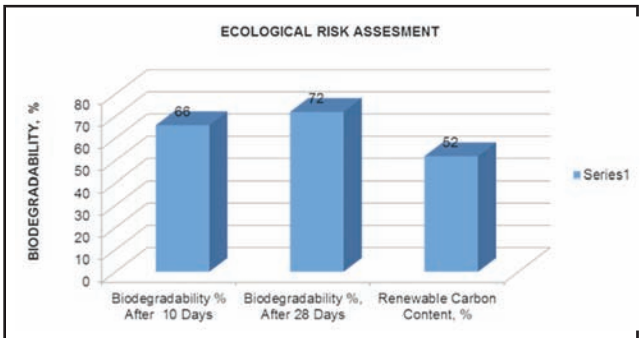


FIG. 2 RESULTS OF ECOLOGICAL RISK PARAMETERS

C. Synthetic Ester Df - Moisture Tolerance & Breakdown Voltage

Synthetic ester dielectric fluids have 4-Ester linkages per molecule as compared to 3-ester linkages per molecule in natural ester dielectric fluids. Mineral dielectric fluids are non-polar in nature. Silicone fluids are slightly polar in nature. Ester linkages are highly polar in nature. Because of their polar nature they attract water molecules in large quantity by forming hydrogen bonding as shown in figure 3.

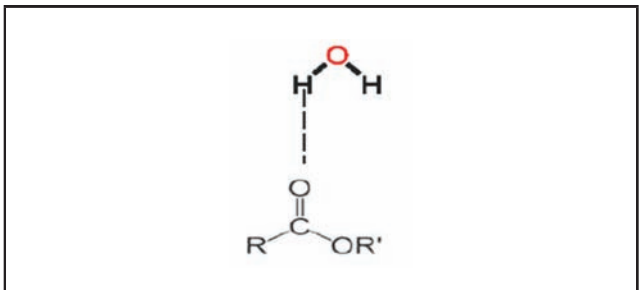


FIG 3 A VIEW OF WATER ATTRACTION

- Synthetic Esters absorbs large amounts of moisture with no reduction of breakdown voltage (up to 700ppm at ambient temperature)
- Synthetic Ester Dielectric Fluid allows moisture to migrate from cellulose into the fluid
- Potentially it keeps the cellulose dry and slows the rate of ageing
- It has very high moisture saturation limit.
- Reduces the risk of bubble formation and least worries of low energy discharges
- Synthetic ester dielectric fluids maintain high breakdown voltages even with significantly larger amounts of dissolved moisture as shown in figure 4.

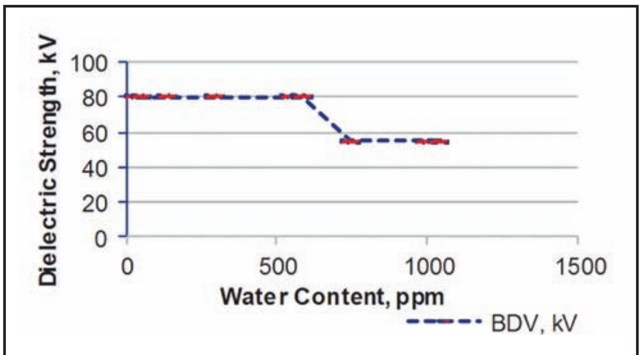


FIG. 4 BDV VS MOISTURE CONTENT

D. Oxidation Stability Test- Synthetic Ester Dielectric Fluid

Oxidation Stability (essential and most important property) of the dielectric fluid is also known as life test on oil which will give an indication of the oil's ability to withstand ageing in the form of oxidation and will give an indication of the life expectancy of oil which is extremely important to the asset managers in the utility.

OST tests on synthetic ester dielectric fluids were conducted in the laboratory for 164, 500 & 1000 hours of test durations as per IEC 61125 Method C at 120 °C to understand the formation of harmful oxidation by-products such as polar compounds (acids), insoluble sludge etc., in the oil and its impact on dielectric properties [6]. The properties are as mentioned in Table 3 and the graphical representation as shown in figure 5.

TABLE 3					
EXTENDED OXIDATION STABILITY OF SYNTHETIC ESTER DIELECTRIC FLUIDS					
Property	**Specified IEC Limits for 164 Hrs. (Tested as per 61125 Method C)**	**Results Before Oxidation Test**	**Results After Oxidation Test**		
Time, Hours	164	0	164	500*	1000**
Total Acidity, mg KOH/g	0.3	0.012	0.013	0.013	0.045
Total Sludge, by Wt. %	0.01	Nil	Nil	0.013	0.021
Tan Delta @90°C	No Requirement	0.012	0.018	0.0214	0.49
Resistivity @90°C, 10 12 Ω-cm	No Requirement	21	10	0.155	0.06
Colour	No Requirement	0	<0.5	1.5	2.5
*(Optional test and No requirement as per IEC 61099), ** (No Requirement as per IEC 61099)					

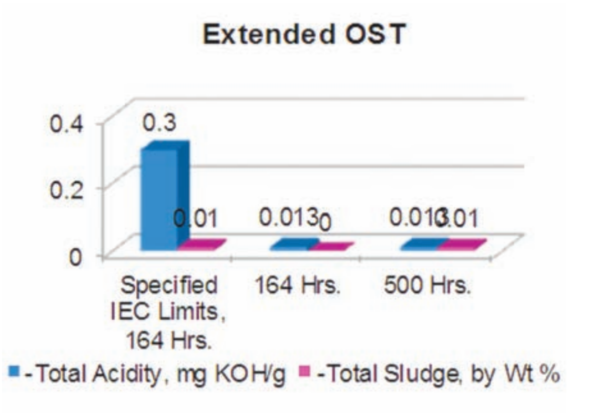


FIG. 5 RESULTS OF OXIDATION STABILITY

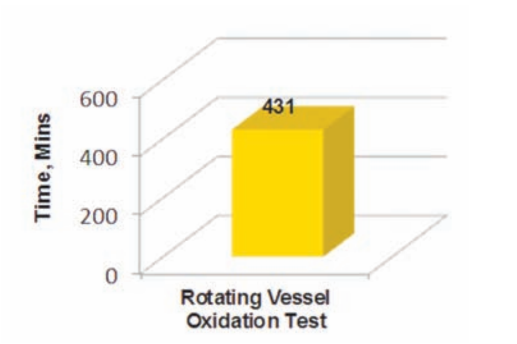


FIG. 6 RESULTS OF RVOT

E. Rotating Vessel Oxidation Stability Test

RVOT [7] was conducted in accordance with ASTM D2112e to understand the synthetic ester dielectric fluid resistance to oxygen. In this experiment the synthetic ester oil (50 g +/- 0.5) was subjects to pressurised oxygen (90 psi @ 25 °C) at elevated temperature of 140°C in the presence of copper catalysts (surface area 95.34cm²) and moisture (10 %) at the rotation speed of 100 +/- 5 RPM. Measuring the time for the oxygen pressure to drop to a predetermined level (25psi) gives an understanding of the stability of the fluid against oxygen as shown in figure 6

F. Dga - Fault Gases Evolved By Simulated Low-Energy Arc Tests

TABLE 4				
DGA RESULTS				
Results of Dissolved Gas Analysis After Simulated Low-Energy Arc Test				
Oil Type	**Mineral Oil (Conventional Naphthenic)**		**Synthetic Ester Dielectric Fluid**	
Sample	Control	After Low Energy Arc Test	Control	After Low Energy Arc Test
H2	0	89	0	9
CH4	0.3	23	0.3	8
C2H6	0	9	0	4
C2H4	0	34	0	14
C2H2	0	502	0	174
CO	0.3	10	0.3	2
CO2	122	598	82	330
TDCG	13	646	5	160

In the laboratory fault gases were simulated by using 220V/100kV, 900VA test transformer to generate breakdowns across mushroom shape and needle electrode configuration with an oil gap distance of 2.5 mm. When the breakdown occurs in the dielectric fluid, it will degrade the oil molecule locally as the energy being dissipated causes the molecular structure of the synthetic ester dielectric fluid to be disrupted. To ensure a sufficient concentration of fault gases, a total number of 180 breakdowns were produced in the oil. This allows the formation of fault gases like acetylene. There was one minute interval between each breakdown [8]. The results are compared with conventional mineral oils as shown in Table 4 and Figure 7.

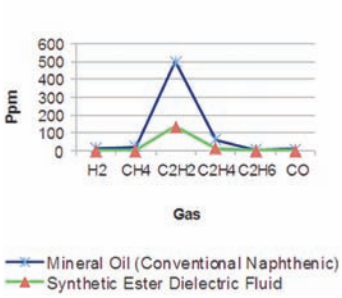


FIG 7 COMBUSTIBLE GAS CONCENTRATIONS

From the simulated low energy arc test results it is obvious that generation of volatile gas acetylene is far low compared conventional naphthenic oil. Synthetic ester dielectric fluid has the same DGA fingerprints as conventional naphthenic oils with lower volumes of gas produced.

G. CAPILARY ACTION & CELLULOSE IMPREGNATION

Since the viscosities of alternative fluids are of varying nature at 40 °C. It was necessitated us to study and understand the capillary action of 3 mm thick pressboard blocks in synthetic ester dielectric fluid at room temperature (~26°C) and at 60 °C. The rate of rise of capillary action of synthetic ester dielectric fluid at 60°C was found to be equivalent to the rate of mineral oil at room temperature ~26 °C. The study indicates that the rate of impregnation of synthetic ester dielectric fluid at 60°C would be equivalent to the rate of Mineral oil impregnation at room temperature ~26 °C. The viscosity of synthetic ester dielectric fluid at 60 °C is equivalent to that of mineral oil at ~26°C. This property is utmost important during processing of transformers & reactors [9].

Material compatibility with transformer construction materials is very important factor to design transformers with alternative fluids to understand their reactivity,

H. MATERIAL COMPATIBILITY [10, 11]

TABLE 5
TRANSFORMER CONSTRUCTION MATERIALS COMPATIBILITY WITH SYNTHETIC ESTER DIELECTRIC FLUID

COMPATIBLE MATERIALS				NON-COMPATIBLE MATERIALS
Seals, O-rings & Joints	Tank Coatings, Insulating Varnishes & Paints	Films	Miscellaneous	Elastomers
Viton (FKM)	Acrylic	Cellulose Triacetate	Kraft Paper	NR (Natural Rubber)
Nitrile Rubber (NBR) >30% nitrile	Epoxy	Mylar	Cotton Tape	IR (Polyisoprene Rubber)
Silicone (VMQ)	Polyurethane	-	-	(NBR) Nitrile Content <30%
Fluoro Silicone (FVMQ)	Alkyd	-	-	EPDM (Ethylene Propylene)
Polyurethane, AU	-	-	-	CSM (Chlorosulfonated Polyethylene, Hypalon)
Teflon	-	-	-	
Nylon	-		-	-
Nitrile Cork Rubber	-	-	-	-

till date we use mineral oil. Compatibility study was conducted in the laboratory in accordance with ASTM D 3455 with most of the materials used in modern transformer manufacturing except few elastomers such as Natural Rubber, poly-isoprene rubber, nitrile rubber with less than 30% nitrile content, EPDM, chlorosulfonated polyethylene hypalon which are found as non-compatible as shown in Table 5.

3.0 CONCLUSIONS

- Synthetic ester dielectric fluid is best option to address fire & pollution risk when the product needs protection from fire and pollution
- Synthetic ester dielectric fluid is the best solutions for traction, bio-slim, turbine, marine, mine, compact distribution transformers & compact special transformers including indoor applications
- Synthetic Esters are compatible with most of the materials used in modern transformers
- Synthetic Ester Dielectric Fluid can tolerate substantially larger amounts of moisture in comparison and still work effectively
- Synthetic ester DF has the potential to keep cellulose dry, extending the life of the transformer
- Synthetic ester dielectric fluid has extremely good oxidation stability which will last longer in the equipment
- Synthetic ester dielectric fluid have the same DGA fingerprints as conventional naphthenic oils with lower volumes of gas generation
- Overall synthetic ester dielectric fluid protects the equipment maintaining the reliability of the grid

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REFERENCES

[1] H.Borsi, E. Gockenbach , K. Dumke “A synthetic Insulating Liquid for application in transformers” 9th International Symposium on High Voltage Engineering, Graz, 1995

[2] IEC 61099:2013, “Specifications for unused synthetic organic esters for electrical purposes”

[3] IEC 61100:93, “Classification of insulating liquids according to fire-point and net calorific value”

[4] IEC 62770:2013 Fluids for electrotechnical applications - Unused natural esters for transformers and similar electrical equipment

[5] IEC 60836:2015 Specifications for unused silicone insulating liquids for electrotechnical purposes

[6] IEC 61125:1992/08 “Unused hydrocarbon-based insulating liquids – Test Methods for evaluating the oxidation stability”

[7] ASTM D2112: (2015), “Standard Test Method for Oxidation Stability of Inhibited Mineral Insulating Oil by Pressure Vessel”

[8] Imad-U-Khan, Zhongdong Wang, Ian Cotton & Susan Northcote, “Dissolved Gas Analysis of Alternative Fluids for Power Transformers” IEEE Electrical Insulation Magazine, 2007 pp 5-14

[9] Jie Dai, Z. D. Wang, P. Dyer, A. W. Darwin and I. James “Investigation of the impregnation of cellulosic insulations by ester fluids” Conference paper on impregnation technology with ester oil (CEIDP Canada 2007)

[10] ASTM D3455 -11 “Standard Test Methods for Compatibility of Construction Material with Electrical Insulating Oil of Petroleum Origin”

[11] K. Baburao et all, “Superior Dielectric Fluids for Modern Instrument Transformers for Power System & Grids” Tech IT 2014

BIOGRAPHY

K. Baburao has been employed at Raj Petro Specialities Pvt Ltd since 2011, and currently works as an Assistant General Manager in the Research & Development Department. He is a CIGRE India Member.

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He has 31 years of work experience in the field of new product development, new process development, new material development and new application development in Transformers & Switchgears including Condition Monitoring & Diagnostics of Power Transformers. He has worked on the Development of Bio-Degradable Oils.

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K. Baburao has received his Master's Degree in Chemistry from Osmania University, Hyderabad in 1984 and M. Tech Degree in Materials Science (Polymer Specialization) from Indian Institute of Technology (IIT) Bombay in 1986.

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