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Comparison of Ageing Characteristics of Superior Insulating Fluids With Mineral Oil for Power Transformer Application

RAYMON ANTONY RAJ, RAVI SAMIKANNU, (Member, IEEE), ABID YAHYA, (Member, IEEE), AND MODISA MOSALAOSI, (Member, IEEE)

Department of Electrical, Computer and Telecommunications Engineering, Faculty of Engineering and Technology, Botswana International University of Science and Technology, Palapye, Botswana

Corresponding author: Raymon Antony Raj (raymonhve@gmail.com)

ABSTRACT Natural Esters (NEs) with a high proportion of Unsaturated Fatty Acids (UFAs) were used in this research. A Superior Insulating Fluid (SIF) is prepared by blending NEs like Baobab Oil (BAO) and Mongongo Oil (MGO) with a pure dielectric like Kerosene (KER) and subjected to ultrasonic wave treatment at 30 *kHz*. Then, accelerated heating of SIF is carried out in the presence of Kraft Paper (KP) and Copper Plate (CP) for 10 hours a day at 90 $^{\circ}C$ for 30 successive days. The deterioration of the dielectric characteristics of SIF, KP, and CP was measured as per IEC and ASTM standards before and after the schemes of stressing. The failure rate of SIF, KP and CP was compared to understand the influence of KER in NEs. The KER addition at 5% proportion protects the oil from dielectric weakening, copper from ageing and likewise, the viscosity remains at the original level. The use of KER in NEs have thin the oils and protects the copper from oxidation, thus preserving the quality of oils for several years. The extrapolation of data is done using a polynomial function and for 90 days, where the selected SIFs show 7% of ageing rate when compared to MO that shows 50% ageing rate. This affirms that SIFs are a suitable substitute for Mineral Oil (MO) and reclamation SIFs are achieved using natural reclamation/filtration techniques using Activated Bentonite and Activated Carbon. Hence spilling and reusing the SIFs does not harm the environment as that of Mineral Oil (MO).

INDEX TERMS Ageing, Kraft Paper, mineral oil, natural ester, pressboard, power transformer.

I. INTRODUCTION

Energy sectors across the world are focusing on the utilization of renewable sources to create a carbon-free environment. Power transmission units like the power transformer have been using Mineral Oil since 1890 to present [1]. The demand for power is rising day-by-day and the number of power transformers in the network is increasing as well. Therefore, the utilization of insulating fluids in power transformers has attracted the attention of researchers in recent years [2]. The use of MO in power accessories like transformers [3], high voltage cables [4], high voltage capacitors [5] and high-pressure oil circuit breakers [6] is necessary for achieving insulation and cooling. But the adverse effects of using MO during operation followed by reclamation or post-disposal will affect the environment with Particulate Matters Emission (PME) [7], [8]. Shifting the focus towards edible markets offers several options in the form of NEs which have superior insulation and cooling properties [1] than commercially used MO. NEs on the other hand, are amply available and must therefore, be investigated for their suitability as dielectric fluids and possible substitute to MO. The dielectric strength is the qualifier line for any oil to be used as a dielectric fluid, MO has a poor dielectric strength much less than NEs [9]. Moreover, many transformer fires are because of the poor cooling performance due to low thermal characteristics of MO. The NEs thermal characteristics are double to thrice that of MO provided with better dissipation constant [10]. To a large extent, the solid insulation in MO-filled power transformers deteriorate at a faster rate than those with NEs because both the NEs and solid insulations (Kraft Paper (KP) and Pressboard (PB) are environmentally compatible [11]. Even though the oxidation rate of MO is much lesser than that of NEs, MO in contact with solid

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insulation and copper windings increases the oil's acidity and sludge [12]. This tends to increase the copper-oxidation and conductivity; therefore, oil's dielectric strength gets reduced to increase the probability of insulation failure. Hence, to reduce such failure the use of NEs is the only environmentally friendly choice for enhanced power transformer life and its service reliability.

II. MATERIALS AND METHODS

A. UNSATURATED FATTY ACIDS (UFAs) RICH NATURAL ESTERS (NE)

NEs which are naturally highly viscous needs treatment before installation in power transformers [13], [14]. Many researchers place greater attention on the composition of Saturated Fatty Acids (SFAs) where more of it offers better oxidation stability when compared to oils with higher content of UFAs [15]. The SFAs rich NEs are hydrogenated oils with more Hydrogen (H) molecules that mix with the sulfur in the oil resulting in the post-production of sulfur oxides. Sulfur in oil is a warning sign that the solid insulation is at greater risk [7], [16] and deterioration will increase [17], [18]. The NEs rich in UFAs do not contain H molecules in the fatty acid chain and thus no production of sulfur oxides, reducing the risk of deterioration of solid insulation. With regards to viscosity, NEs with high SFAs have an H molecule between every Carbon-Carbon *(C-C)* chain and it is difficult to alleviate the *(C-C)* length unless using any ultrasonic wave treatment [19], [20]. But the effect could be short-term so that the *(C-C)* length begins to shrink as the viscosity matrix is rigid to restore to its initial length. On the other hand, NEs with high proportion of UFAs containing *(C-C)* chain without *H* molecule by nature possess flexible viscosity matrix [21] which will show a good response to ultrasonic waves.

B. KEROSENE (KER) - $C_{10}H_{22}$

Kerosene (KER) has been used as a burning fuel before the existence of Mineral Oil for transformer application [22]. KER is a pure mineral oil that burns pure and possesses miscible property when blended with high-density solvents like diesel, paints and high-grade engine oils [23]. Studies have shown that biodiesel prepared from kerosene and edible oil have identical carbon chain length [24]. It is a class-3 flammable liquid with a good dielectric permittivity of 1.86 (at $21°C$), thus preventing electric field conduction in the dielectric. This can be deduced from the relation $E = \sigma/\xi$, where E is electric field, σ is conductivity, and ξ is permittivity that exists within the dielectric by keeping the conductivity minimum [25]. KER, when blended with a solvent will produce a homogeneous mixture and no agglomeration in the post phase. KER has a pour point of $-47°C$ that helps to keep the oil circulating in the transformer during extreme cold weather [26]. The alkali metals are usually stored in KER to protect them from oxidation, hence it acts as a good lubricant against metals like Iron *(Fe)*, Aluminium *(Al)*, and Copper *(Cu)* [27]. KER protects metals from corrosion and oxidation provided the enclosure is watertight and oxygen sealed. The insulation property of KER does not allow ionization to happen in the insulating oil and thereby eliminates/delays the avalanche process. KER is mainly used in rocket propulsion systems as a cooling fuel because it possesses excellent heat dissipation than any other dielectric fluid [28]. These attributes prove that KER has better insulation and cooling properties in addition to the miscible property. KER has little volatility and does not produce smoke without preheating [26]. The mixture of Oil:KER is homogeneous and will have a better dissipation factor as the oil possesses an auto-ignition point greater than $300°C$.

C. COPPER PLATE (CP) AND KRAFT PAPER (KP)

The oil used in power transformers must possess properties like good insulation and cooling [29]. Whenever it is used in a composite phase like solid in oil, it must extract heat from the windings and dissipate it to the external atmosphere. But oil is not ideal insulation to sustain any balance between heat generated by the winding and heat dissipated to the environment. Hence the solid insulation and winding must meet certain heat throughout the working of the power transformer. The solid insulation like KP is made of cellulose material obtained from pulp and it readily deteriorates when in contact with oil containing saturated hydrocarbons like Mineral Oil [30]. Similarly, the prolonged exposure of copper windings immersed in Mineral Oil is susceptible to corrosion due to oxidation [31]. As the heat dissipation of Mineral Oil is very less when compared to Natural Esters, the CP and KP immersed in Mineral Oil deteriorates at a much faster rate than in Natural Esters [32]. Additionally, CP will start producing copper oxides which increase the acidity of the oil and thereby increasing the conductivity of the oil. When conductivity increases, an electric field is setup in the oil and leads to dielectric breakdown. On the other hand, the acidity of the oil increases the polymerization of KP and mixes finely with oil [33]. Furthermore, the reaction initiates the electric field in the oil which subsequently raises oil sludge and acidity. The use of Natural Esters, however, provides better rust protection and lubrication for CP because NE dissipates heat at a higher rate than MO. Also, with the good heat dissipation property, the KP immersed in NE deteriorates at a much slower rate and thereby maintaining the quality of oil for several years.

III. SUPERIOR INSULATING FLUID (SIF)

Superior Insulating Fluid (SIF) is prepared using the methodology presented in Figure 1. The UFAs rich NEs are initially treated with Activated Bentonite Clay for the removal of moisture/ionic impurities followed by heating at $100°C$ [34]. Then, the ultrasonic waves with $30kHz$ at $90°C$ are used to alter the molecular structure of the oil, which affects the viscosity of oil [20]. The UFAs rich oils are a loosely packed chain structure without a hydrogen molecule which when subjected to ultrasonic waves, the oil experiences compression and expansion forces acting between the carbon atoms. This stretches the molecular structure of the oil unless

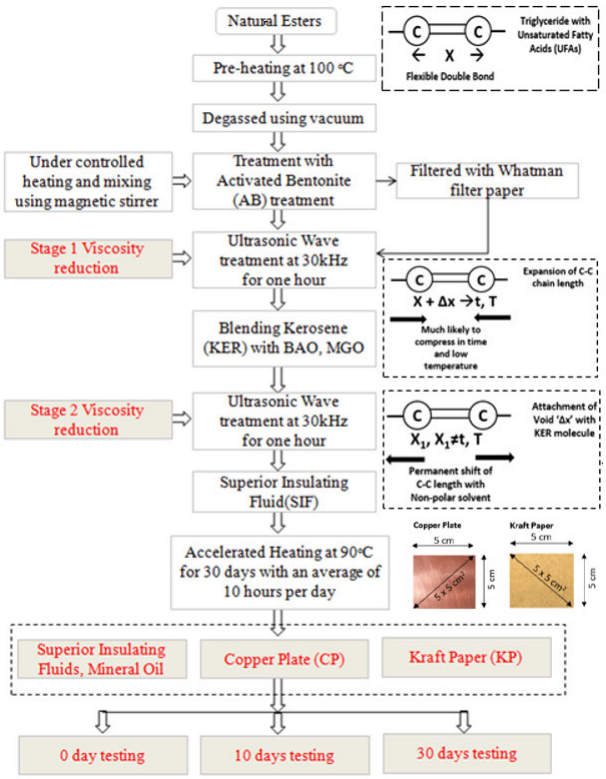


FIGURE 1. Methodology for preparation of superior insulating fluids (SIFs).

a thinner medium is used to fill the voids developed because of molecular expansion. The molecular expansion is affected by lower temperatures and therefore the *C-C* molecule gap reduces to its original level. The higher carbon atom of KER is used to fill the NEs chain gaps and the effect is permanent. Since KER is not affected by low temperature because of its low pour point, the low-temperature effect on NEs is not effective. The reduction of viscosity of NEs after ultrasonic treatment and low-temperature impact on NEs is presented in Table 1. A miscible pure dielectric solvent like KER is blended with oil and subjected to ultrasonic treatment with $30kHz$ at $100°C$. The viscosity profiles of NEs without KER, before/after treatment with ultrasonic waves, and NEs with KER, before/after treatment with ultrasonic waves are presented in Table 2. Compositions of KER:Oil taken are 5%:95% ($5ml$:$95ml$), 10%:90% ($10ml$:$90ml$) for the SIF preparation. After the preparation, the Superior Insulating Fluid (SIF) samples are subjected to dielectric tests as per the standards of IEC and ASTM.

IV. TEST METHODOLOGY

The Copper Plate (CP) and Kraft Paper (KP) samples are taken and placed in SIFs prepared using BAO, MGO, and conventional naphthalene grade mineral oil with KER added in different proportions. A total of 13 samples ('A1-A6', 'M', and 'B1-B6') were prepared for the investigation as presented in Table 3.

TABLE 1. Kinematic viscosity and breakdown voltage of BAO after treatment.

BAO	Kinematic Viscosity (cSt)		% Decrease	Breakdown Voltage (kV)		% Improvement
	BUW*	AUW**		BUW*	AUW**	
without KER	84	76	-9.5	40	42	5.0
with 5%	55	47	-14.5	41	45	9.8
with 10%	36	31	-13.9	42	49	16.7

*Before Ultrasonic Wave (BUW) treatment ** After Ultrasonic Wave (AUW) treatment

TABLE 2. Kinematic viscosity and breakdown voltage of BAO after treatment.

MGO	Kinematic Viscosity (cSt)		% Decrease	Breakdown Voltage (kV)		% Improvement
	BUW*	AUW**		BUW*	AUW**	
without KER	95	84	-11.6	37	38	2.7
with 5%	82	69	-15.9	40	43	7.5
with 10%	64	45	-29.7	45	47	4.4

TABLE 3. List of SIFs and MO samples prepared.

Sample Description	Acronym
SIF (BAO + 0% KER)	A1
SIF (BAO + 5% KER)	A2
SIF (BAO + 10% KER)	A3
SIF (MGO + 0% KER)	A4
SIF (MGO + 5% KER)	A5
SIF (MGO + 10% KER)	A6
MO+ CP+KP	M
SIF (BAO + 0% KER + CP +KP)	B1
SIF (BAO + 10% KER + CP +KP)	B2
SIF (BAO + 10% KER + CP +KP)	B3
SIF (MGO + 0% KER + CP +KP)	B4
SIF (MGO + 5% KER + CP +KP)	B5
SIF (MGO + 10% KER + CP +KP)	B6

The test samples were subjected to accelerated heating test where the samples are heated at $90°C$ for 30 days with 10 hours a day. The samples were allowed to cool between the heating cycles at room temperature and they are transferred to tight containers. Dielectric testing on the samples

was performed after 10 days and 30 days, which includes breakdown voltage, thermal conductivity, kinematic viscosity, auto-ignition point, and acid number.

V. RESULTS AND DISCUSSION

The test results of the samples are used to state the dielectric nature of the SIF samples with and without KER, CP, and KP. The performance statistics are presented in each section of the discussion.

A. ELECTRICAL CHARACTERISTICS

1) AC BREAKDOWN VOLTAGE

AC breakdown voltage is the deciding property of the insulating fluid when proposed for power transformer application. The test results conducted as per the IEC standard [35] using breakdown testing kit with 2.5mm spacing between the spherical electrodes, comply with the ASTM standard for loading Natural Ester in power apparatus [36]. The voltage is applied at a rate of 2kV/s until a regular breakdown appears in the liquid. Every five measurements are taken average given a time gap of 2-5 minutes between the measurements. The comparison of the results of samples 'A1-A6' and 'B1-B6' are compared with the results obtained with the sample 'M' that was prepared using Mineral Oil. The breakdown voltage variations of BAO samples (A1-A3, B1-B3), M and its corresponding insulating life degradation are presented in Figures 2 and 3. The sample M show 21kV

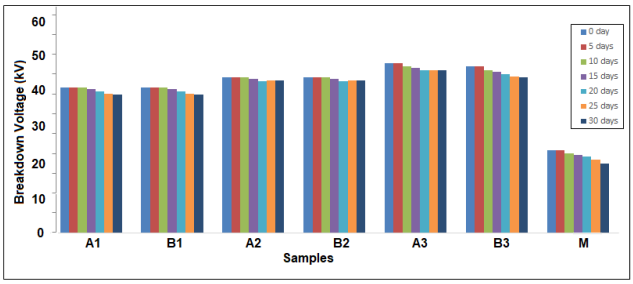


FIGURE 2. Comparison of breakdown voltage characteristics of SIF prepared using BAO with mineral oil.

Though, the dielectric breakdown voltage value of samples with high KER proportion is greater in samples 'A2', 'A3', 'B2', and 'B3' from figure 2. The breakdown voltage reduction of samples with 10% KER is higher (4%−6.3%) than samples with 5% KER proportion that has 1.1%−2.2%. Here, the data within 30 days are interpolated using linear and polynomial (third-order) equations, where the best fit of the trend show $R^2 = 0.812$ to 0.967 and $R^2 = 0.813$ to 0.984 for the linearity and polynomial interpolation function, respectively.

Further extrapolating the data using the polynomial function from figure 2 there is a noticeable 4.8% reduction after 30 days in breakdown voltage of samples 'A1' and 'B1' that takes 315 days to deteriorate 50% breakdown voltage from

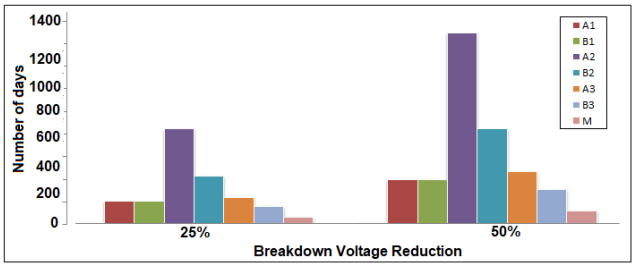


FIGURE 3. 50% Breakdown voltage life expectancy of BAO.

Figure 3. On the other hand, the sample 'M' has a reduction of 16% in 30 days and will take 90 days to deteriorate 50% insulation strength. Considering the sample 'A2' and 'B2', they have the least 50% of insulation strength degradation in 1350 and 675 days, respectively. An average difference of two-time is seen between sample 'B2' and 'A1', and seven-time is observed between sample 'B2' and 'M' after the accelerated heating test. This extrapolation informs the power engineers about the weakness of insulation and help them to refill the oil with fresh one or reclaim the used oil upon reaching 50% of life.

The dielectric breakdown voltage and the insulation degradation characteristics are presented for the samples prepared using MGO and MO. Like the BAO characteristics in Figures 2 and 3, the samples (A4-A6, and B4-B6 show superior breakdown voltage with higher KER proportion seen from Figure 4.

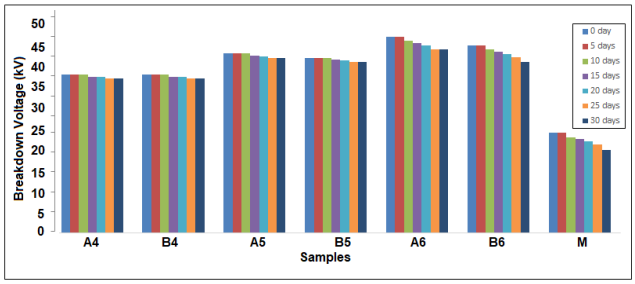


FIGURE 4. Comparison of breakdown voltage characteristics of SIF prepared using MGO with mineral oil.

But the samples 'A4' and 'B4' containing no KER show a 2.6% breakdown voltage reduction for the measurement carried out for 0 to 30 days. The linear and polynomial interpolations show a trend fit of the curve with conformity of $R^2 = 0.968$ and $R^2 = 0.987$ for the linear and polynomial functions, respectively. On the other hand, the samples 'A6' and 'B6' show a 6.4-8.9% reduction in insulation strength, with the other samples 'A5' and 'B5' showing the least value of 2.3-2.4% for the 0 to 30 days span. Basically, when comparing all the SIFs in Figure 4, the sample 'M' shows the highest drop of 16.7% breakdown voltage in the presence of CP and KP components.

Further, extrapolating the data using polynomial functions the figure 5 shows the insulation reduction to several days for MGO based SIF where sample 'B5' takes 630 days to reach 50% insulation strength reduction. The sample 'M' has the least in the record with an average of 90 days to reach 50% insulation reduction. The sample 'B5' has an average difference of 1:7 times life expectancy than samples 'B4' (without KER) and 'M' respectively. The life expectancy of the samples from Figure 5 shows that the sample 'B5' with 5% KER (includes CP and KP) holds the longest life for liquid insulation in the power transformer.

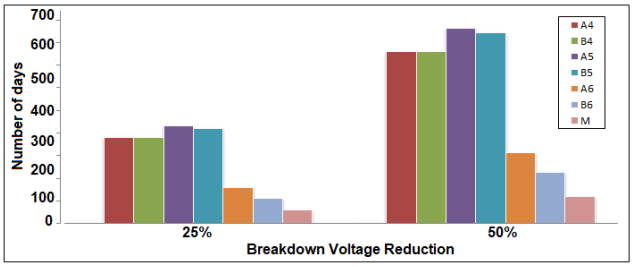


FIGURE 5. 50% Breakdown voltage life expectancy of MGO.

B. THERMAL CHARACTERISTICS

1) AUTO-IGNITION POINT

NEs possess high auto-ignition point greater than 300°C compared to Mineral Oil which is only 150°C. But the NEs that are supposed to be mixed with KER at different proportions, heated along with CP and KP show changes in the actual strength. The thermal withstands capacity of samples which are measured according to ASTM [37] are depicted in figures 6 and 8, where their percentage reduction from actual strength is presented in Figures 7 and 9. As the reduction in the auto-ignition point is less than 2%, the data within 30 days are interpolated using a logarithmic function which gives the best fit of conformity $R^2 = 0.769$. From Figure 6 and 8, the actual auto-ignition points of samples prepared using BAO and MGO and subsequently treated with CP and KP are seen. The reduction in the auto-ignition point is shown in Figure 7 and 9 and the percentage reduction is highest in sample 'M' over other samples. BAO and MGO with 0 to 10% KER proportion with CP and KP have a reduction of less than 1%. In contrast, sample M shows a greater reduction of 1.9% in auto-ignition for over 30 days. Extrapolation indicates that, upon subsequent heating of sample 'M', the thermal stability of the sample will drop below 100°C in 790 days. But NEs with 5% KER and 10% KER will take several years to decline the auto-ignition point to less than 50% of actual capacity.

2) THERMAL CONDUCTIVITY

The thermal conductivity is measured using the KS-1 probe at room temperature and elevated temperature compared to the loading standard of Natural Ester in ASTM [36] and

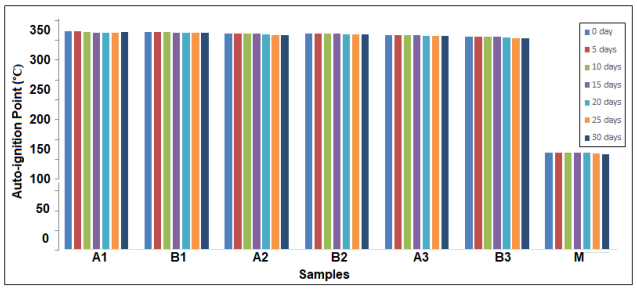


FIGURE 6. Comparison of auto-ignition point of SIF prepared using BAO with MO.

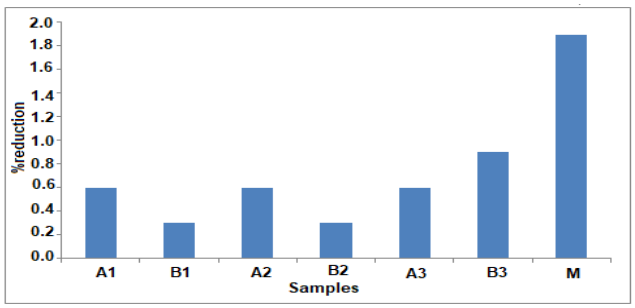


FIGURE 7. Auto-ignition point reduction of SIF containing BAO and MO in 30 days.

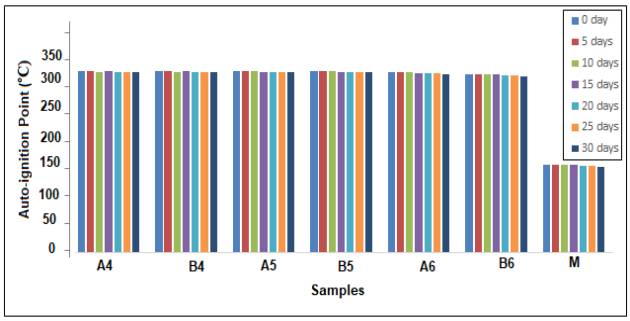


FIGURE 8. Comparison of auto-ignition point of SIF prepared using MGO with MO.

IEEE [38] at 30, 60, 90 and 110°C for 10 days and 30 days durations. The results are presented in Figure 10, 11, 13, and 14. The percentage of variations of samples prepared using BAO and MGO with CP and KP are presented in Figures 12 and 15, respectively. The thermal conductivity of NEs is higher than that of MO at both low and elevated temperatures where the heat dissipation capacity of NEs is excellent at higher temperatures. The presence of CP and KP does not affect the thermal conductivity of BAO and MGO samples except the samples containing 10% KER show the lowest percentage difference from the Figures 12 and 15. BAO Samples with 5% KER has shown excellent thermal conduction peaks compared to MO which has the least thermal conduction at elevated temperature and low temperature.

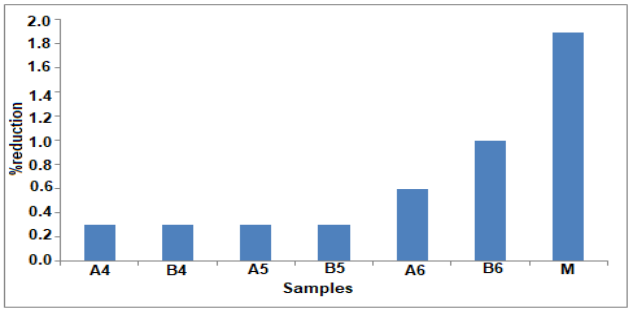


FIGURE 9. Auto-ignition point reduction of SIF containing MGO and MO in 30 days.

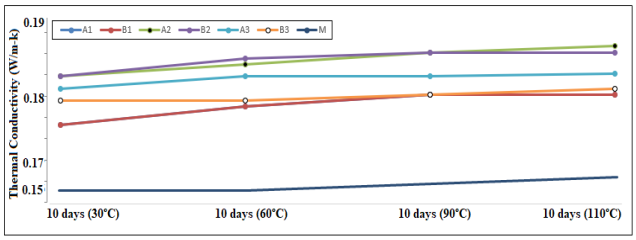


FIGURE 10. Comparison of thermal conductivity of BAO after 10 days with MO.

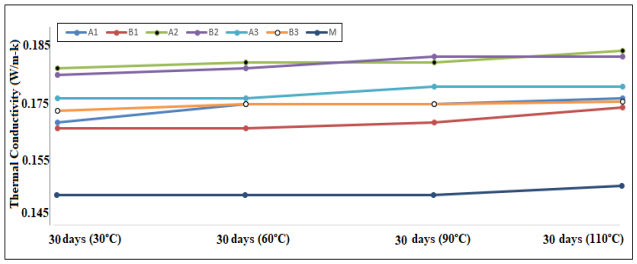


FIGURE 11. Comparison of thermal conductivity of BAO after 30 days with MO.

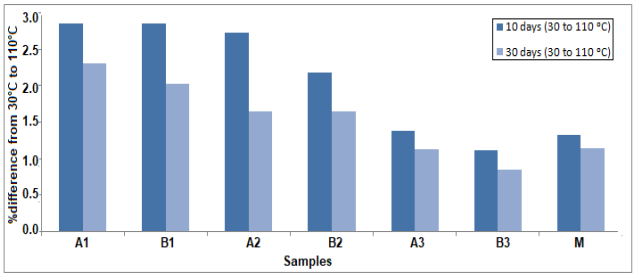


FIGURE 12. Percentage difference in thermal conductivity of BAO from 30°C to 110°C.

Similarly, samples prepared with MGO show greater conductivity at elevated temperature and lower temperature than MO which is poor in heat dissipation. Figures 13 and 14 show that the thermal conductivity of MGO prepared samples is

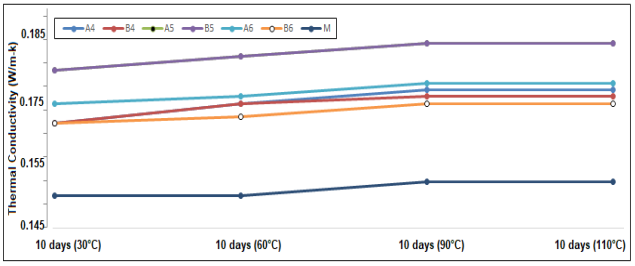


FIGURE 13. Comparison of thermal conductivity of MGO after 10 days with MO.

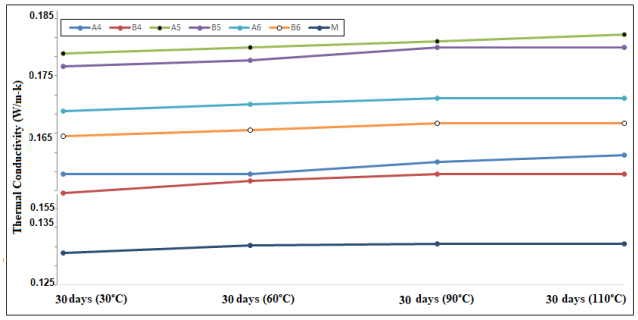


FIGURE 14. Comparison of thermal conductivity of MGO after 30 days with MO.

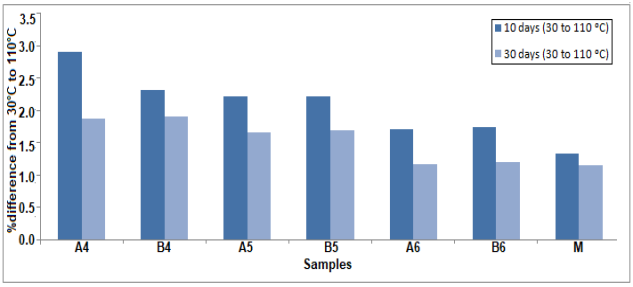


FIGURE 15. Percentage difference in thermal conductivity of MGO from 30°C to 110°C.

consistently higher when compared to that of MO. The difference in thermal conductivity of samples in 10 days and 30 days for temperature changes from 30°C to 110°C is presented in Figure 15 where the maximum difference is achieved without the CP and KP component. But the samples A5 and B5 with CP and KP component show similar values after the 10- and 30-days span. In all the experiments, the difference in conductivity from 30°C to 110°C is higher in the 10days span than in the 30days.

However, the thermal conductivity of NEs at elevated temperatures is higher due to molecular relaxation achieved using ultrasonic waves and KER. On the other hand, MO with random carbon molecules has no significant tolerance to heat and likely to affect the internal parts of the power transformer.

C. PHYSICAL CHARACTERISTICS

1) KINEMATIC VISCOSITY

The kinematic viscosity measured according to ASTM D6871 [39] shows that the NEs are three to four times heavier than MO, but treatment with ultrasonic waves and KER reduces the viscosity as presented in Figures 16 and 18. At a temperature of 40°C the oils have a viscosity of 50cSt as specified by the standard of ASTM D445 and this further indicates a reduction in the oil's viscosity. Changes over 10- and 30 days are presented in figure 17 and 19. NEs treated with ultrasonic waves along with KER show lower values of viscosity with the increase in KER proportion. However, accelerated heating with CP and KP components over 30 days with the measurement taken on the day '0', '10', and '30' show viscosity value between 40cSt and 60cSt at 5% KER proportion at 30°C. The days between 0 day to 30 days are interpolated using third-order polynomial function with $R^2 = 0.93$ as the best fit of the trend. When the temperature increases, the viscosity value of samples 'A2' and 'B2' is 17cSt and 25cSt at 90°C which is desirable for the higher heat dissipation. Mineral Oil, on the other hand shows the lowest value of viscosity in 0 days and starts to rise to 25% at the end of 30 days. Furthermore, extrapolating the curve using the polynomial function concerning the increase in heating hours the fade away of viscosity could be reached within six months.

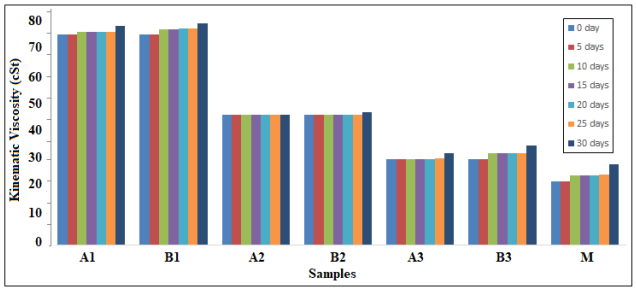


FIGURE 16. Kinematic viscosity of SIF prepared using BAO with MO for 0 to 30 days measured at 30°C.

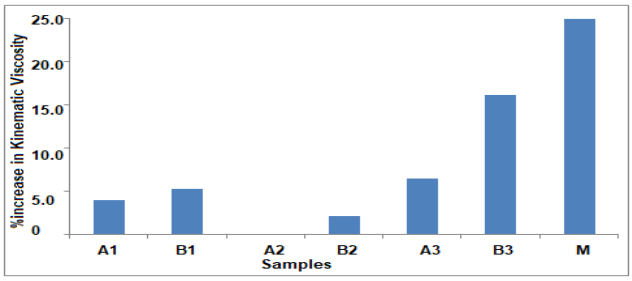


FIGURE 17. Percentage kinematic viscosity changes in SIF having BAO and MO over 30 days.

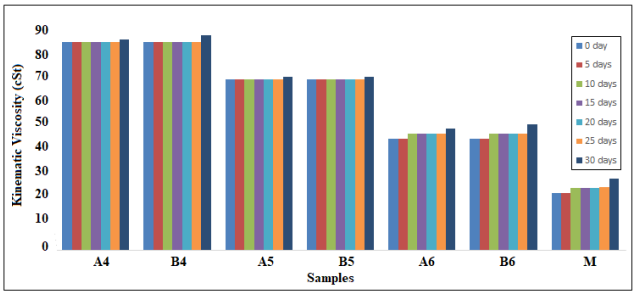


FIGURE 18. Kinematic viscosity of SIF prepared using MGO with MO for 0 to 30 days measured at 30°C.

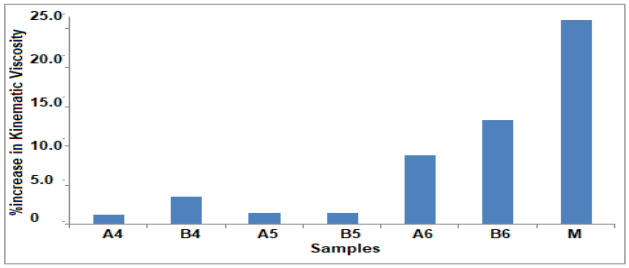


FIGURE 19. Percentage kinematic viscosity changes in SIF having MGO and MO over 30 days.

Like the BAO characteristics in Figures 16 and 17, MGO shows a similar trend with fitting accuracy $R^2 = 0.815$ when interpolated using polynomial function than linear function as shown in Figures 18 and 19. The addition of KER to MGO shows similar values of viscosity with and without the CP and KP component as seen through samples 'A5' and 'B5' in Figure 18. An increase in the viscosity of the sample 'M' when compared to other samples can be seen in Figure 19. Similarly, the extrapolation of viscosity with temperature shows that the samples 'A5' and 'B5' will have a viscosity value between 23cSt to 31cSt with temperature increased from 30°C to ≥90°C.

D. CHEMICAL CHARACTERISTICS

1) ACID NUMBER

Upon adding KER to NEs and MO, the samples are heated with the CP and KP components for 30 days. The acid number is measured according to ASTM [40] after 10 days and 30 days to estimate the depreciation of insulation with KER, CP, and KP. The acid number measurement results for BAO and MGO are presented. The interpolation of the data obtained between 0- to 30-days has best fitted using the polynomial function with accuracy $R^2 = 1$. Figure 20 and 22 show no change at 0% and 5% KER proportion without CP and KP components. Also, a less than 4% increase in acid number is observed in sample A2 which has 5% KER with CP and KP components. But the trend remains the same for the NE without KER proportion as seen in Figure 21. Increasing the KER proportion to 10% shows a nearly 10% increase in the acid number. The acid number of sample M shows almost shows a 30% increase in acid number after 30 days of accelerated heating. The observation from figure 21 is that CP and KP components in NE with 5% KER

proportion have consistency with three times lesser effect on solid insulation and windings of the power transformer.

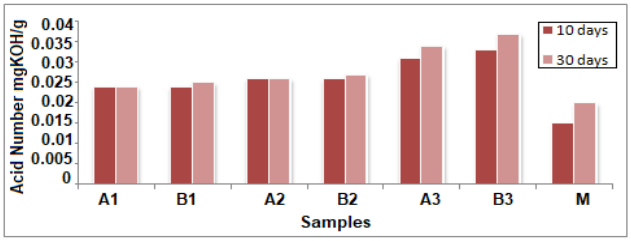


FIGURE 20. Changes in acid number of SIF having BAO compared with MO.

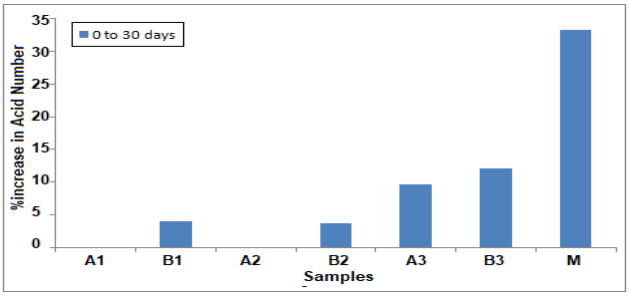


FIGURE 21. Percentage rise in acid number of BAO based SIF over 30 days.

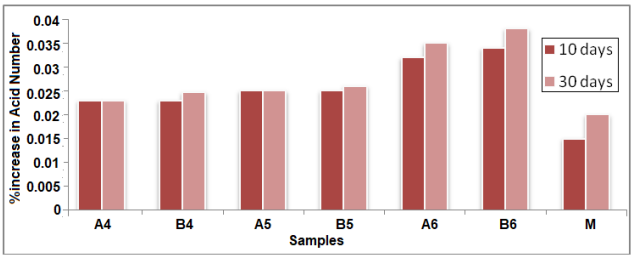


FIGURE 22. Changes in acid number of SIF having MGO compared with MO.

A similar interpolation trend and observation are seen from Figures 20 and 22, which show 5% KER with BAO and MGO with CP and KP components have lesser ageing effects over 30 days. The percentage rise in acid number from figure 23 shows that NE with 5% KER has reduced the ageing of the components (sample B2) than the NE sample without KER which shows an increase of acid number which doubles in 30 days.

This is because of the KER in BAO and MGO has higher thermal conductivity than SIF without KER proportion. In addition to that, KER can protect oxidation of metal from thermal stresses that reduces the production of metal oxides in the oil and thereby reducing the acidic components. Here also the sample 'M' shows the maximum rate of ageing when compared to other samples.

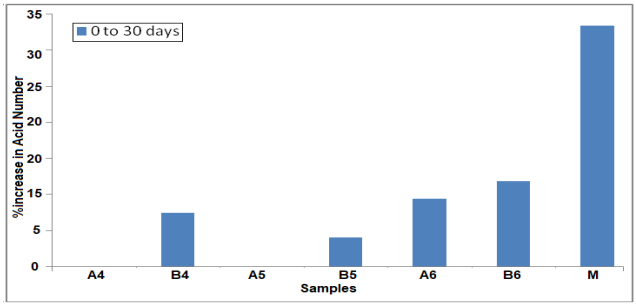


FIGURE 23. Percentage rise in acid number of MGO based SIF over 30 days.

VI. DETERIORATION RATE OF DIELECTRIC CHARACTERISTICS OF OILS WITH LIFE EXPECTANCY

The investigation of SIFs samples with CP and KP components, the sample B2 and B5 has noticeable observations like higher breakdown voltage strength and auto-ignition point, slower diminution of viscosity and acid number, better thermal conduction at low and high temperatures when compared to the Mineral Oil sample M that can be seen from Table 4 and Figures 24-28. Here a comparison of dielectric parameters of SIFs with MO is presented to show that the SIFs have extended life compared to MO in the presence of CP and KP. The SIF is subjected to online condition, usually where the liquid insulation in power transformer will experience a temperature $\geq 90°C$. The breakdown voltage of sample M from Figure 24 clearly shows the end of breakdown strength at the end of 90 days whereas the samples B2 and B5 show a consistent strength. The breakdown voltage of SIF will increase further due to the extension of *(C-C)* bonds due to the temperature effect. Also, a steep rise in the kinematic viscosity is observed in Figure 25 for the sample M that almost doubles its actual value. On the other hand, samples B2 and B5 show a 2 to 3 % rise in the kinematic viscosity for the 90 days. The kinematic viscosity of SIFs samples 'B2' and 'B5' reduces below $30cSt$ at $\geq 90°C$ to take out more heat from the windings and core of the power transformer. The auto-ignition points of SIFs prove to be thermally stable to any electrical stresses that occur, and the thermal conductivity of SIFs increases with the higher relaxation distance of the viscosity matrix caused by ultrasonic waves and KER. The MO shows a poor thermal characteristic due to the improper distancing of the Carbon chain in the oil matrix. From Figure 26 the thermal conductivity of samples B2, B5 and M in Figure 28 show that M has nearly lost the oil's heat dissipation property in 90 days. But the samples B2 and B5 have a long way to lose its heat dissipation property, thereby exhibiting excellent breakdown strength and slow rise in viscosity. The auto-ignition point of samples B2, B5 and M from Figure 26 show a similar kind of trend as that in Figures 23 and 24. Here the auto-ignition point of sample M drops from $155°C$ to $100°C$ in 90 days which decreases the rate of heat convection by the oil and thereby leads to transformer fire or explosion. Comparatively, the auto-

TABLE 4. Comparison of degradation of selected SIFs containing 5% KER proportion with MO for 30 days and extrapolating to 90 days.

Sample	Breakdown Voltage	Auto-ignition Point	Thermal Conductivity	Kinematic Viscosity	Acid Number
B2	44*kV*	343°*C*	0.181-0.184*W/m-K* from 30°*C* to at 110°*C*	48*cSt*	0.027*mgKOH/g*
End of life	90 days to 6.66%	0.3% lose in 30 days and 4% in one year	-	2.1% rise in 30 days	Max 3.8% rise in 30 days
B5	41*kV*	319°*C*	0.177-0.180*W/m-K* from 30°*C* to at 110°*C*	70*cSt*	0.026*mgKOH/g*
End of life	90 days to 7.14%	0.3% lose in 30 days and 12.5% lose in one year	-	1.4% rise in 30 days	Max 4% rise in 30 days
M	20*kV*	152°*C*	0.130-0.131*W/m-K* from 30°*C* to at 110°*C*	29*cSt*	0.02*mgKOH/g*
End of life	90 days to 50%	1.9% lose in 30 days and 12.5% lose in one year	-	26.1% rise in 30 days	Max 33% rise in 30 days

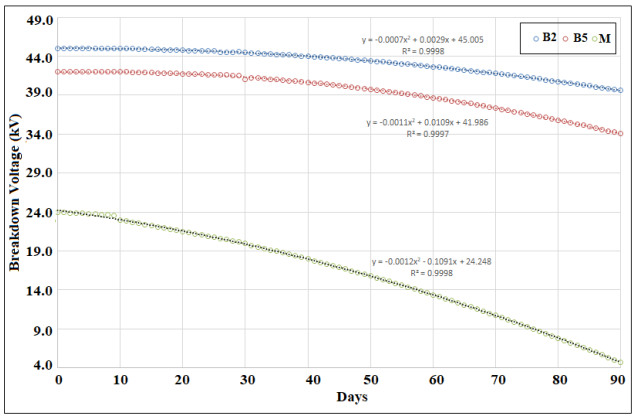


FIGURE 24. Comparison of breakdown voltage of SIFs (B2, B5) with mineral oil (M) for 90 days.

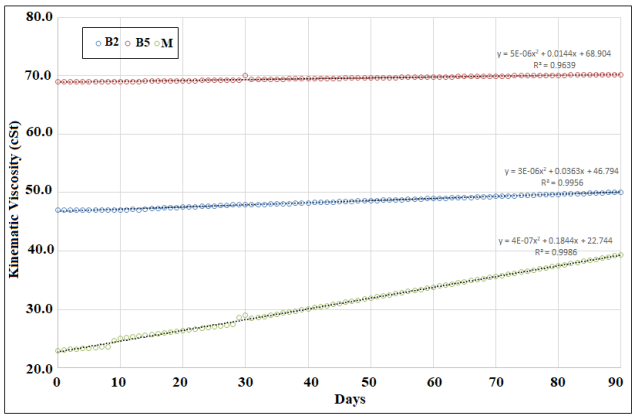


FIGURE 25. Comparison of kinematic viscosity of SIFs (B2, B5) with mineral oil (M) for 90 days.

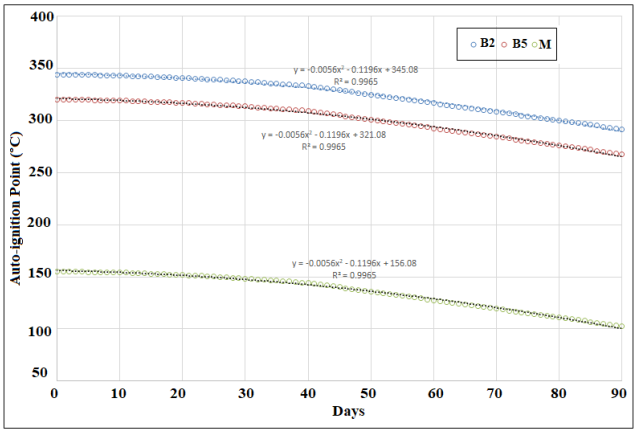


FIGURE 26. Comparison of auto-ignition point of SIFs (B2, B5) with mineral oil (M) for 90 days.

ignition points of samples B2 and B5 are 225°*C* and 290°*C* respectively and can perform extensive heat dissipation function.

The presence of CP and KP components does not alter the acid number of SIFs when compared to MO from Table 4. The acid number has a steep rise for the sample M than B2 and B5 from Figure 27. The acid number of M from Figure 27 clearly indicates its increase in 90 days which increases the hydroperoxides in oil and in turn increases the oil kinematic viscosity. Although, the samples B2 and B5 show slower acid rise with the CP and KP components measures like refilling/reclamation of oil must be taken before the acid number reaches 0.03*mgKOH/g*. Lastly from Figure 28 thermal conductivity of samples is observed to weaken after temperature effect for the 90 days. But for the sample M, thermal conductivity is less than 0.13*W/m-K* which shows heat dissipation of the oil is not enough to maintain the transformer components in a healthy

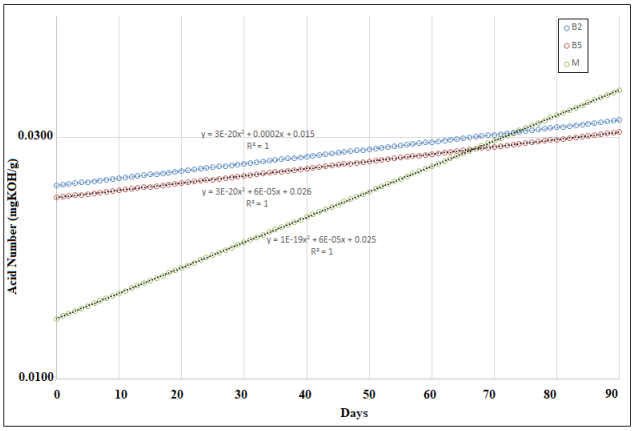
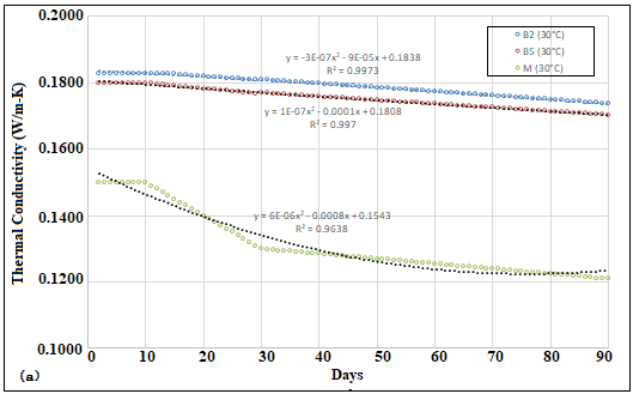
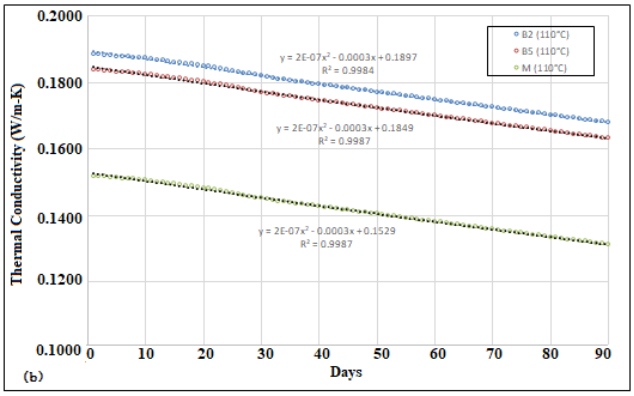


FIGURE 27. Comparison of acid number of SIFs (B2, B5) with mineral oil (M) for 90 days.



(a) at 30 °C for 90 days



(b) at 110 °C for 90 days

FIGURE 28. Comparison of thermal conductivity of SIFs (B2, B5) with mineral oil (M).

state. This is commonly observed in all the dielectric properties from Figures 24-28 where the samples B2 and B5 have managed to age slowly and for the sample M the ageing has been ceased in the 90 days. However, the sample M needs replacement in the early stage when compared to the samples B2 and B5.

VII. CONCLUSION

The tests conducted on the NEs and MO prove to support strong decision to use NEs in power transformers. The NEs with 0% KER proportion show initial performance without CP and KP components after accelerated heating test, but its reduction in strength is higher with the components of CP and KP. However, the NEs with 5% KER show a slower ageing rate of oils, most likely the SIFs after 30 days show a slower ageing rate than the NEs without KER proportion. On the other hand, the SIFs with 10% KER show slightly higher rate of ageing but quite slower than MO. Upon evaluating the performance of MO with/without CP and KP components it is observed that the highest ageing rate of the oil's dielectric characteristics in the order of three to four times compared to SIFs (B2 and B5). With respect to auto-ignition point, the MO has reduced by 66.6%, kinematic viscosity has doubled, and acid number has surged to lead in 70 days. This shows MO have shown the highest extrapolated degradation rate within 90 days to reach 50% of strength. The breakdown voltage of the NEs with 5% KER shows a better life span with a reduction of 10% from the maximum level, whereas MO shows a life expectancy of less than 90 days. These results prove that KER as miscible dielectric not only as thinner medium but exhibit better insulation over Copper Plate and better heat dissipation. Then again, KER in lower proportion says as 5% would not affect the cellulose insulation Kraft ageing and NEs can maintain a substantial level of acid number over several months. Hence ultrasonic waves relax the molecular distance between carbon atoms in NEs, but the addition of KER has shown potential in viscosity relaxation on NEs by rightly filling the voids of *(C-C)* gap. Thus, the addition will not allow reduction of viscosity in the meantime. The SIFs upon accelerated heating have shown superior performance over MO and SIFs increase the life time of solid insulations and internal parts of the power transformer. Based on the overall results SIFs are proposed as suitable liquid insulation for power transformer.

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RAYMON ANTONY RAJ was born in India in 1987. He received the B.Eng. degree in electrical and electronics engineering from P.S.R. Engineering College, India, in 2009, and the M.Eng. degree in high voltage engineering from National Engineering College, India, in 2013. He is currently pursuing the Ph.D. degree with the Botswana International University of Science and Technology (BIUST), Palapye, Botswana. He was an Honor recipient in UG and PG studies. He joined Integrated Wireless Solutions Pte. Ltd., Noida, where he worked as an RF Engineer for a while. He has also worked as an Assistant Professor and Head In-charge of the Electrical and Electronics Engineering Department, Kalasalingam Institute of Technology, Krishnankovil, India. He has published research papers in reputed Journals such as the IEEE Transactions on Dielectrics and Electrical Insulation, the *Australian Journal of Electrical and Electronics Engineering*, *Springer Lecturer Notes*, and so on. His areas of interest include transformer liquid insulation, as well as enhancement theories of liquid dielectric and eco-friendly fluids.

RAVI SAMIKANNU (Member, IEEE) received the Ph.D. degree in electrical engineering from Anna University, Chennai, India. He is currently working as an Associate Professor with the Electrical, Computer, and Telecommunications Engineering Department, Botswana International University of Science and Technology (BIUST), Palapye, Botswana. He is working on research projects in power systems, energy systems, and smart grid. He is actively engaged in teaching, research, and academic admiration. He has played a major role in setting up various laboratories for different electrical engineering courses and prepared the department for accreditation from different quality agencies like NBA, AICTE, and UGC. He has a total teaching experience of 15 years at undergraduate and postgraduate levels. He has conducted a total of four National Level Symposiums and a Science Exhibition. He has delivered special guest lectures in many international and national conferences. He is an active member of IDDS and has participated in different rural community development projects. He has published 60 research papers in International Journals. He has presented 50 papers in International and National Conferences. He is a Life Member of the IE(I) and ISTE. He has received the Best Paper Award two times for his presentation. He is a Reviewer in the IEEE and other reputed journals.

ABID YAHYA (Member, IEEE) received the bachelor's degree in electrical and electronic engineering, majoring in telecommunication, from the University of Engineering and Technology, Peshawar, Pakistan, and the M.Sc. and Ph.D. degrees in wireless and mobile systems from Universiti Sains Malaysia, Malaysia. He is currently working with the Botswana International University of Science and Technology (BIUST), Palapye, Botswana. He has applied the combination of practical and academic experience to a variety of consultancies for major corporations. His career on an engineering path is rare among other researcher executives. He has many research publications to his credit in numerous reputable journals, conference papers, and book chapters. His recent four books, including *Emerging Technologies in Agriculture, Livestock, and Climate* (Springer, 2020), *Mobile WiMAX Systems: Performance Analysis of Fractional Frequency Reuse* (CRC Press | Taylor & Francis, 2019), *Steganography Techniques for Digital Images*, and *LTE- A Cellular Networks: Multi-Hop Relay for Coverage, Capacity, and Performance Enhancement* (Springer International Publishing, July 2018 and January 2017) are being followed in national and international universities. He has received several awards and grants from various funding agencies and supervised several Ph.D. and master's candidates. He is a Professional Engineer registered with the Botswana Engineers Registration Board (ERB).

MODISA MOSALAOSI (Member, IEEE) received the B.Sc. degree in electrical engineering, and the M.Sc.Eng. and Ph.D. degrees in electronic engineering from the University of KwaZulu-Natal, Durban, South Africa, in 2009, 2015, and 2017, respectively. He is currently a Lecturer with the Botswana International University of Science and Technology (BIUST). His research interests include power line communication, RF and Microwave propagation, free-space optics, and green power technologies. He is a member of the IEEE-HKN Mu Eta Chapter.