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Review of Accerlated Thermal Aging Models of Conditioning Assessment of Power Transformer Insulation

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ABSTRACT: Oil immersed power transformer being very important and highly expensive is main backbone and hub of power transmission & distribution system. Its failure not solely causes its own harm but directly affect the protection, stability and reliability of the power grid system. A power transformer needs to be tested periodically for its protection and safe operation. These test include routine test, temperature rise test, dielectric type tests, short circuit withstand test, sound level test, insulation monitoring tests, impulse test, field service test etc. Transformer reliability is totally dependent on these test results. A vital decision regarding transformer diagnostic and condition monitoring is made on basis of these test results. But, it's well known proven fact that all of the desired tests mustn't be performed on a power transformer in commission because a number of these tests are harmful in nature. Because of test results of these experiments are essential in diagnostic and observance procedure for transformers in actual operating conditions. Therefore, so as to perform these tests, scaled-down or prorated models of actual power transformers are utilized in experimental studies. This paper presents the various models, experimental setups and numerous methodologies are used till date to work out the aging issue of transformer insulation system.

KEYWORDS: Power Transformer, Thermal Aging models, Aging Time, Aging Temperature, Mineral Oil, Paper Insulation.

I.INTRODUCTION

Safe operation of electrical equipment is the initial line of defence to ensure the protection of power system [1]. Oil immersed power transformer is the core and hub of power transmission and distribution. It is one amongst the foremost vital and very costly equipment in the power system [2-3]. Its running state directly affects the protection, stability and continuous operation of power system. Its failure not solely causes its own harm, however conjointly results in the interruption in continuity of power and large economic losses.

Liquid immersed power transformers containing insulation system consisting of natural cellulose-based materials and transformer oil for over a hundred years [4]. Oil inseminated paper in power transformers suffers complicated physical and chemical reactions and bit by bit deteriorates in long run operation subjected to mechanical, electric and thermal stress, and environmental conditions[5]. These kinds of stress acts as a promoter to the chemical reactions & affects the electrical, chemical and mechanical properties of the insulation result in degradation in insulating system. The degradation leads to variation of physical, mechanical and dielectric properties of oil inseminated paper which further end in shortening lifespan of transformer and surprising transformer failure [6]. So, it’s necessary to review the aging state of insulation fairly, accurately and conveniently [7-8]. The frequency domain spectroscopy analysis (FDS) was introduced to evaluate the aging condition of oil inseminated paper with-n the early nineteen nineties [9-11] where it pay attention on the characterization of aged oil inseminated paper through aging-related parameters [13-14] and its variations with temperature [14-15] like; the variations of aging byproducts such as water content [16-20], dissolved gases [21-22] and carboxylic acid [23] were consistently investigated.

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Also mineral oil, a kind of insulating and cooling oil, must be tested sporadically to make sure that it is still suited for usage. Testing sequences and procedures are outlined by numerous international standards like IEEE, ISO, ASTM, TAPPI etc. Testing consists of measure breakdown voltage and different physical, chemical and dielectric properties of mineral oil, either during laboratory work or using transportable test equipment on spot. But, it's a undeniable truth that all of the desired tests mustn't be performed on a power transformer in commission because a number of these tests are disparaging in nature. Because the test results of those experiments are very important in analyzing and diagnosing the condition of transformers in actual operating conditions. Therefore, so as to perform these tests, scaled-down or prorated models of actual power transformers are used in the literature for the experimental study of aging [8].

In this paper, aging cycles for various prorated models are reviewed. These models supported long and short run accelerated & thermal aging in the power transformer. In long run accelerated aging, experiments are conducted at temperatures within the range from 90°C -145°C for time periods of up to 100 weeks e.g. Montsinger [24] conducted experiments at temperatures range from 90°C - 110°C maximum up to 70 weeks, Dakin [25] used temperature range from 100°C - 135°C maximum for 100 weeks, Shroff et al. [26] preferred 110°C - 140°C for 180 days, Moser et al. [27] completed experiments from 90°C - 135°C up to 400 days, to investigate behaviour and life span of insulating system in long run. On the other side, to complete the experimental study of accerlated aging in a short time period, experiments are conducted at high temperatures within range from 130°C-190°C for a short time period. As an example, Oomen [28] preferred temperature range from 120°C to 180°C for up to 7 days only for experimental study, Moser et al. [27] completed experiment within temperature range from 145°C- 190°C for up to 20 days, Singh et al. [4] performed the aging of kraft paper in mineral oil within temperature range from 120°C -160°C for 1440 hours, Rao et al. [39] completed aging of paper samples within temperature range from 110°C -200°C for 96 hours.

II. THERMAL AGING MODELS

Power transformer's life is purely dependent on its insulation system so it is very important to recognize the behaviour of solid and liquid insulation to calculate the remaining life of oil filled transformer [29]. Mechanical and thermal stresses are the basic cause of degradation of transformer insulation. Amount and period for which these stresses remains, decide the aging of insulation. To acquire the credible failure data, long time duration is required to carry out the aging experiments under normal operating stress conditions for which it implies costs of running, expenditure and time. But to acquire failure data in a short time period, stress is increased during the aging experiments by use of controlled and carefully designed experiments which are either stepped appropriately or be continues in time. These experiments set up situation for quick drop in strength of insulation for aging and quantify properties essential to cause failure [30]. Breakdown voltage (BDV), moisture content, furan, dissolved gasses analysis, partial discharge, degree of polymerization, capacitance & Tan &, interfacial tension (IFT), are the most responsive parameters which can serve as indices of aging [31]. Several different models, experimental setups and numerous methodologies used till date to work out on aging issue of transformer insulation system are as below:

A. Thermal Aging Chamber [5]

To improve the accuracy of oil impregnated paper, Y. Zhu et al. employed thermal aging chamber (shown in figure 1(a)) consisting of two parts; lower part being barrel in cylindrical shape made of stainless steel with height and diameter of 250 and 325 mm. The inner part of the barrel is connected using 03 metallic pipes for the purpose of oiling, vacuuming and oil removal. Oil pillow and vacuum pressure gauge are used to buffer the mineral oil and are coupled to the upper cover of thermal aging chamber. Polytetrafluoroethylene (PTFE) gaskets were used for integrally sealing of upper and lower part of the barrel. Preheated treatment was given to the samples and thermal aging chamber before start of the aging process. A heat resistance test at temperature 200^0C was performed on thermal aging chamber. Simultaneously preheated treatment was also given to insulating paper and mineral oil. The insulating paper of 70 micrometer was selected for the experimental study. For the removal of moisture content, 60 mm pieces of kraft paper were cut and placed in vacuum oven for 96 hours at 0.5 Pa pressure and 80^0C temperature during preheated treatment. Then samples are analyzed at room temperature with 0.5 Pa pressure for complete one day. Then moisture content of samples of preheated paper is examined and found to be 0.2% following are engineering requirements. Simultaneously for the preparation of mineral oil for aging requirement, it is first filtered and then heated and vacuum at 80^0C for

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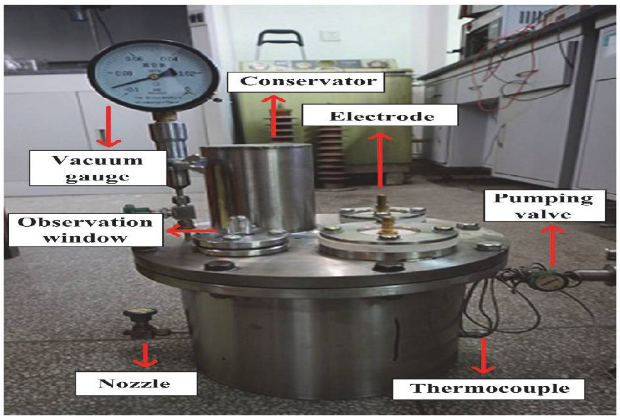
continues four hours and placed at room temperature to cool down. Water and air content in mineral oil was ≤ 5 ppm and ≤ 0.1 % respectively after the preheated treatment. For the process of aging, first pre-heated insulation paper is placed in a clean chamber with 0.5 Pa maintained air pressure and then pre-heated transformer mineral oil is injected. Now the thermal aging chamber consists of samples of oil impregnated paper and thermal aging process is started at temperature 140^{0}C in the hot air oven. The samples of aged oil impregnated paper were collected sequentially at interval of 100 hours, 200 hours, 400 hours, 700 hours and 1000 hours during aging process.

Thermal aging chamber model distinguishes the polarization in insulating materials using thermal stimulated current (TSC) test resulting in multiple polarizations. Through this aging process three dielectric process such as; electric conduction, interfacial polarization and dipole polarization are observed in oil impregnated paper and *M"* spectrum of 0-1000h aged samples were jointly analyzed.



(a) Thermal aging chamber [5]   (b) Test set up for thermal faults [32]

Figure 1: Pictorial view of test models used to detect the influence of thermal stress on power transformer insulation

Mathalage et al.[32], used the test set up (shown in fig. 1 (b)) for thermal aging of mineral and copra type coconut oil. Test cell used in this experimental study is of stainless steel with volume of 1500 mL. Before starting the process of thermal aging, water content for both of oil's was evaluated and found to be 47 and 42 ppm for MO and CO. Because of high value of water content observed, no further drying process was adopted like in other studies in the literature, as the objective was to age the liquids in worst conditions. Total 03 samples of CO and 06 samples of MO were prepared for the aging purpose. The detail of the samples prepared is mentioned in table 1. To make the test cell conditions like an actual transformer, various metallic parts like; zinc 0.5 gm/liter, iron 2.5 gm/liter, copper 2.5 gm/liter and aluminum 0.5 gm/liter were added to the test cell [33]. Further, pieces of naturally wet pressboard (100 gm/liter) were also added to the all samples of CO and 03 samples of MO for investigating the moisture effect during aging process. The test cell was sealed with separate lids. One kilogram of weight was also provided on the top of each test cell for tightness. The remaining 03 test cells of MO were placed in dry condition. Total 09 test cell are aged in the hot air oven at temperature 120^{0}c as shown in figure 1(b). The sealed condition of the test cell is to create worst case in comparison to experimental study without sealing [34]. Duration for aging was selected as 2 weeks, 5 weeks and 7 weeks for the samples prepared (see table 1)[33].

Table 1: Details and aged duration of coconut oil and mineral oil samples

Dry Transformer mineral oil	Wet Coconut oil	Wet Transformer mineral Oil	Duration (Weeks)
TD	CA	TW	0-new
TD2	CA2	TW2	2
TD5	CA5	TW5	5
TD7	CA7	TW7	7

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D-Dry, CA-Coconut oil, T- Mineral oil and W-Wet
Visual scrutiny of the samples such as variation in colour, electrical tests such as Breakdown voltage, FDS and non-electrical tests like, interfacial tension (IFT), acidity of the oils used are evaluated after aging the samples.

B. Electrothermal Transformer Model [35]

Mantilla et al., studied that voltage and current harmonic distortions are the important factors other than electrical and thermal stresses reported earlier for aging in power transformers, having great effect on the transformer temperature rise and its impact on transformer aging. Joule's effect i.e increase in current magnitude is the main cause for thermal stresses in power transformer. However, the changes in voltage affect the no-load losses of transformer resulting into change in magnitude and frequency spectrum. Electro-thermal transformer model basically comparing both harmonic distortion for different levels of voltage and current distortion characterise the transformer loss of life.
Electrothermal model is focused to identify the type of stress which causes degradation in insulation system and hence reduce power transformer life. As a result mechanical and thermal stress found to be prominent and plays important role in degrading the solid and liquid insulation of the transformer. The thermal stress depends on the transformer losses, which are mainly associated to stationary voltage and current disturbances. The current harmonics increase the current over the rated value which is studied frequently by putting the temperature of insulation to levels above rated temperature which also allows identifying Hot-Spot Temperature θ_H. No load loss model has parameters which assumes unsaturated core. If the core is considered saturated then no load losses would be greater with a noticeable increase. The effects of current harmonics are more dominant over the effect of voltage harmonics has concluded by electro-thermal model. When voltage distortion is below 10% there is no significant increase in life loss and its hot spot temperature but with the increase of voltage harmonics no load losses are increased which has negligible effect.

C. Time Domain Electrical Conductivity Model [1]

Aging of oil impregnated paper can also be evaluated by current polarization/depolarization method which is non destructive in nature and there is no need to hold electrical device. This model is used to be familiar with characteristics of time domain dielectric response on the basis of polarization/depolarization current [36]. Time domain dielectric response model for the measurement of dielectric properties of insulating paper is designed (figure 2) and run according to polarization/depolarization current measuring principal diagram (figure3).

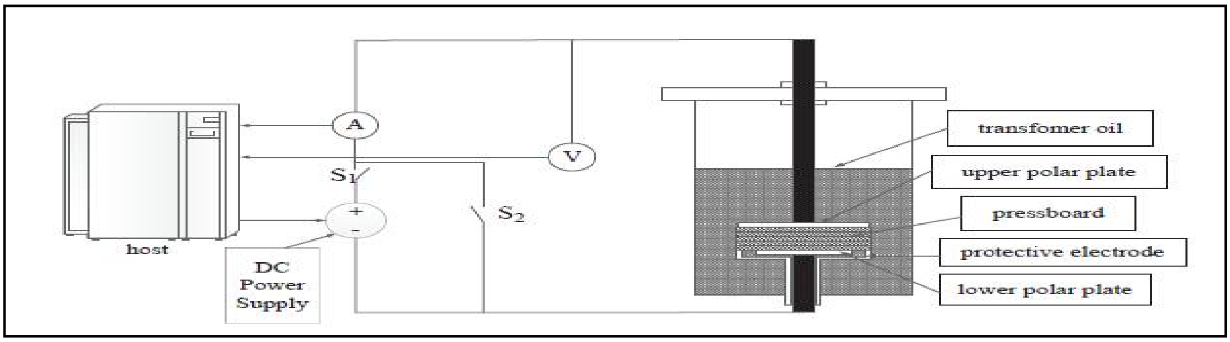

Figure 2: Dielectric measurement system diagram

The insulating paper (130 mm dia. and 1 mm thickness) for which polarization/depolarization current is to be tested is preheated first. For the removal of water content gained during shifting of insulating paper, it is preheated at 90 ◦C for 5 hours in the oven and simultaneously transformer mineral oil is degassed. Firstly dried samples of insulating papers were stored in mineral oil for 48 hours and then shifted to aging tank for aging purpose maintain a constant temperature of 130◦C. Different samples were analyzed for thermal aging by collecting samples at different time eg. 7, 14, 21, 28, 35, 49 days. A charging voltage of 1000 V and the charging time of around 2000 second are selected for experimental study. Edge effect is eliminated by introducing protective electrode in the system and the device is maintained at constant temperature of 30^0 c for controlling the PDC characteristics.

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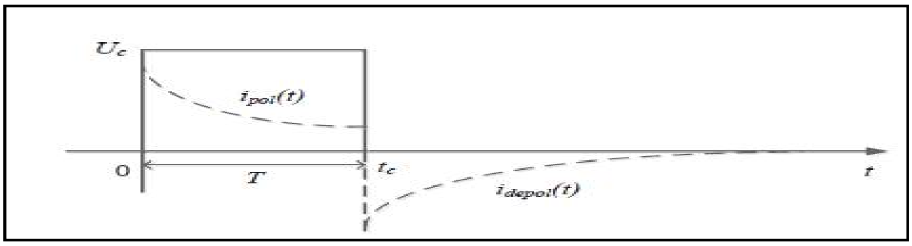

Figure 3: Polarization/depolarization current measuring principal diagram

PDC measuring principal diagram decides the time domain electrical conductivity. At time t_c switch S_1 is closed and switch S_2 is open and when DC voltage U_0 applied, conduction current produces polarization current (I_p). After time t_c, switch S_1 is open and switch S_2 is closed and depolarization current (I_d) is produced. Polarization/depolarization current of oil filled insulating paper was studied through this model and polarization conductivity was measured using relationship between PDC and dielectric response. As a result it was found that I_p & I_d both currents start increasing with the increase in aging time and there is an exponential increase in polarization conductivity due to degradation byproducts produced during the process. The polarization and depolarization current converged eventually to a stable value because of the degradation byproducts which have accumulated on the cardboard. The insulating papers degrades due to decrease in degree of polarization and polymer chain rapture which gives the insulation paper more uneven and evacuated structure. Polarization probability of insulation oil immersed paper is increased which enhance the polarization intensity. The conductivity of drying cardboard is increased due to presence of degradation products and polar residues.

D. Modified Debye Model [37]

Dielectric properties of insulating material of electrical device depend on its geometry and size. It means the properties examined for particular insulating system cannot be treated same for analysis of other electrical device such as; transformer, even if loading capabilities is same for both of them. Debye model didn't think about the consequence of temperature variation with effects of length of insulation; that means the degradation in paper is independent of the distance of paper from the winding as shown in figure 4 (a), whereas modified debay model recognizes the effect of temperature which does not remain uniform with the length being influenced in the aging process considerable for better understanding and accurate modeling. Oil immersed insulating paper under the influence of distance from the winding and consideration with change in temperature which is non uniform is predicted in figure 4(b). The conventional debay model describes that influence of thermal or electrical stress on oil-paper combination in transformer with effect to winding remain uniform throughout i.e when the oil-paper combination showing a temperature gradient T(x) during normal operation of transformer where x is the distance of paper from main winding which acts as the source of the heat generation leading to the different temperature at the oil volume affected by the distance from the winding. The figure 4 (a) represents combined effect of temperature gradients subjected to the temperature [14]. But if the thermal aging analysis of the insulating system is influenced by thermal stress, expanded experiences to temperature raise T(x) resulting non homogeneous aging of kraft paper. It means aging strictness is maximum at $x=x_{min}$.

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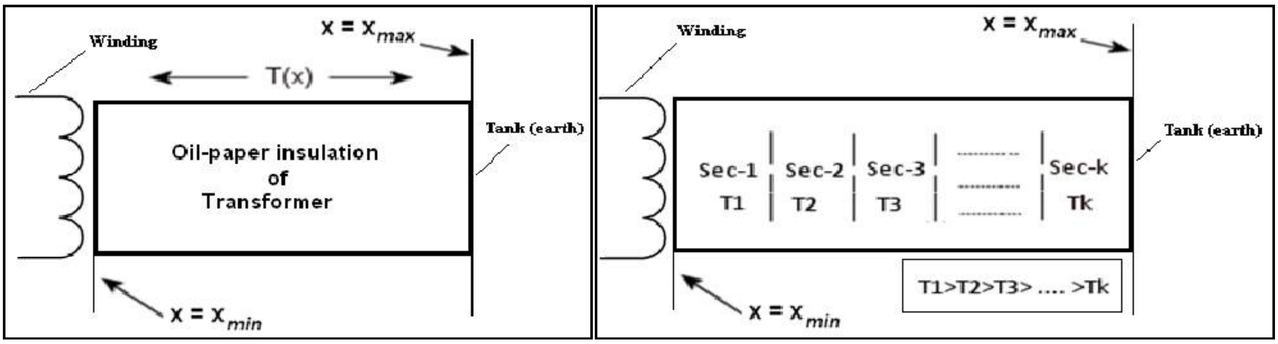
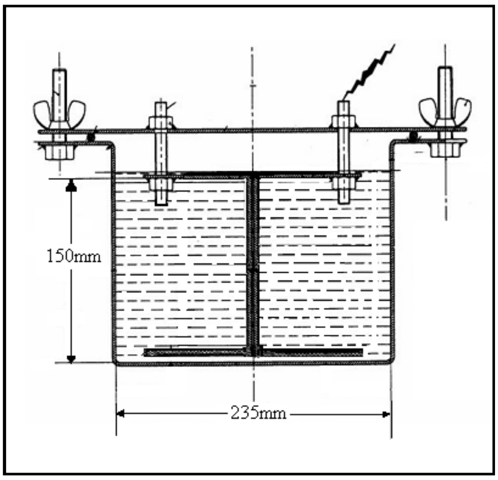
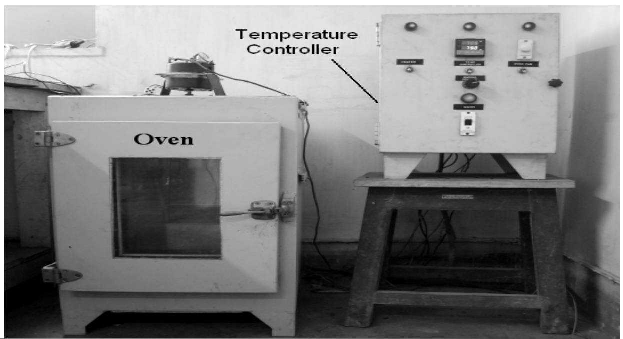


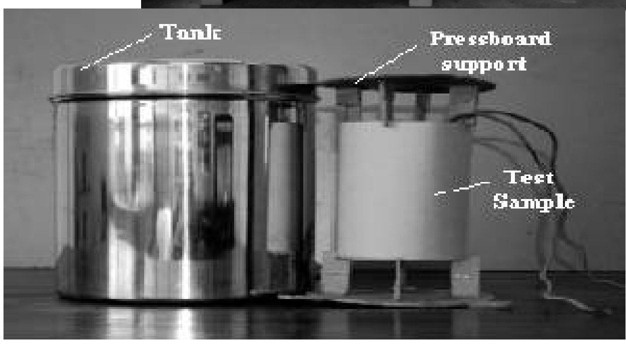
(a) Conventional Debye Model (b) Modified Debye Model

Figure 4: Oil paper insulation under the influence of temperature gradient and distance from winding

Modified Debye model segmented different isothermal zones from section 1 to section k (shown in figure 4(b)) showing whole dielectric length from x_{min} to x_{max} assume to be maintained at same temperature during ordinary process of transformer where T_1, T_2, ……..T_k is the temperature of these zones (figure 4 (b)). So to analyze the effect of temperature on insulating system, a test sample is prepared (shown in figure 5(b)). The process to design the test sample can be seen from the paper [38]. The test cell is finally placed in a steel tank and aged in an electric oven with temperature variation in steps of 10^0C from 40^0C to 50^0C. Polarization and depolarization current of each period is recorded for each of the sample. The view of the test sample prepared, steel container and electric oven used for aging purpose is shown using figure 5(a) and 5(b).







(a) Temperature controlled heating unit. (b) Test Sample along with the steel tank.

Figure 5: view of sample prepared, steel container and oven used for the thermal aging

E. Test cell model [4]

To perform accerlated thermal and electrical aging experiment on transformer oil and insulating kraft paper, special test cell model was designed by singh et. al. as shown in figure 6. The test cell with a capacity of 03 liters was made from a

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mild steel sheet of thickness of 3.5mm. Inner part of test cell was polished using high temperature resistance paint and it was sealed using silicon to prevent leakage at high temperature. Two (2) Copper strips covered with insulating papers are tested in the presence of mineral oil. The samples of the insulating papers and the mineral oil used for the experiment were selected as per the ISO: 9335 and ISO: 335. The temperature of the hot air oven was maintained within the temperature controlled within $\pm$ 2^0C. Various thermal and electrical stresses were given to the test cell (see table 2) to study the behaviour of dielectric and physical properties of the combination of the oil and paper. The parameters like; dielectric strength, mechanical strength, furan content, specific resistance, density, viscosity, colour degradation, partial discharge, water content, capacitance & tan delta, degree of polymerization (DP), dissolved gas analysis, dissipation factor were studied which are the most sensitive to the electrical stresses. The scanning electron microscope (SEM) and TEM techniques were also used to study the morphology of the aged samples [38].

Figure 6: Pictorial view of test cell

Table 2: Thermal, electrical and aging accerlated experiments

Temperature (^{0}C)	Voltage Stress (KV)	Aging time (hours)
120	1.0, 2.0 & 2.5	360,720 & 1440
140	1.0, 2.0 & 2.5	360,720 & 1440
160	1.0, 2.0 & 2.5	360,720 & 1440

F. Ampoules/Vial model/ Borosilicate Glass:

Higher temperature resistance borosilicate glass test model with different names such as; Ampoules model/Vial model/ Borosilicate Glass model, regent bottles model as shown in figure 7.

Ampoules model [29] used the glass ampoules as the apparatus for aging experiments which contain copper conductor of length 210 millimeter was cut and wrapped using kraft paper (figure 7(a)). The ampoules were of 45 millimeter in diameter consisting 230 mL of oil with 8 conductors in one ampoule giving approximately 86 mg/mL of paper to oil ratio. The ampoules are heated with the temperature variation of ± 2^0C per heating cycle using controlled aluminum heater block and placed in vacuum oven with temperature 80°c for complete one day before start of aging. For moisture removal, the conductor is transferred in the ampoules maintaining pressure 10^{-3} Torr for 02 days and at 145°C for 1 hour. New Shell Diala B type mineral oil is further filled in ampoules to make the copper conductor and insulating paper totally engrossed in oil and cooled at room temperature. Karl Fischer titration technique was implemented to determine the absorbed water content. Various accerlated aging experiments are performed for different temperature and different period of time under air and nitrogen environment.

Rao et al [39]. used the borosilicate glass ampoules (figure 7 (c)) to conduct thermal aging experiment using four (04) copper and cellulose winding strips where four (04) unvarnished copper bar (90 mm x 13 mm) being wrapped with 11 turns of 0.3 mm thickness of kraft paper was selected which are allowed to dry for ten hours at 80˚C for removal of water content. To conduct the experiment natural ester (NE), synthetic ester (SE), mineral oil (MO) and mixture oil (MSO) (developed by 80% of MO and 20 % of SE) were selected [40]. 800 mL sample of each type of oil was transferred to separate borosilicate glass ampoules and pre-heated for 12 hours at 110˚C to remove moisture content. Glass ampoules were further placed in air circulating oven for aging with a temperature range from 110^0C – 200^0C for 96 hours at each temperature. The physical and dielectric properties such as physical appearance (colour), interfacial tension (IFT), rate of degradation, water content of aged samples were compared in different MO,SE,NE and MSO and found better in synthetic ester.

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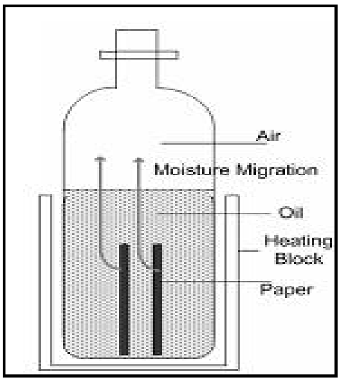
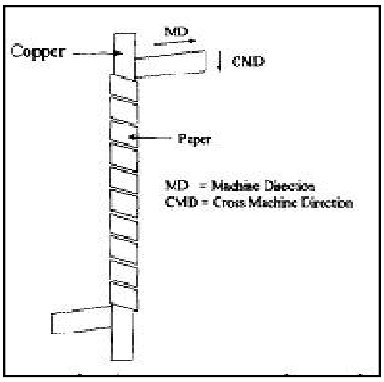


(a) Ampoules model



(b) Paper wrapped copper conductor

(c) Glass ampoules used for thermal aging

(d) Bottles

(e) structure of test vials

Figure 7: View of the glass wear ampoules used for the thermal aging of solid and liquid insulation in oven

Suwarno et al. [41] used the glass bottles for the thermal aging of insulation system as shown in figure 7 (d). The samples used in the experiment were mineral oil and thermally upgraded kraft insulating paper. 800 mL of mineral oil with 6 gram of insulating kraft paper were inserted in hermetical bottles to form a oil filled paper. Kraft paper to -oil ratio reflects the typical ratio of oil and kraft paper inside a real transformer. The hermetical bottles containing samples of oil filled paper were given thermal stress at 120^0 C and 150^0 C in a controllable oven for a period up to 4 weeks. The selected temperature is in accordance with Mc Shane [42], while 120°C is maximum hotspot temperature as per the IEEE [43]. Prior to aging, the sample is preheated with 100^0 c temperature for complete one day.

B.Garcia et al. [44], used test vial model to investigate the effect of water content on accerlated thermal aging process. The structure of the test vial of volume 125 mL used for the experiment is shown in figure 7 (e). The Kraft paper which was examined during the aging process was taken from a wrapped copper conductor. To start the experimental procedure, copper conductor firstly unwrapped and kraft paper of thickness 50 µm with temperature index of 105^0C was collected and placed in the test glass vials for accelerated aging. Each test glass vials which was placed in hot air oven for aging process was containing 100 mL of new dry NE or MO, a paper wrapped copper conductor of 65 cm length, 2 mm diameter and 8.6 g of mass. In addition to this 12 strips of Kraft paper of length 12.6 cm, width 1.3 cm and mass of 0.26 g of each, were also added to each test glass vial. Each test glass vial was sealed using polytetrafluoroethylene-silicone septum, and placed at room temperature until aging commenced. In order to simulate contact between oil and air, as occurs in free-breathing transformers, a small head of air (10 mL) was left at the top of each vial (Figure 7(e)). A total of 432 vials were prepared, of which 234 contained NE and 198 contained MO. Thermal aging process was completed at temperatures with interval of 10°C from 110°C -130°C, for three (03) months. The Degree of polymerization, moisture content of the paper, dissolved gases absorption, furfural content in the oil within test vials were measured during the aging process.

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III.CONCLUSION

The most wide used test to diagnose the condition of transformers are still accerlated thermal aging tests and dielectric properties tests. The use of alternative tests is increasing however restricted by numerous issue such as; cost, data interpretation, reliability, compatibility. The ultimate goal of transformer monitoring and diagnostic techniques is to possess a set of devices/system/models to observe and anticipate the transformer failure, so that acceptable actions can be taken before forced outage happens. Different kinds of test model like; prototype model, dual temperature aging model, ampoule model, aging vial model, thermal aging chamber, electro-thermal conductivity model, time domain dielectric response test model, debay model, modified debay model, test cell model are employed in assessment of condition of transformer insulating aging. Basic idea of these models is to check the accelerated thermal, electrical stresses with aging on oil and paper insulation of power transformer. This paper provides an outline of aging models employed in conditioning monitoring of lifetime of power transformers. This paper will be useful for academicians, research scholars and engineering communities worldwide who are working in this area.

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