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REGULAR PAPER

Effect of Copper on Ageing Behavior and Breakdown Voltage Properties of Transformer Oil

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Abstract

In this paper, the "Breakdown Strength" of ester base liquid MIDEL 7131(MIDEL Ltd), Mineral Transformer oil (Grosvenor Oil Service), Diala D (Shell Ltd) and THESO insulating oil (Tetra Corp) that are subjected to three different ageing conditions is examined. The breakdown strength of thermally aged insulating oils with copper and without copper has also been tested. Therefore the effect of copper as a catalyst in ageing of insulating liquids was also examined. After analyzing the effect of copper on ageing indicated that, copper had a huge influence on darkening all the insulating oils except MIDEL 7131 and thereby accelerating the ageing process. The breakdown mechanism of oils has changed due to ageing with copper. In this paper, breakdown comparison of transformer oils are analyzed with different insulating oils like un-aged and aged. Transformer oils breakdown voltage test under 0.9 mm gap spacing and the average breakdown voltage behaviour, field behaviour, maximum field at the needle tip transformer oils are also investigated.

Keywords Breakdown strength · Ageing process · Copper · Insulating oils

1 Introduction

In the field of High Voltage Engineering, insulation plays a vital part because its failure has got a major economic impact on consumers, suppliers and distributors of electrical energy. Implementation of new application in the existing power system leads to additional stress in the insulating system. Because of these reasons it is very important to gather a deep knowledge about the residual life time of the insulation system used in the high voltage engineering [1, 2].

Condition Monitoring and life time predictions are gaining more importance in high voltage engineering especially in high voltage plants including cables. Therefore the better way to identify the plant health is to determine the characteristics of insulating oil used in power system. Many studies on the ageing behavior of various insulating oils have been done. Data regarding the indicators of oil ageing can be reliable to identify the plant health especially applications in high voltage transformers.

According to IEEE standard 57.1000, the expected minimum service lifetime of a liquid immersed distribution transformers and power transformers operating at an average ambient of 30 °C is about 20.55 years. Ageing deterioration of an insulating system influences the average service life time of a transformer. Ambient temperature, load, moisture content, oxygen content and configuration of materials are the major ageing factors that affect the life time of transformers. Determination of ageing and failure mechanism gives a clear picture about the insulation system and there by equipment's used in power system.

This particular project utilizes the breakdown test in order to analyze the ageing behavior of four insulating liquids named MIDEL7131, Diala D, Mineral Transformer oil and THESO insulating oil. MIDEL 7131 developed by MIDEL Ltd is an ester base liquid with 100% fire safety records. Diala D developed by shell Ltd istransformer oil used in high power and pulsed power applications. Mineral transformer oil is widely used conventional transformer oil. THESO Insulating oil is used in high density energy storage system because of its high relative permittivity.

Ageing study conducted by Hosier [3–6] reveals that the presence of copper leads to significant oxidation and

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dielectric loss. This project also tries to determine the influence of copper on ageing. The other major objective of this project is to examine the ageing of Ester base Liquids used in high voltage engineering applications. The main reason for including MIDEL 7131 is the most commonly used ester base liquid. It can completely or partially replace the conventional Mineral Transformer oil. The main advantage of MIDEL 7131 is high ignition resistance, low-toxicity and moisture absorbing capability [7].

Various research works has previously existed in the literature based on the effect of copper on ageing behavior and breakdown voltage properties of transformer oil using different aspects. Some of them are reviewed here.

Cheng et al. [8] have illustrated the movement and accumulation behavior of fiber particles and copper particles in mineral oil and natural ester were recorded and simulated. Then, the influence of fiber and copper particles on the oil conductivity was analyzed. Finally, the DC breakdown strength of mineral oil and natural ester with different particles concentration was compared. Rahman and Nirgude [9] have explained the investigations on Partial Discharge (PD) behaviour of irregular-shaped copper particle in oil with pressboard barrier placed in two positions under uniform field with different moisture contents. Frequency Domain Spectroscopy (FDS) was used to estimate percentage moisture in pressboard. Recovery Voltage Measurement was used to confirm obtained FDS results. PD characteristics like magnitude, number, discharge power, rise time and duration time of PD pulse were analyzed. Dan et al. [10] have performed a simulation method is provided to explore the motion mechanism and accumulation characteristics of different particles. This is utilized to explain the effects of particle properties on the breakdown strength of mineral oil. Experiments on particle accumulation under DC voltage as well as DC breakdown were carried out.

Most publications analyzed the influence of particle on the breakdown voltage of insulating oil by means of the mass weight or concentration. However, the number of particles was seldom precisely considered, let alone the relationship between particle number and breakdown voltage at combined AC and DC voltage.

2 Experiment

Majority of high voltage cables and transformers in high voltage engineering uses mineral oils and cellulose based porous material as their insulation system despite of their environment impacts since this particular insulation system has proven to be very reliable in high voltage engineering. Therefore experiment conducted in this particular project is mainly based on the comparison of breakdown voltage of MIDEL 7131 with Diala D, Mineral Transformer oil and THESO insulating oil. Breakdown test of un-aged MIDEL 7131, Un-aged Mineral Transformer oil and Un-aged Diala D has been done. After that the breakdown test of thermally aged oils (MIDEL7131, Diala D, Mineral Transformer oil) with copper and without copper has been done.

2.1 Ageing of Insulating Oils

2.1.1 Experimental

In order to do breakdown test of aged insulating oil with copper and without copper, all the insulating oils used in the procedure are thermally aged in fan ovens at 120 °C for a period of two weeks. Three 100 ml samples of MIDEL 7131, Mineral Transformer oil, Diala d and THESO insulating oil were placed in a glass vial. In order to minimize evaporation during ageing, all the samples were covered with the help of an aluminum paper. Each 100 ml sample from different insulating oils was kept at three different conditions for two weeks. The conditions include:

- Room Temperature (without adding copper).
- Oven at 120 °C (without adding copper).
- Oven at 120 °C (with copper).

2.1.2 To calculate amount of copper

In order to understand the effect of copper as a catalyst fixed amount of copper was added to above 100 ml oil samples at a fixed surface area of about 64 cm^2. All the glass vials were kept covered in order to reduce evaporation during ageing, but the glass vials were not sealed. Therefore a total of 8 glass vials were kept inside a fan assisted temperature controlled ovens for a period of two weeks and maintaining a constant temperature of about 120 °C.

Throughout studies of oil ageing, a surface area to insulating oil volume ratio of 3.2 cm^2 in 5 ml of insulating oil was used. The diameter of the copper wire used in this project is 0.2 mm. Copper surface area matches that used in experimental work by Hosier [3].

Surface Area = 3.20 cm^2 in 5 ml of insulating oils.
Therefore for 1 ml of insulating oil Surface Area = 3.2/5 = 0.64 cm^2 = 6400 mm^2.
Equation for surface Area = $2\pi rl$ (Consider copper wire as a cylinder).
Where r = radius of the copper wire.
l = length of the copper wire.
Therefore $2\pi rl = 6400\ \mathrm{mm}^2$.
$l = 6400/2\pi r$.
Radius of the copper wire used here is equal to 0.1 mm.
Therefore $l = 6400/2\pi\ (0.1) = 10{,}185.916$ mm.

Volume of copper wire can be calculated using the formula $\pi r^2 l$.

Using the above formula volume of copper can be calculated.

Volume = $\pi*(0.1)*10{,}185.916 = 319.83\ mm^3$.

Density = Mass/Volume.

Density of copper = 8930 kg/cu m

Therefore mass of copper used for 1 ml of insulating oil can be calculated:

Mass = Density*volume = $(8.93*319.83)/10^6$.

$= 2.85615*10^{-3}$ g/ml.

Therefore for each 100 ml samples, copper strands weighing 0.285615 g is added on to the glass vials.

2.2 Influence Of Copper On Ageing

The main reason behind the addition of copper inside the insulating oil is to get more darkening of oil to occur during ageing. Addition of copper also increases the effect of oxidation. From [4] it is clear that due to ageing with copper, dielectric strength of the insulating oil was reduced. Copper is a chemical substance, which is used here in order to increase the rate of reaction without being consumed. Experiments conducted by Hosier [5] shows that due to ageing of insulating oil with copper increases the overall absorbance reflecting its catalytic effect. Another advantage of using copper in ageing process is that, it will reduce the required temperature for ageing. Therefore it can clearly say that, copper has the ability to act as a catalyst and it will contribute to the deterioration of electrical insulating oils with least detrimental surroundings. Dissipation factor of insulating oil deteriorates rapidly due to the concurrent presence of electrical stress and copper catalyst. The deterioration will be rapid if the atmosphere is nitrogen or oxygen but the insulating oil will deteriorate less under carbon dioxide atmosphere.

2.3 Analysis of Ageing Behavior

Figure 1 represents photographs of insulating oils used in this project.

From the Figs. 2, 3 and 4 the effect of copper catalyst on oil ageing can be clearly identified. In the case of THESO insulating oil, thermally aged oil without copper is not darkened while thermally aged THESO oil with copper darkened more. That clearly shows the effect of copper catalyst on

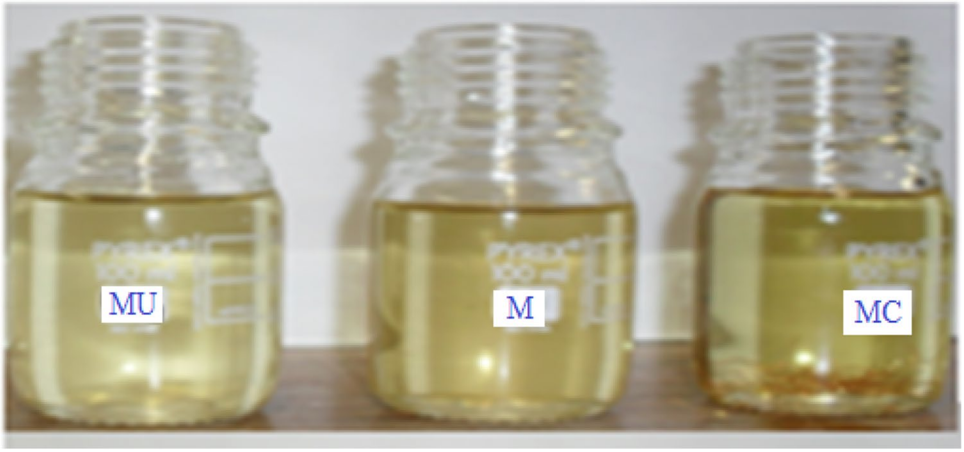

Fig. 1 MIDEL 7131, MU-Un-aged MIDEL7131, M-Thermally aged MIDEL7131 without copper, MC-Thermally aged MIDEL7131 with copper

Fig. 2 Diala D, Du-Un-aged Diala D, D-Thermally aged Diala D without copper; DC-Thermally aged Diala D with copper

Fig. 3 Transformer Oils, TRu-Un-aged Transformer Oil, M-Thermally aged MIDEL7131 without copper, MC-Thermally aged MIDEL7131 with copper

Fig. 4 THESO Oils, THu-Un-aged THESO Insulating Oil, Th-Thermally aged THESO without copper, THC-Thermally aged THESO with copper

darkening the oil. At the same time, in the case of Diala D and Mineral Transformer oil, thermally aged ones with copper darkened more. These results support the experimental results obtained from [6].

Oils that were kept at three different ageing condition In order to analyze ageing behavior of insulating oil, breakdown test of these insulating Oils has been examined and detailed description of this is included. Thermally aged insulated oils were kept under 120 °C for about two weeks. Therefore it also shows effect of temperature on ageing. That is higher temperature increases rate of ageing and vice versa. This result also support the result obtained in [7].

Oxidation and formation of extended conjugation are considered to be the reason behind the color change on ageing otherwise called darkening while the presence of red absorbers in insulating oils is due to the specific chemical process and it is related to dissolution of copper. Presence of red absorbers followed by the production of precipitate was identified quickly when the insulating oil kept at 135 °C with copper. Due to the influence of higher temperature and copper catalyst, the dielectric loss and conductivity of insulating oil is increased and thereby deteriorate the insulating oils [11].

2.4 Breakdown Testing

A good insulating liquid must possess high breakdown voltage. The voltage at which an electrical breakdown occurs in an insulating medium is called breakdown voltage (V_{bd}). It is also known as sparking voltage or sparking potential [12]. At this point a complete channel is formed between anode and cathode also to flow of electrons though the insulating medium between the two electrodes. However all insulating material has got high resistance to the flow of electrons and atoms have very tightly bound electrons. But with the application of huge amount of voltage most of the insulating material is influenced by the electrical pressure and leads to flow of electrons. If the applied voltage is higher than the threshold, there will be a huge amount of current flow between the electrodes and contributes to electrical breakdown of insulating medium.

3 Testing Procedure

The main objective is to describe the breakdown testing procedure of three insulating oils (MIDEL 7131, Mineral Transformer oil and Diala D) and to compare and analyze the breakdown behavior of above three oils. Experiment conducted by Leask [13] shows that Diala D has got high breakdown voltage compared with Mineral Transformer oil and MIDEL 7131. Therefore the main aim is to compare the breakdown voltage (V_{bd}) of these three insulating liquids that were kept at three different conditions. The other objective of this section is to determine, whether the addition of copper catalyst affect the electrical breakdown voltage of the insulating liquids. Therefore breakdown test of thermally aged oils without copper and thermally aged oils with copper has been done. A direct comparison of breakdown voltage of un-aged oils, aged oils without copper and aged oils with copper has been done.

Figure 5 represents the schematic version of test cell that has been used in the high voltage lab in order to find the breakdown voltage values of each individual oils. The test cells consist of a plastic shell which was made of plastic tube with insulating seals on either side of the shell. The proposed liquid was inserted into the test cell from the top of the plastic seal with the help of a plastic syringe. The test cell also consists of two electrodes, one is pointed electrode and other one is plane. So it is called point plane electrode geometry. Radius of needle type is 0.1 mm and plane electrodeis 5 mm. Plane electrodes are grounded throughout the testing procedure. A voltage transformer is connected to the high voltage electrode (in this case pointed electrode) and it supplies a high voltage across the needle leading to discharge on the circular electrode.

Figure 6 represents the actual test cell used within the high voltage laboratory. Gap between the two electrodes is very important while measuring the breakdown voltage of insulating liquid. There is an adjustable screw pin fixed

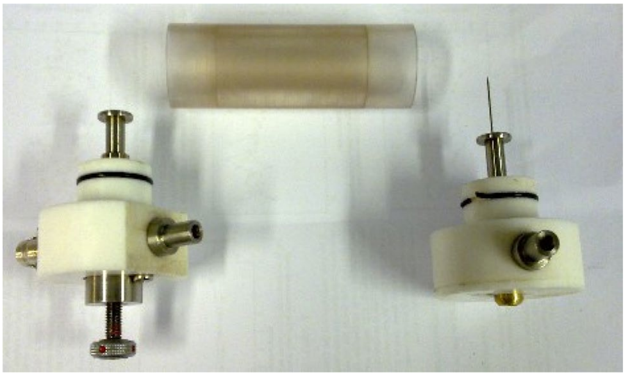

Fig. 6 Actual test cell used in the laboratory

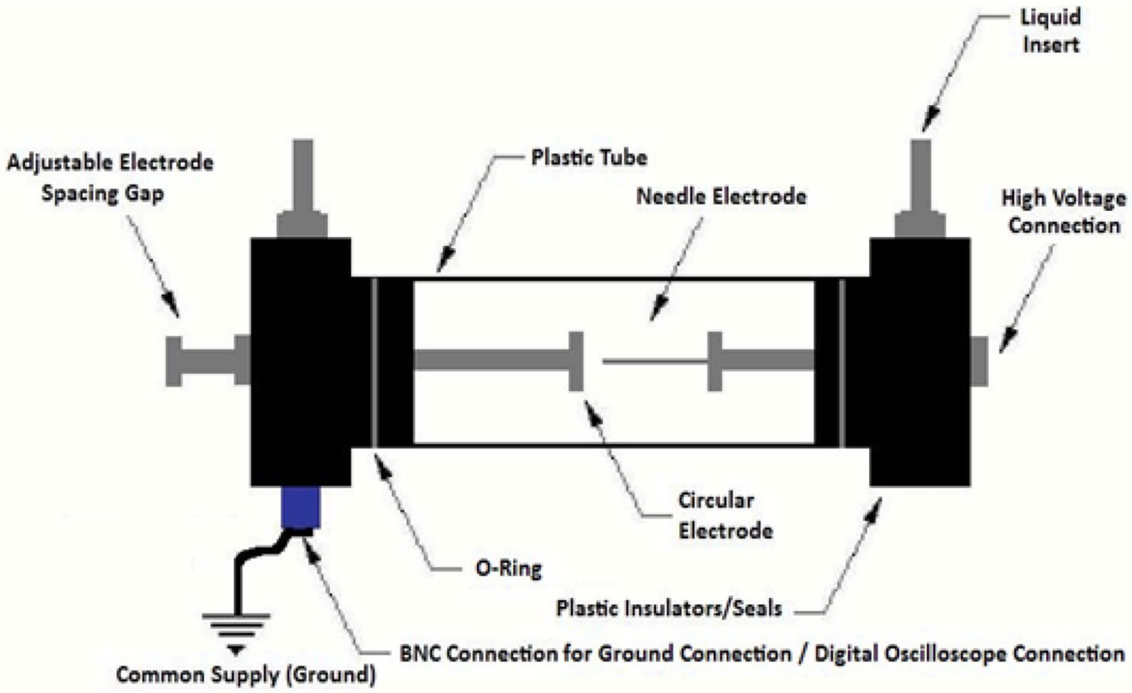

Fig. 5 Test cell used for breakdown testing

at the side of the test cell, by rotating the screw pin the electrode gap spacing can be adjusted. Breakdown voltage measurement of each individual oils at four different gap spacing has been measured in order to maintain consistency within the result. One end of the test cell is grounded and the other end with the needle electrode is connected to high voltage supply. With the help of voltage transformer high voltage is applied across the electrodes through a 0.5 MΩm resistor. Voltage transformer used here is capable of supplying voltage up to 25 kV. The main aim of 0.5 MΩ resistors is to reduce the current through the insulating medium after breakdown has occurred, thereby it act as a protection system [14].

Breakdown testing procedure used within the laboratory is shown below Fig. 7.

By applying high voltage via 0.5 MΩ resistor, a voltage is developed across the point plane electrodes inside the test cell and leads to breakdown between the electrodes. In order to measure the breakdown voltage across the test cell, a divide by 1000 voltage probe is used and for displaying these voltages, a digital multi-meter is used.

After completing all the testing set up, breakdown voltage of un-aged Mineral Transformer oil has been measured. The electrode gap was set at 0.4 mm. Thirty breakdown test were conducted in order to in order to remove stochastic variation and an average of these has been calculated. After that the gap between electrodes was increased to 0.9 mm and same procedure was repeated. Similarly thirty breakdown test of un-aged Mineral Transformer oil has been measured at various electrode gaps (1.3 mm and 1.9 mm). After completing all the breakdown test of un-aged Mineral Transformer oil, the test cell was cleaned and kept it for a while in order to dry the test cell. After that, the breakdown test of aged Mineral Transformer oil without copper and aged Mineral Transformer oil with copper has been measured at four different gap spacing. Similarly breakdown test of all samples that were used in this project was calculated and recorded. These will be analyzed in the following sections.

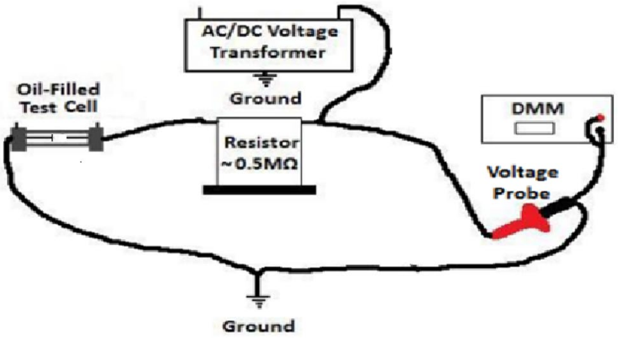

Fig. 7 Testing procedure

4 Test Results

4.1 Breakdown Voltage Comparison of Un-aged Oils

Several comparisons have been done in order to analyze the ageing behavior of three insulating oils MIDEL 7131, Diala D and Mineral Transformer oil. Initially breakdown voltage comparison of un-aged MIDEL 7131 with transformer and Diala D oils has been done and it can be seen below.

In Fig. 8 *VbdTr* represents Breakdown Voltage of transformer Oils, *Vbd M* represents Breakdown Voltage of MIDEL 7131, *Vbd D* represents Breakdown Voltage of Diala D.

Figure 8 represents the 30 breakdown measurements at 1.9 mm electrode gap spacing that were obtained for each un-aged insulating oils. The average value has been examined and included in the later graphs. Comparing the breakdown voltage of un-aged oils, it can be identified that unlike, the breakdown voltage of Diala D has a lower value when compared with Mineral Transformer oil and MIDEL 7131. Among the three oils, MIDEL 7131 has got higher breakdown voltage. This result supports the results shown in [15]. Breakdown voltage values of Mineral Transformer oil are in-between MIDEL 7131 and Diala D oil.

Graph below represents the average breakdown voltage Vs gap spacing.

An average of thirty breakdown measurements of each individual oils has been obtained and shown in the Fig. 9. Standard deviation at each gap spacing has been calculated and shown in the above graph as error bars. From graph it can be seen that the breakdown voltage is increased with increasing gap spacing in all the cases. Electrode gap spacing is very important in breakdown voltage testing. From the above graph it is evident that, the breakdown voltage of

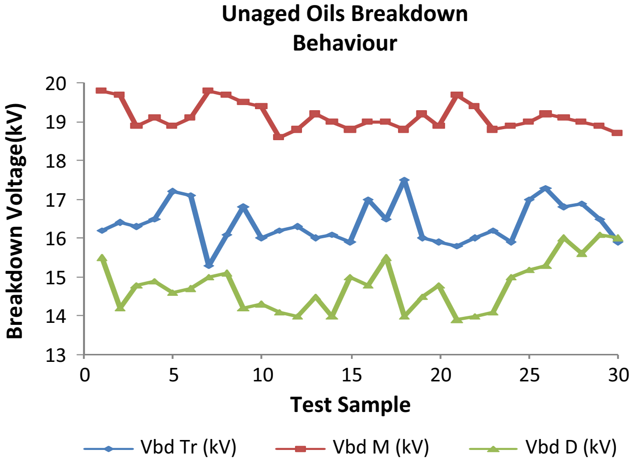

Fig. 8 Un-aged oils breakdown voltage test results

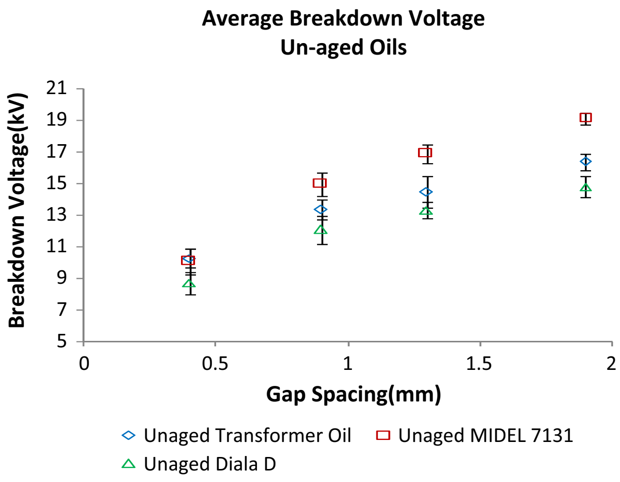

Fig. 9 Average breakdown voltage of un-aged oils

MIDEL 7131 is higher than Mineral Transformer oil and Diala D at all gap spacing. It also indicates breakdown voltage of Mineral Transformer oil is lower than MIDEL 7131 but higher than Diala D.

Figure 10 represent the average breakdown field versus gap spacing and maximum value of field at the tip of the needle at breakdown. Electric field at breakdown can be defined as maximum dielectric strength that the insulating material can withstand without breakdown. It can also be defined as the maximum electric stress (maximum electric field) that produces breakdown in insulation system. Using the formula: $E = V/2$ the average breakdown field has been calculated. Where $E =$ Average breakdown field (kV/mm). $V =$ Voltage at breakdown (KV). $d =$ Distance between electrodes (mm).

Figure 10 indicates that the average breakdown field decreases with the increase in electrode gap spacing since it follows the relation $E = V/d$ From the above graph it is clear that the breakdown field follows power law and it indicates that the breakdown field depends on the electrode gap spacing. It indicates that when the electrode gap spacing is increased, the probability of electron avalanche reduces and thereby it reduces the probability of formation of conducting channel. It is very difficult for the electric field to develop. Higher voltage is necessary in order for the breakdown to occur, when the electrode gap spacing is high. Therefore the result obtained supports the theories explained in [16].

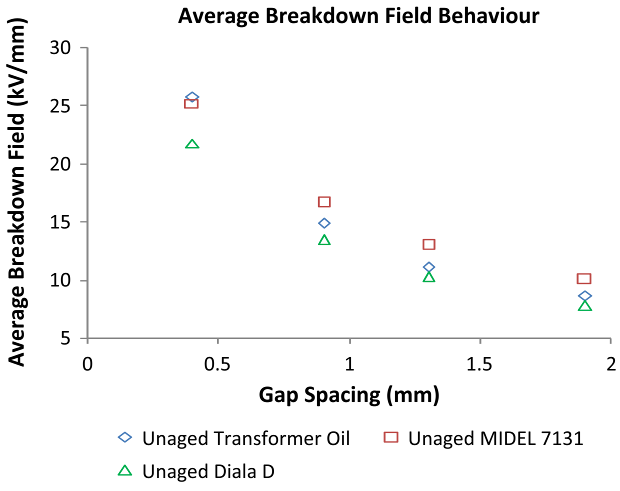

Fig. 10 Average breakdown field comparison

Similarly the breakdown voltage comparison of thermally aged oils without copper and thermally aged oils with copper has been done and included in the appendix. The value of maximum electric field at the tip of the needle during breakdown has been calculated using the formula:

$$E_{tip} = 2U/r * \ln(1 + 4d/r)$$

where $U =$ Breakdown voltage in kV. $R =$ Radius of curvature of needle tip $= 0.1$ mm, $D =$ Distance between two electrodes.

Figure 11 represents the relation between maximum fields at tip of the needle during breakdown and various gap spacing. From the graph it can be identified that maximum fields at the tip of the pointed electrode shows slight variation when increasing gap length. It indicates that the electrical breakdown of insulating oil is due to the maximum field at the tip of the needle.

For gap spacing of 0.9 mm and above, the field at the tip of the needle at breakdown is almost constant. However at the lower gap spacing this value is lower. It indicates that changes occurring in the breakdown mechanism at small gap spacing. Approximation for the electric field is not valid at this small gap. The graph clearly indicates that in the case of

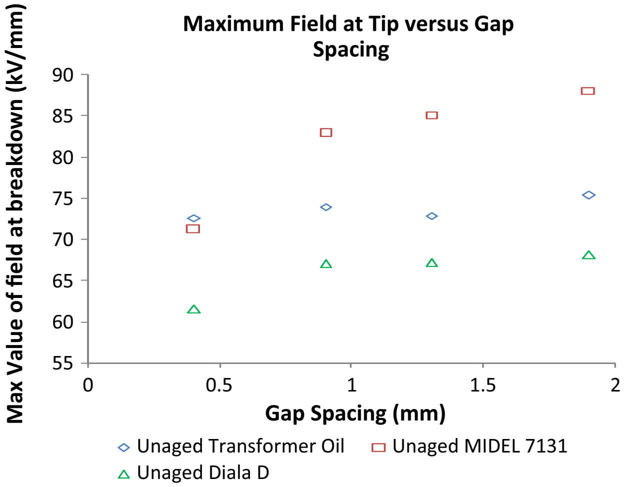

Fig. 11 Relation between maximum field at tip versus gap for breakdown

MIDEL 7131, the maximum field at tip is higher when compared with Mineral Transformer oil and Diala D. It clearly indicates that in order for the breakdown in MIDEL 7131, high electric field at the needle tip is necessary. While in the case of Diala D, low electric field at the needle tip is sufficient in order for the breakdown to happen. These results clearly indicate that MIDEL 7131 has got better breakdown characteristics when compared with Diala D and Mineral Transformer Oil. The breakdown characteristics of Mineral Transformer oil is in-between MIDEL 7131 and Diala D.

4.2 Influence of Cu on Breakdown Voltage In

4.2.1 Mineral Transformer Oil

Table 1 represents the average voltage, standard deviation, average breakdown field and maximum field at the tip of the needle at breakdown at different gap spacing. Graph (Fig. 12) represents 30 breakdown measurements of Mineral Transformer oil(un-aged, thermally aged without copper and thermally aged with copper) at an electrode gap spacing of 0.9 mm. Vbd Tr U indicates breakdown measurements of Mineral Transformer oils kept at room temperature. VbdTrANC indicates breakdown measurements of Mineral Transformer oils that are thermally aged without copper. VbdTrAC indicates breakdown measurements of thermally aged Mineral Transformer oil with copper.

From the Fig. 12 it can be identified that, Mineral Transformer oil does not show significant breakdown voltage variation after thermal ageing without copper and with copper. The Fig. 12 indicates that the addition of copper does not have a huge influence in the breakdown voltage of Mineral Transformer oils. Even though, slight reduction of about 0.55 kV in the breakdown voltage at 0.9 mm gap spacing has been occurred due to thermal ageing with copper. Therefore in order to get a clear picture, average breakdown voltage of each Mineral transformer oils at four different gaps has been calculated and included in this section. Similarly graph representing 30 breakdown measurements of Mineral Transformer oils after different ageing at various gaps condition has been included in the appendix. Analysis of breakdown behavior of Mineral Transformer oils at various electrode gap spacing indicates that, the addition of copper catalyst does not make a huge impact on the breakdown voltage of oils.

In order to gets a clear picture about breakdown analysis of Mineral Transformer oil, Fig. 13 representing average breakdown voltage of Mineral Transformer oils at different gap spacing. Figure 13 indicates relationship between average breakdown voltages versus electrode gap spacing. An average on thirty breakdown measurements at various gap spacing has been done and shown in the Fig. 13. Standard deviation has been calculated and shown in Fig. 13 as error bars. It indicates that the average breakdown voltage of Mineral Transformer oils at various electrode gap spacing shows

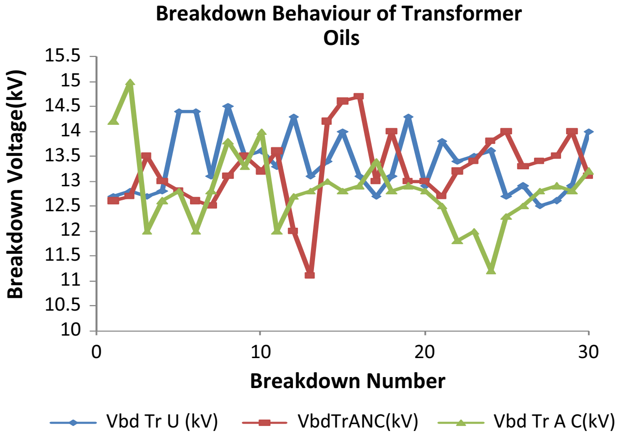

Fig. 12 Transformer oils breakdown voltage test results (0.9 mm gap spacing)

Table 1 Breakdown comparison of transformer oils

Insulating oils	d (mm)	Ave Vbd (kV)	SD (kV)	Ave field (kv/mm)	Max field
	0.4	10.28667	0.612	25.71668	72.61486
Un-aged	0.9	13.3533	0.616	14.837	73.9607
Transformer	1.3	14.47	1.01	11.13077	72.89137
Oil	1.9	16.38	0.525	8.621053	75.41774
Aged	0.4	9.2766	0.802	23.1915	65.48466
Transformer	0.9	13.23667	0.738	14.70741	73.31471
Oilwithout	1.3	14.13	0.6	10.86923	71.17865
Cu	1.9	16.89	0.357	8.889474	77.76591
Aged	0.4	10.1	1.29	25.25	71.29714
Transformer	0.9	12.82	0.758	14.24444	71.00688
Oil With Cu	1.3	13.83667	0.922	10.64359	69.70102
	1.9	15.48667	0.599	8.150879	71.30462

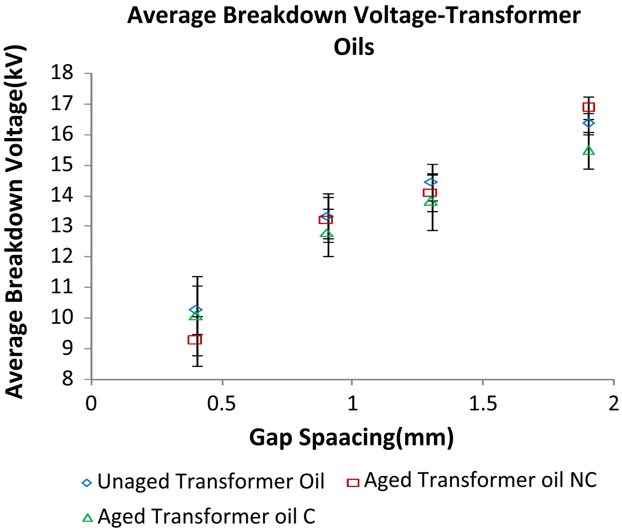

Fig. 13 Average breakdown voltage behaviour

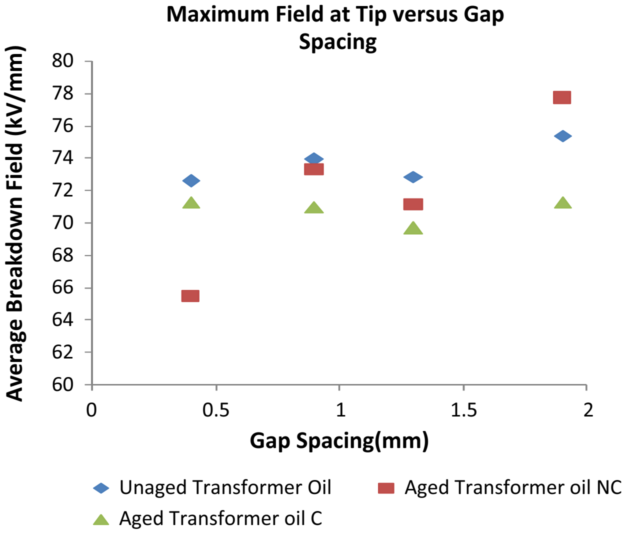

Fig. 15 Maximum field at the needle tip-transformer oils

slight variations after thermal ageing without copper and thermal ageing with copper.

Figure 14 shows the relationship between average breakdown fields at breakdown versus different gap spacing. As already mentioned electric field at breakdown can be defined as maximum dielectric strength that the insulating material can withstand without breakdown. From Fig. 14 it is clear that the average breakdown field follows power law and at higher gap spacing the breakdown voltage is high but the average field is low since it follows the relation $E = V/d$.

The Fig. 15 represents the maximum field at the tip of the needle versus gap spacing**.** In this case also the value of maximum electric field at the tip of the needle during breakdown has been calculated using the formula: $E_{tip} = 2U/r^{*}\ln(1 + 4d/r)$. The graph representing the relation between maximum field at the tip and various gap spacing has been obtained and shown in the Fig. 15. In the case of thermally aged Mineral Transformer oil without copper, the maximum field at the tip of the needle at breakdown shows random variations. It shows the changes in breakdown mechanisms. After analyzing the effect of ageing on breakdown voltage of Mineral Transformer oil, it is clear that due to thermal ageing without copper and thermal ageing with copper darken the Mineral Transformer oil but it does not made a huge impact in the breakdown voltage. This may due to the ageing period, electrode gap spacing, amount of copper etc. However slight reduction in the breakdown voltage has been noticed.

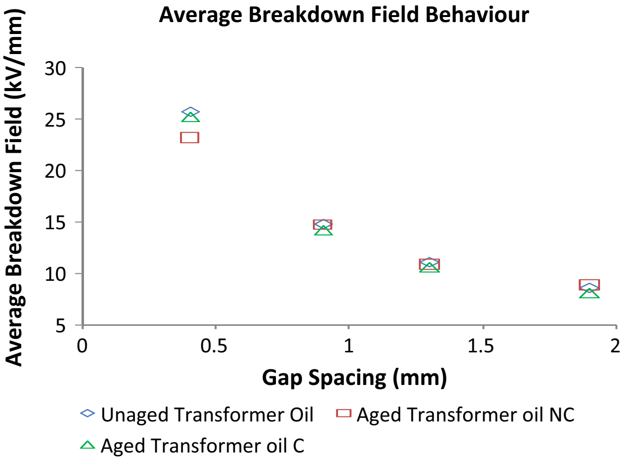

Fig. 14 Average breakdown field behavior-transformer oils

5 MIDEL 7131 Breakdown Test Results

MIDEL 7131 is a synthetic ester base liquid which is capable of substituting conventional mineral oil. The main advantage of MIDEL 7131 is that, it has got 100% fire safety records and it has also got a flash point of 264 °C. Table 2 represents the average voltage, standard deviation, average breakdown field and maximum field at the tip of the needle at breakdown at different gap spacing.

Figure 16 consists of 30 breakdown measurement of un-aged and aged MIDEL7131 without copper and with copper. The electrode gap spacing is 0.9 mm. After analyzing the above graph (Fig. 16), it can be seen that similar to breakdown behavior of Mineral Transformer oil, breakdown voltage of MIDEL7131 also not influenced much by the thermal ageing without copper and with copper. However slight variation of about (~1.3 kV) has been occurred after thermal ageing with copper. Similarly 30 breakdown

Table 2 Breakdown comparison of MIDEL 7131

Insulating oils	d (mm)	Ave Vbd (kV)	SD (kV)	Ave field (kV/mm)	Max field
	0.4	10.0866	0.538025	25.2165	71.20254
Un-aged	0.9	14.97	0.580814	16.63333	82.91521
MIDEL 7131	1.3	16.9	0.402578	13	85.91521
	1.9	19.13	0.343561	10.068842	88.07945
	0.4	9.3433	0.896616	23.35825	65.9555
Aged	0.9	14.34	0.55627	15.93333	79.42579
MIDEL 7131	1.3	16.11	0.55108	12.39231	81.15272
Without Cu	1.9	18.5166	0.482153	9.745579	85.2552
	0.4	9.033	0.587416	22.5825	63.76505
Aged	0.9	13.667	0.449009	15.18556	75.6982
MIDEL 7131	1.3	15.306	0.28519	11.77385	77.10264
	1.9	17.32	0.412227	9.115789	79.74575

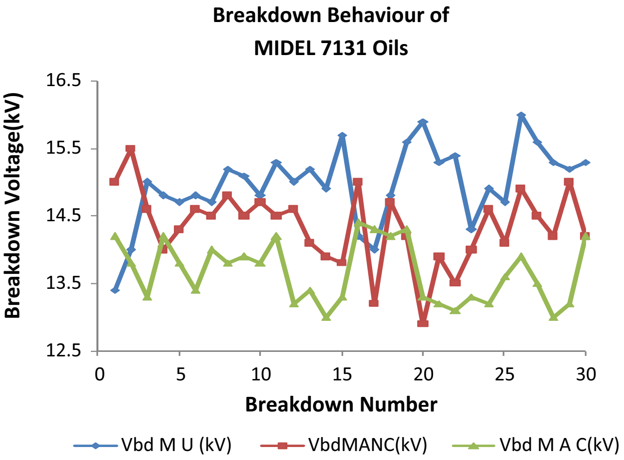

Fig. 16 Breakdown voltage test results MIDEL 7131 (0.9 mm gap spacing)

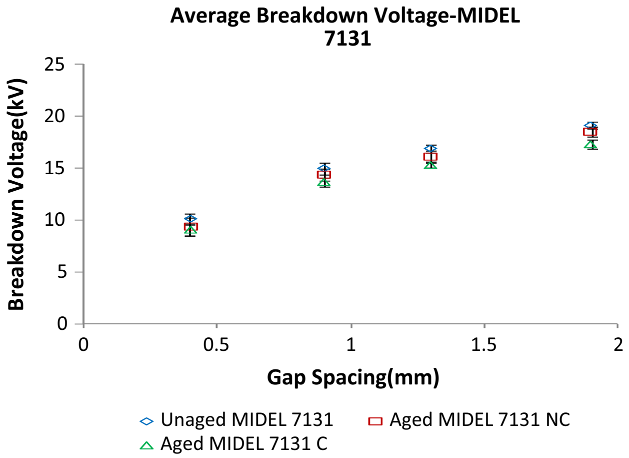

Fig. 17 Average breakdown voltage behaviour MIDEL 7131

measurements of MIDEL7131 oils at different electrode gap spacing have been done and comparison of these three oils has been including in the appendix. All the above analysis indicates that thermal ageing without copper and thermal ageing with copper does not have a huge influence in the breakdown voltage values.

Table 2 in the summary section below represents the average breakdown values of un-aged MIDEL 7131 and aged MIDEL 7131 with and without copper. It also represents the standard deviation that has been measured from 30 breakdown tests of each individual oils. Average field at the breakdown was also calculated using the formula E = V/d and included in the table below.

Graphs representing relationship between breakdown voltage and gap, average breakdown field and gapand maximum field at the tip and gap has been obtained and shown in Figs. 17, 18 and 19.

Figure 17 showing relationship between average breakdown voltage and electrode gap spacing indicates that the

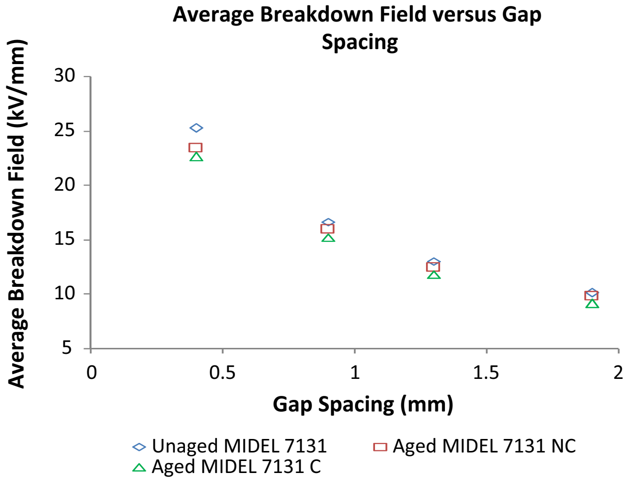

Fig. 18 Average breakdown field behaviour-MIDEL 7131

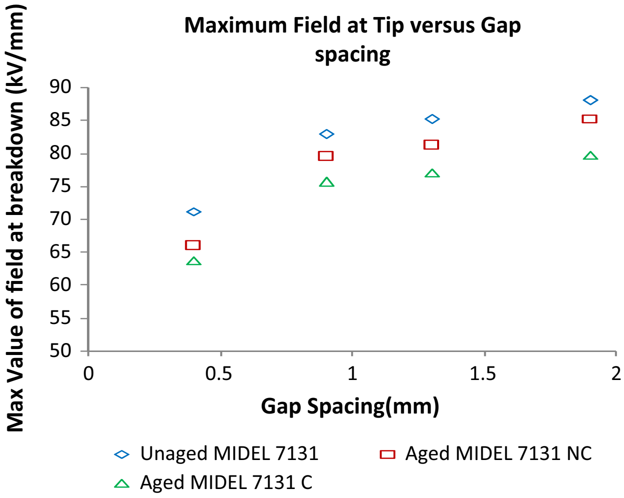

Fig. 19 Maximum field at the tip versus gap spacing MIDEL 7131

MIDEL 7131 has got high resistance against ageing with and without copper. Standard deviation has been calculated and shown in the above graph as error bars. Even though the breakdown voltage of MIDEL 7131 is slightly reduced offer ageing with copper in all gap spacing but when compared with Mineral Transformer oil and Diala D the reduction in breakdown voltage is very small. From the above table and graph it can be identified that the thermal ageing with copper slightly affects the breakdown voltage of MIDEL 7131. But reduction in breakdown voltage is always less than 1.8 kV, therefore it can be say that the addition of copper catalyst doesnot made a huge impact in the breakdown voltage of MIDEL 7131.

The Fig. 18 represents the average breakdown field versus various gap spacing. Similar to Mineral Transformer oil the average breakdowns field is reduced with increase in the gap spacing. From the above graph it can be identified that the average breakdown field does not made a huge variation after thermal ageing with and without copper. However slight reduction in average breakdown field has been occurred after thermal ageing with copper since it follow the relation E = V/d.

Another graph (Fig. 19) which represents the relationship between maximum field at the tip of the electrode and gap spacing indicates that the electrical breakdown in the insulating liquid is due to the maximum field at the tip. When applying high electric field at the tip of the needle electrode, micron sized vapor pressurized bubbles will form near the high field region. The bubble will extend in the direction of field and leads to the breakdown of liquid.

The graph (Fig. 19) indicates that at low gap spacing, maximum field at the needle tip is less compared with values at higher gap spacing. At higher gap spacing, high electric field at the needle tip is necessary in order for the breakdown of the oil. As already mentioned here also for gap spacing of 0.9 mm and above, the field at the tip of the needle at breakdown is almost constant. However at the lower gap spacing this value is lower. It indicates that changes occurring in the breakdown mechanism at small gap spacing. Approximation for the electric field is not valid at this small gap. From the graph it is apparent that due to thermal ageing with copper, maximum field at the tip of the needle at breakdown is increased by 10% indicates changes in breakdown mechanism due to ageing.

5.1 Diala D Breakdown Test Results

Inorder to analyze the effect of thermal ageing without copper and thermal ageing with copper on breakdown voltage in the case of Diala D, the breakdown voltage comparison of Diala D oils has been done and is included in this section. Table 3 represents the average voltage, standard deviation, average breakdown field and maximum field at the tip of the needle at breakdown at different gap spacing.

Table 3 Breakdown comparison of Diala D

Insulating oils	d (mm)	Ave Vbd (kV)	SD (kV)	Ave field (kv/mm)	Max field
Un-aged Diala D	0.4	8.72	0.716986	21.8	61.55555
	0.9	12.0966	0.901142	13.44067	67.00014
	1.3	13.333	0.528716	10.25615	67.16383
	1.9	14.79	0.65303	7.784211	68.09697
Aged Diala D Without Cu	0.4	7.0833	0.661286	17.70825	50.00188
	0.9	10.36	1.021696	11.51111	57.38153
	1.3	11.373	0.585417	8.748462	57.2905
	1.9	12.93	0.588481	6.805263	59.53305
Aged Diala D With Cu	0.4	6.54	0.596359	16.35	46.16666
	0.9	9.3166	0.861868	10.35178	51.60239
	1.3	10.47	0.587768	8.053846	52.74171
	1.9	12.27	0.664199	6.457895	56.49424

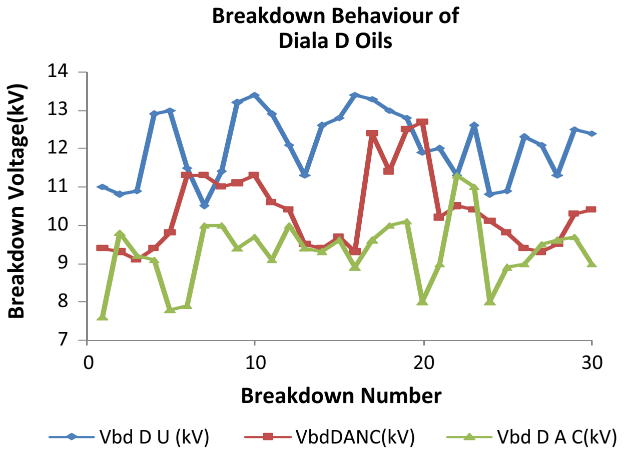

Fig. 20 Breakdown voltage test results Diala D (0.9 mm gap spacing)

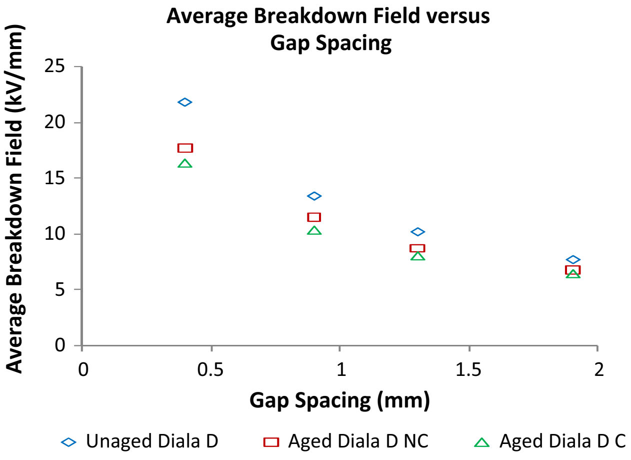

Fig. 22 Average breakdown voltage versus gap spacing

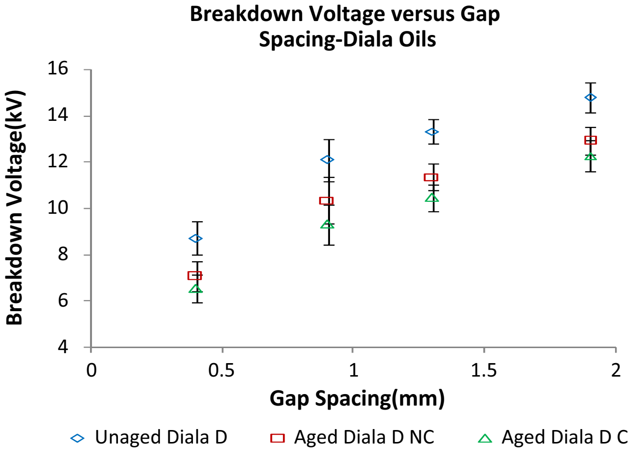

Fig. 21 Average breakdown voltage versus gap spacing

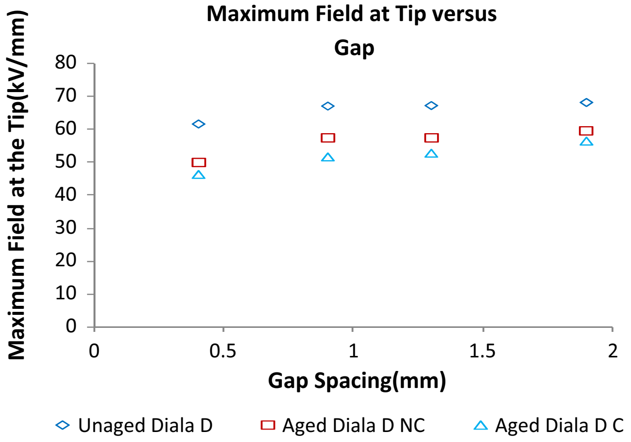

Fig. 23 Maximum field at the tip versus gap spacing

Comparison of 30 breakdown measurement of each individual Diala D oils has been done and is shown in the graph below (Fig. 20). Figure 20 represents the 30 breakdown measurements of Diala D at 0.9 mm electrode gap spacing.

From Fig. 20 it can be identified that the breakdown voltage has been reduced significantly (~3 kV) after thermal ageing with copper. It will be clearer after analyzing the average breakdown values and standard deviations of Diala D insulating oils. The graph below (Fig. 21) represents the average breakdown voltage of Diala D at different gap spacing.

From the below graph (Fig. 21) it is apparent that the breakdown voltage of Diala D has been reduced significantly after thermal ageing without copper and thermal ageing with copper. At all gap spacing the reduction in breakdown voltage is significant. Standard deviation has been calculated and shown in the above graph as error bars. Compared with MIDEL 7131 and Mineral Transformer oil, Diala D shows significant variation in breakdown voltage. It clearly indicates the effect of copper on breakdown voltage.

Similar to Mineral Transformer oil and MIDEL 7131 the average breakdowns field is reduced with increase in the gap spacing. It clearly follows the power law and it depends on the maximum field at the needle tip and gap spacing. From Fig. 22 it can be identified that the average breakdown field does not made a huge variation after thermal ageing with and without copper. However slight reduction in average breakdown field has been occurred after thermal ageing with copper since it follows the relation E = V/d. the graph below represents the average field at breakdown versus gap spacing.

Another graph (Fig. 23) which represents the relationship between maximum field at the tip of the electrode and gap spacing indicates that the electrical breakdown in the insulating liquid is due to the maximum field at the tip. The figure below represents the relation between maximum electric field at the tip versus gap spacing. From the Fig. 23 it can be seen that maximum field at the tip at all gap spacing is almost constant. The effect of copper can be clearly identified from the Fig. 23 because maximum field at the tip during breakdown in un-aged Diala D is higher when compared with the maximum field values in thermally aged oils with copper. It indicates that un-aged oils need high field at the needle tip in order for the breakdown to occur since it is not deteriorate due to thermal ageing. While Diala D that was kept at 120 °C was deteriorate due to ageing and therefore it needs less electrical field at the needle tip in order for the breakdown to occur. Similar to MIDEL 7131 here also due to thermal ageing with copper, maximum field at the tip of the needle at breakdown is increased by 10% indicates changes in breakdown mechanism due to ageing. That clearly indicates the influence of copper on breakdown voltage in Diala D oils.

After analyzing the breakdown voltage characteristics of Diala D, it is apparent that Diala D has got lower breakdown voltage when compared with Mineral Transformer oil and MIDEL 7131. Another important fact regarding Diala D is that, significant reduction in breakdown voltage (~ 3 kV) has been occurred due to thermal ageing with copper.

6 Summary

After analyzing the breakdown voltage of each individual oils, it is clear that due to thermal ageing with copper, variations in breakdown voltage has been occurred. In the case of Mineral Transformer oil and MIDEL 7131, the reduction in breakdown voltage is not significant. While due to thermal ageing with copper, the breakdown voltage of the Diala D has been reduced significantly. Graphs showing the relation between maximum field at tip of the needle at breakdown and gap spacing indicate that due to thermal ageing with copper the maximum field at the tip has been reduced indicating the changes in breakdown mechanism.

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