Thermal Modeling and Experimental Analysis of Power Transformer oils Insulation Level at varied operating Temperature.

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Abstract: The incessant failure in the insulation level of power transformers has necessitated a veritable approach in determining factors that impede its life expectancy and its performance efficiency. The Hot Spot Temperature (HST) which is dependent on the ambient temperature has contributed significantly in per unit insulation life of the transformer. Basically, transformers are insulated using a standard insulating oil of high dielectric strength for high voltage applications. In this paper, thermal modeling and simulation of major deterministic factors such as: transformer's oil viscosity, its specific heat capacity, thermal conductivity, acceleration factor, insulation life and coefficient of thermal expansion were carried out in MATLAB 7.11. A comparative test analysis was done in High Voltage laboratory on three different transformers oil samples using Megger OTS60AF kit to illustrate the interrelatedness in break down voltage and specific resistance of the oil as the operating temperature is varied. The laboratory test showed that Silicon oil exhibited perfect breakdown voltage characteristics over Naphtha and Paraffin oil within the same temperature variation with a breakdown voltage of 48.88Kv and specific resistance of $244.42\mathrm{e}^{-16}\Omega/\mathrm{cm}$ at optimum temperature of $70^{0}\mathrm{C}$ as against 41.77Kv break down voltage, and specific resistance of $208.83\mathrm{e}^{-16}\Omega/\mathrm{cm}$ for Paraffin oil and 29.08Kv breakdown voltage with specific resistance value of $145.4\mathrm{e}^{-16}\Omega/\mathrm{cm}$ for Naphtha oil at the same $70^{0}\mathrm{C}$. Simulation results indicate that thermal conductivity of the oil decreased from 0.1360 $\mathrm{Ws}/\mathrm{Kg}^{0}\mathrm{C}$ at $20^{0}\mathrm{C}$ to 0.1315$\mathrm{Ws}/\mathrm{Kg}^{0}\mathrm{C}$ at $70^{0}\mathrm{C}$ whereas oil density correspondingly decreased from 972 Kg/m3 at $20^{0}\mathrm{C}$ to 927 Kg/m3 at $70^{0}\mathrm{C}$ Thermal power dissipated in watts also increased from 1478Watts at $20^{0}\mathrm{C}$ to 1600Watts at $70^{0}\mathrm{C}$.

Key Words: Hot Spot Temperature, Breakdown Voltage, Aging Acceleration Factor, specific resistance, thermal conductivity and thermal dissipation.

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1.0 Introduction

Power transformers are the main components that constitute a large portion of capital investment in voltage transmission and distribution processes. When a power transformer fails, a shut-down in the operation of voltage transmission and distribution is inevitable. This obviously may result to the decrease in the reliability of the electricity delivery to the consumer’s load end in due time.

Transformer aging can be evaluated using the Hot Spot Temperature (HST) and Top Oil Temperature (TOT). An increase in TOT and HST has the effect of reducing the insulation level of the transformer oil [1]. Abnormal conditions such as overloading, injection of non-sinusoidal loads (Harmonics) or exposure of the transformer oil to higher ambient temperature than normal, can accelerate transformer ageing and accordingly accelerate the time to end of the transformers life span [2-3]. Aging or deterioration of transformer insulation is a time function of temperature, moisture content and oxygen content. The moisture and oxygen contributions to insulation breakdown can be minimized with modern oil preservation systems leaving insulation temperature as the primary parameter [3]. The variation of power transformer loading beyond its name plate rating in both normal and emergency cases increase the temperature inside the transformer tank and may also cause a rapid thermal deterioration of the insulation level [4]. Hence, to ensure that power transformers in terminal stations operate at full capacity without failures due to temperature increase, a careful study of their entire thermal behaviour is needed. In reference [5], a model oriented to top oil temperature was discussed but emphasis on data requirement from design stage and data from heat run tests of the transformer were not inclusive. In [6] the change in parameters of the thermal model when the cooling system is controlled was presented with no emphasis to experimental investigation of the transformer oils insulation level at varied temperature. The concept applied in [7], considered the finite element method in the determination of the Hot Spot Temperature, insulation level of the transformer in terms of its winding temperature and power losses. Though reference [7] was too analytical but emphasis on practical determination of the various oils insulation level in terms of their break down voltages and specific resistance values at varied temperature was not reflected. This paper, therefore, presents an accurate method on how to determine transformer's oil viscosity, specific heat of the oil, thermal conductivity, acceleration factor, insulation life and coefficient of thermal expansion of three selected transformer oils at varied operating temperature. It also showed the laboratory evaluation of the three oil insulation level in terms of their breakdown voltages as their temperature values vary when subjected to high d.c voltage (80kV) within a gap of 2.5mm between two oil test pots.

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2.0 Thermal Modeling of Power Transformer.

When a transformer is energized and loaded at ambient temperature θ_a, dissipation caused by core losses, winding losses, stray losses in the tank and metal support structures are the major sources of heat which can cause a rise in the transformer oil and winding temperature. This rise in transformer oil usually is cooled by the radiator assembly. Hot spot temperature usually is the sum of ambient temperature, top oil temperature rise and the corresponding bottom oil temperature gradient [8]. Hot spot temperature real value is usually imprecise in realization since transient and thermal processes of the transformer are always too complicated. Simple mathematical models with simulations can present a more precise result. The IEEE guide for loading mineral oil immersed transformer as presented in [9] indicates how oil immersed transformers can be operated in different ambient temperature conditions and load levels without exceeding the acceptable deterioration limit of insulation due to thermal effects. According to the loading guides, the Hot Spot Temperature in a transformer winding consists of three components: the ambient temperature rise, the top oil temperature and the Hot Spot Temperature rise over the top oil temperature as shown in figure 1.0

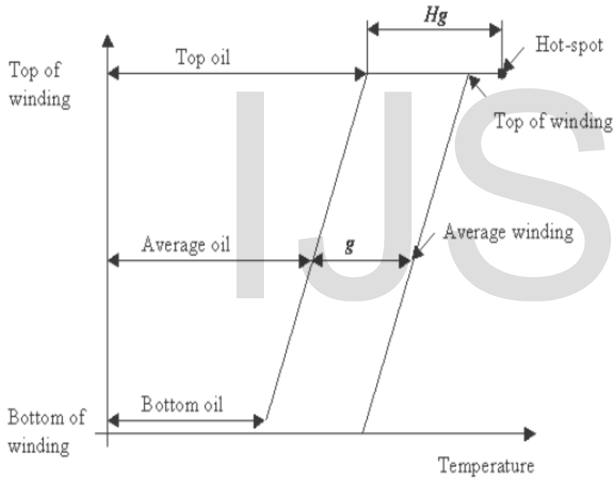


Figure 1.0 Thermal Diagram for oil temperature distribution within the transformer tank.

During a transient period of operation, the Hot Spot Temperature rise over the top oil temperature varies instantaneously with transformer loading and independently of the time [10]. The variation of the top oil temperature is usually expressed by an exponential equation which is based on a time constant (oil time constant). The diagram in figure 1.0 is based on the underlying assumptions:

- The change in the oil temperature inside and along the winding is linearly increasing from bottom to top.
- The increase in the winding temperature from bottom to top is linear with a constant temperature difference of "g".
- At the top of the winding, Hot-Spot-Temperature HST is always higher than the average temperature rise of the winding. The difference in the temperature value is defined by H.g where H is a Hot Spot Factor which varies from 1.1 to 1.5 depending on short circuit impedance, winding design and transformer size.

Basically, two types of transformer oil exist which include the mineral oil and the vegetable oil. Synthetic oil which combines the characteristics of the vegetable oil and mineral oil has been developed as silicon. The major mineral oils discussed in this paper are the Paraffin based mineral oil, Naphtha based mineral oil and Silicon. They differ in physical, chemical and electrical properties albeit being refined from the same crude product. The vegetable oil which is a natural ester is produced from natural animal and plant material. It is also a good transformer oil though has the disadvantage of forming wax and biodegradable clogs at temperature below room temperature [11]. Naphtha based mineral oil though is more easily oxidized, the oxidation product or sludge is soluble and is not precipitated in the bottom of the transformer, hence does not obstruct conventional circulation of the oil. The paraffin based mineral oil has lower oxidation rate but the oxidation product (sludge) is insoluble and precipitate at the bottom of the tank. It obstructs the transformer cooling system due to poor conventional circulation of the oil.

3.0 Dynamics of Thermal Modeling of Power Transformer

The degree to which any electrical device can withstand impulse voltage before a break down occurs is an important parameter in the choice of insulating liquids. The dielectric strength of an insulating fluid or transformer oil depends on the shape of the electrodes and the distance of separation of the electrode pairs. The wider the gap, the higher the breakdown voltage since

$$V = \frac{Q}{C} \qquad (1)$$

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d} \qquad (2)$$

The minimum permissible breakdown voltage of the transformer oil for an ideal medium voltage transformer should fall within the range of 25kV for 11kV and 33kV distribution voltages for most power equipment [11]. The specific resistance of transformer oil is a measure of direct current resistance between two opposite sides of the terminal for a unit volume of transformer oil. The rapid increase in temperature of transformer oil decreases the resistivity value of the oil. Thus, resistivity value of the insulating oil is usually high at room temperature in accordance with thermal and electrical processes as briefly reviewed in [12]. The minimum standard value for specific resistance of transformer oil at room temperature of 25^0C to 27^0C is usually $1500 \times 10^{15} \Omega/cm^3$ at a breakdown voltage value of 30kV and $35 \times 10^{15} \Omega/cm^3$ for a temperature of 70^0C to 90^0C for Hot Spot Zones. By proportion, at the same room temperature, 1kV breakdown voltage will result to $5 \times 10^{16} \Omega/cm^3$ value. This specific resistance value of $5 \times 10^{16} \Omega/cm^3$ for 1kV breakdown voltage was applied in realizing the various values of the three oil specific resistance as their breakdown voltage values change with a corresponding change in temperature.

The IEEE loading guide shows that insulation life is an exponential function of Hot Spot Temperature [13]. Thus, the percentage value of insulation life is expressed in (3).

% Insulation life

$$= \mathrm{A}e^{\left(\frac{\mathrm{B}}{\theta_\mathrm{h}+273}\right)} \times 100 \quad (3)$$

θ_h is the Hot Spot Temperature in ^{0}C. A and B are constants that are determined based on the insulation material. The above expression can be used for both distribution and power transformer since both are manufactured from same cellulose insulation material. Per unit insulation life and aging acceleration factor with temperature are represented by (4) and (5).

Per Unit Insulation Life

$$= 9.8 \times 10^{-18} e^{\left(\frac{15000}{\theta_\mathrm{h}+273}\right)} \quad (4)$$

Aging Acceleration Factor F_{AA}

$$= e^{\left(\frac{15000}{\theta_{\mathrm{amb.}}+273} - \frac{15000}{\theta_\mathrm{h}+273}\right)} \quad (5)$$

Where: θ_{amb}. is the ambient temperature or Top Oil Temperature in ^{0}C. The thermal power dissipated to the atmosphere in a unit time is given by (6).

$$P_{TH} = C_{oil} \times \rho_{oil} \times \psi_{oil} \times (\theta_h - \theta_{amb}) \quad (6)$$

Where: ψ_{oil} = the oil flow rate in m^3/s.

C_{oil} = Specific heat of the oil in Ws/Kg ^{0}C.

ρ_{oil} = the density of the oil in Kg/m^3

The transformer oil viscosity which is synonymous with (3) is modified and presented in (7).

$$\mu = A_1 \times e^{\left(\frac{A_2}{\theta_{\mathrm{oil}}+273}\right)} \quad (7)$$

$$C_{oil} = A_3 + A_4\theta_{oil} \quad (8)$$

$$\rho_{oil} = A_5 + A_6\theta_{oil} \quad (9)$$

$$K = A_7 + A_8\theta_{oil} \quad (10)$$

$$\beta = A_9 \quad (11)$$

Where K = thermal conductivity and

μ = the oil viscosity.

The constants in (7)-(11) as stated in references [14]-[15] are presented in table 1.0.

Table 1. Insulation oil constants for Mineral oil and refined Silicone [14]-[15].

Oil constant	Mineral oil	Silicone
A_1	0.13573×10^{-5}	0.12127×10^{-3}
A_2	2797.3	1782.3
A_3	1960	1424
A_4	4.005	2.513
A_5	887	989
A_6	-0.659	-0.8700
A_7	0.124	0.138
A_8	-1.525×10^{-4}	-9.621×10^{-5}
A_9	8.6×10^{-4}	9.5×10^{-4}

4.0 Experimental Procedure and Simulation Results

The test kit shown in figure 2 produced by Megger and IEC 60256 standard was applied in the experiment. The steps adopted in the experimental work are as illustrated:

- The oil sample was poured into a cleaned vessel containing a pair of electrodes fixed at a gap of 2.5mm between the two electrodes
- The applied voltage between the electrodes was slowly increased to 80kV
- The rate of rise in voltage was kept at 2kV/s and observed closely with time.
- Readings/data were taken at the exact moment sparking occurred between the electrodes.
- The experiment was carried out for temperature values ranging from 20^0C to 70^0C.
- The experiment was repeated six times for each temperature value in accordance with the IEC 60156 standard. Figures 12-15 represent the laboratory results obtained.
- The mean value of the three oil samples in kV was calculated for their break down voltage and specific resistance at different operating temperature as shown in tables 2-4.

Table 2. Break down Voltage and Specific Resistance of Paraffin oil at varied temperature.

Temperature (^{0}C)	Break down Voltage (kV)	Specific Resistance Ω/cm^3
20	13.37	66.83×10^{16}
30	14.18	70.92×10^{16}
40	20.22	101.10×10^{16}
50	52.02	260.10×10^{16}
60	50.28	251.42×10^{16}
70	41.77	208.83×10^{16}

Table 3. Break down Voltage and Specific Resistance of Naphtha oil at varied temperature.

Temperature (^{0}C)	Break down Voltage (kV)	Specific Resistance Ω/cm^3
20	30.10	150.50×10^{16}
30	35.03	175.20×10^{16}
40	37.23	186.20×10^{16}
50	56.47	282.30×10^{16}
60	36.37	181.80×10^{16}
70	29.08	141.40×10^{16}

Table 4. Break down Voltage and Specific Resistance of Silicon oil at varied temperature.

Temperature (^{0}C)	Break down Voltage (kV)	Specific Resistance Ω/cm^3
20	27.70	138.50×10^{16}
30	34.22	171.10×10^{16}
40	55.58	277.90×10^{16}
50	54.83	274.17×10^{16}
60	52.37	261.83×10^{16}
70	48.88	244.42×10^{16}

Simulation was carried out using the data presented in tables 2- 4 to determine the optimal performance of the three oil samples with pertinent to transformer's oil viscosity, specific heat of the oil, thermal conductivity, acceleration factor, insulation life and thermal power dissipation.

In Table 2 and Figure 3, it can be observed that the best operating temperature for paraffin oil ranged from 20^0C to 50^0C after which an exponential fall in the breakdown voltage was detected. At a value below the room temperature, a low breakdown voltage magnitude occurred. This obviously can lead to a flashover at the transformer core during a high voltage application which can also give rise to the formation of sludge. The rise in the value of the specific resistance within the transition period in temperature from 50^0C to 70^0C as evidently presented in table 2 indicates that breakdown voltage proportionately rises with increase in the value of the specific resistance of the transformer oil.

Table 3 and Figure 4 indicated that when a Naphtha based mineral oil was subjected to the same condition as the paraffin oil, the best operating temperature was detected to occur at 50^0C with an optimum breakdown voltage of 56.47kV which corresponds to a specific resistance value of $282.3 \times 10^{16}\Omega/cm^3$ which is comparatively higher than the value of the paraffin oil. Naphtha oil therefore has a better viscosity, pour point at a lower temperature and a good dielectric strength than the paraffin oil.

In Table 4 and Figure 5, there is a total shift from the results obtained from Naphtha and paraffin oil, the best operating temperature ranged from 20^0C to 40^0C. The peak breakdown voltage of 55.58kV was achieved at 40^0C with a specific resistance value of $277.90 \times 10^{16}\Omega/cm^3$ as shown in table 4. A display of relative voltage stability within temperature ranges of 50^0C to 70^0C was obtained which distinguished it from the two other mineral oils that showed various instability in their breakdown voltage values for the same temperature range. Silicon oil therefore offers a better thermal stability than other mineral oil reviewed. It works well for both cold and extreme temperature condition. Its high viscosity contributes to its poor heat transfer.

In Figures 6 and 7, the per unit insulation life and the viscosity of silicon decreases proportionately with increase in the load temperature whereas Figures 8 and 9, the aging acceleration factor and the specific heat capacity of the oil increases appropriately with increase in load temperature which is in conformity with the already established rule on transformer loading guide. At a room temperature range of 20^0C-30^0C, the acceleration factor had a zero value and increased from 35^0C to 0.015 at optimum temperature of 70^0C. In Figures 10 and 11, the inverse relation in density and thermal conductivity with temperature indicates that high temperature reduces the dielectric strength of the oil which invariably decreases the thermal conductivity from 0.1360Ws/Kg^{0}C at 20^0C to 0.1315Ws/Kg^{0}C at 70^0C. The density of the oil also falls sharply from 972Kg/m^3 at ambient temperature of 20^0C to 927Kg/m^3 at 70^0C rise.

In Figure 12, the thermal power dissipated in watts rose from 1478watts at 20^0C to 1600watts at 70^0C which proved that higher temperature reduces the breakdown voltage of the transformer and also increases the rate of power dissipation on loading.

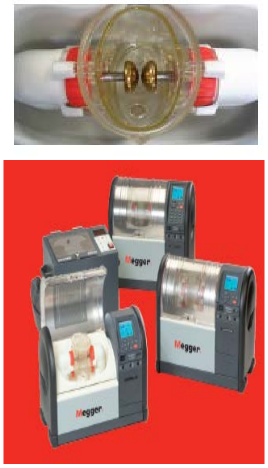


Figure 2: Test Kits with spherical electrode (OTS 60AF)

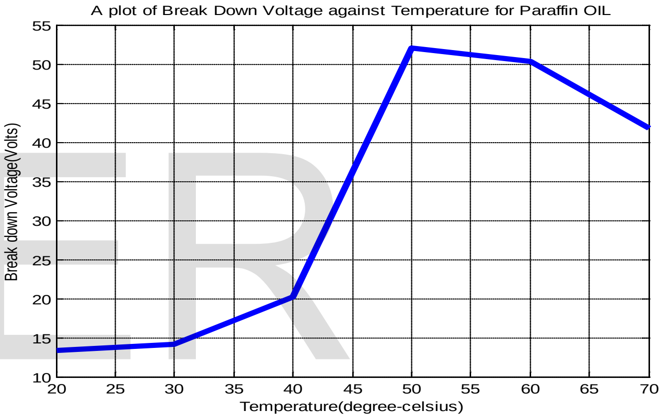


Figure 3: Breakdown Voltage of Paraffin against Temperature.

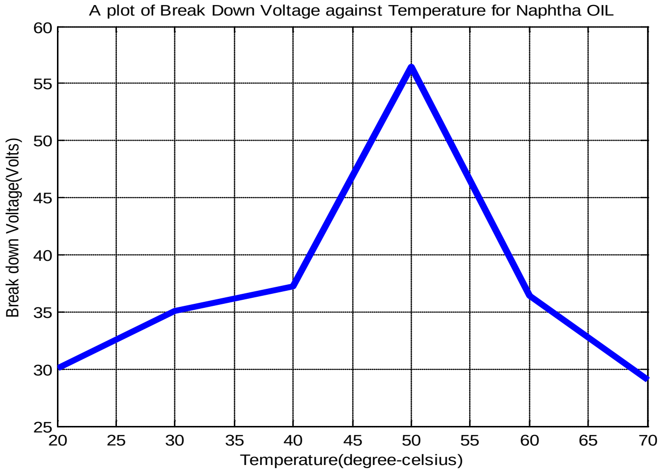


Figure 4: Breakdown Voltage of Naphtha against Temperature.

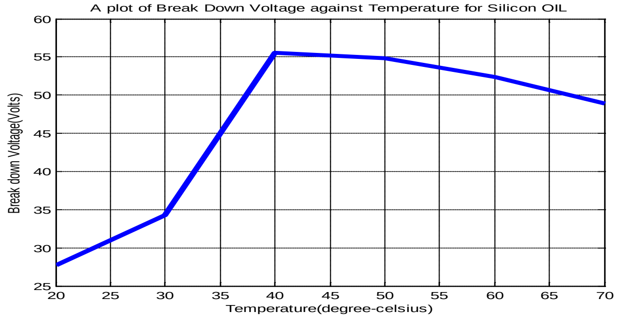


Figure 5: Breakdown Voltage of Silicon against Temperature.

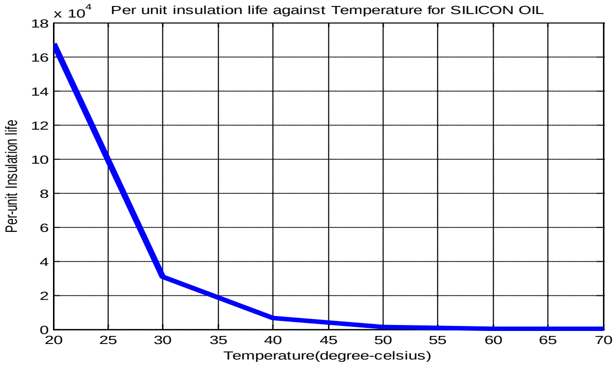


Figure 6: Per Unit Insulation of Silicon against Temperature.

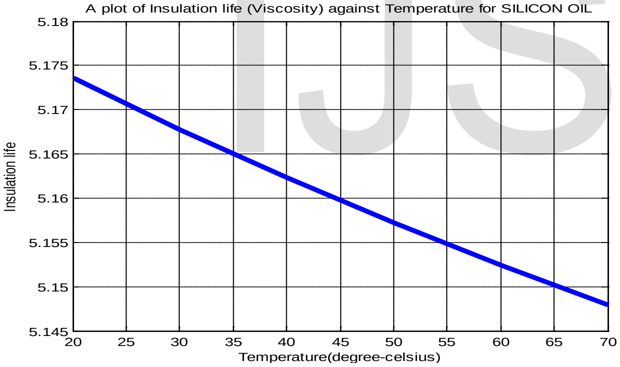


Figure 7: A Plot of Viscosity of Silicon against Temperature.

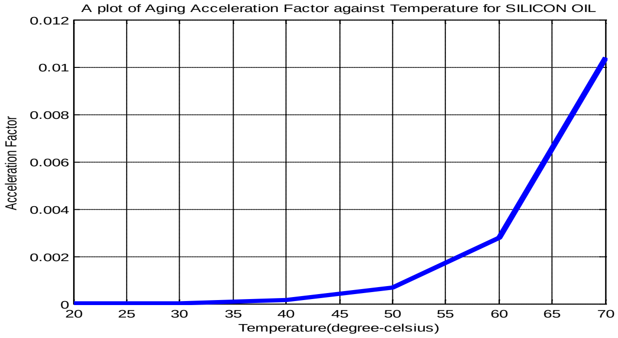


Figure 8: Plot of acceleration factor of Silicon against Temperature.

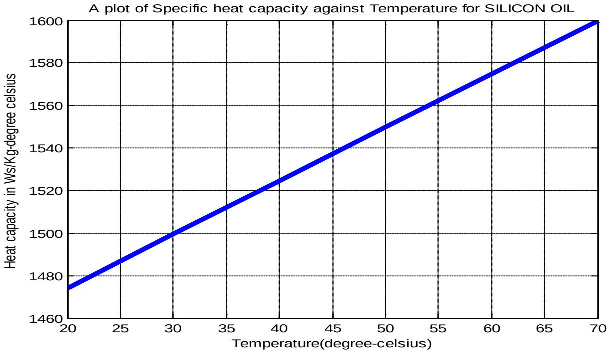


Figure 9: A Plot of Specific heat of Silicon against Temperature.

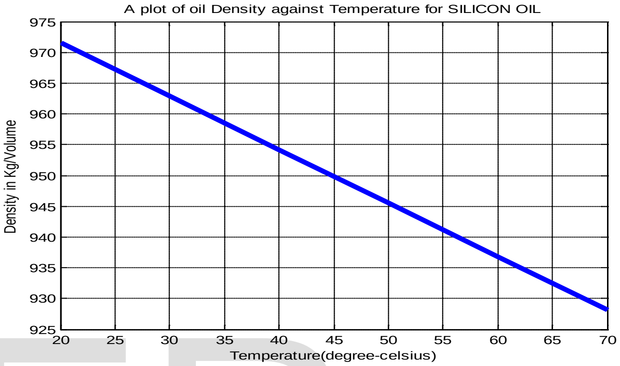


Figure 10: A Plot of Density of Silicon against Temperature.

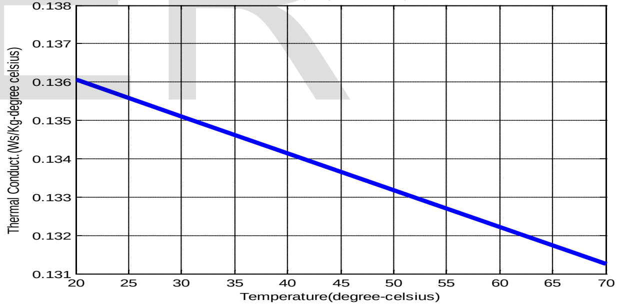


Figure 11: A Plot of Thermal conductivity against Temperature.

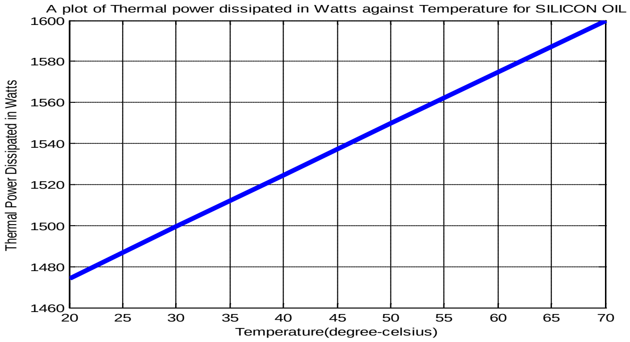


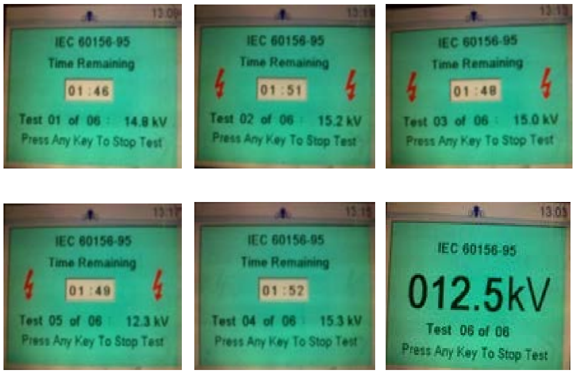
Figure 12: A Plot of Power Dissipation against Temperature.

- 20^0C Test Result for Silicon oil

- 20^0C Test Result for Paraffin oil

- 30^0C Test Result for Silicon oil

- 30^0C Test Result for Paraffin oil



- 20^0C Test Result for Naphtha oil

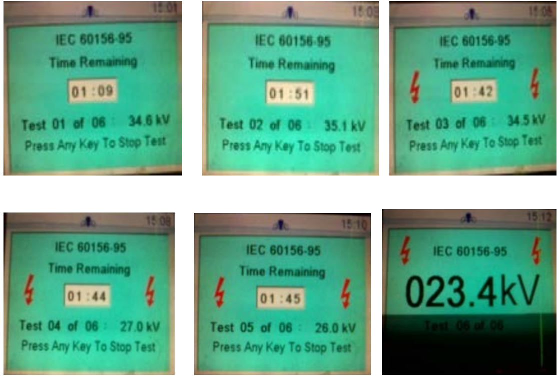


Figure 12: Laboratory Test Results of Silicon, Paraffin and Naphtha oil break down voltage at 20^0C

- 30^0C Test Result for Naphtha oil

Figure 13: Laboratory Test Results of Silicon, Paraffin and Naphtha oil break down voltage at 30^0C

- 40^0C Test Result For Silicon oil

- 40^0C Test Result for Paraffin oil

- 40^0C Test Result for Naphtha oil

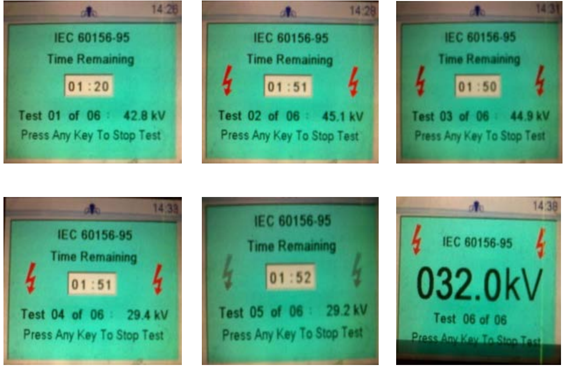
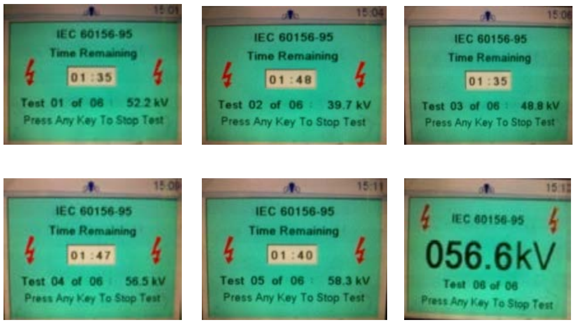


Figure 14: Laboratory Test Result of Silicon, Paraffin and Naphtha oil break down voltage at 40^0C

- 50^0C Test Result for Silicon oil

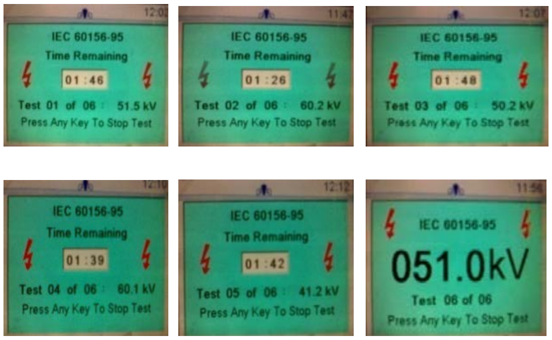
- 50^0C Test Result for Paraffin oil



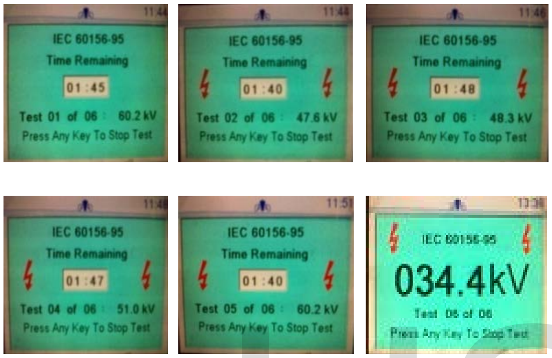
- 50^0C Test Result for Naphtha

Figure 15: Laboratory Test Result of Silicon, Paraffin and Naphtha oil break down voltage at 50^0C

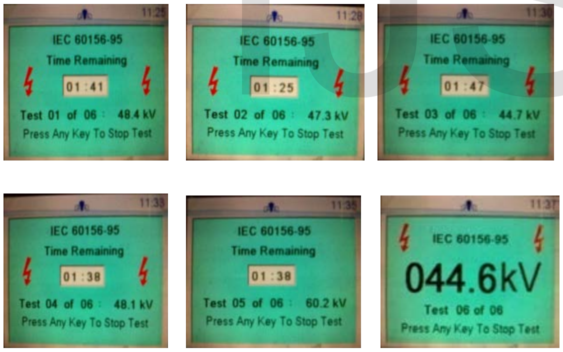
❖ 60^{0}C Test Result for Silicon oil



❖ 60^{0}C Test Result for Paraffin oil



❖ 70^{0}C Test Result for Silicon oil



❖ 70^{0}C Test Result for Paraffin oil

❖ 60^{0}C Test Result for Naphtha oil

Figure 16: Laboratory Test Result of Silicon, Paraffin and Naphtha oil break down voltage at 60^{0}C

❖ 70^{0}C Test Result for Naphtha oil

Figure 17: Laboratory Test Result of Silicon, Paraffin and Naphtha oil break down voltage at 70^{0}C

5.0 Conclusion:

This paper analyzed the thermal model of three transformer oils and experimentally assessed the breakdown voltage of the three oil samples. A detailed simulation results presented showed that the thermal conductivity and the density of the oil samples decreased as the loading temperature increased. The acceleration factor with the specific heat capacity and the thermal power dissipation increased proportionately with the applied temperature. The laboratory test results proved that silicon oil exhibited a perfect breakdown voltage over Paraffin and Naphtha oil thus is recommended for its good dielectric strength. Silicon oil is best used in both warm and cold climates since tests conducted on it at varying temperatures indicates that its breakdown voltage at given temperature falls within the specified value for 11kV and 33kV distribution voltage.

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