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Comprehensive Testing Methods for Evaluating Transformer Paper Insulation: A Critical Component for Power Transformer Performance

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ABSTRACT

A power transformer is a crucial component in power system networks. Ensuring the optimal operation of power transformers is essential for efficiently supplying energy to utilities. A key part of a power transformer is its insulation system, which includes transformer insulation oil and transformer insulation paper. Indeed, paper insulation is a critical component in transformers due to its role in electrical insulation and thermal performance. Since it's challenging to test the paper insulation while the transformer is in operation, comprehensive testing before its application is essential. In the paper, comprehensive test methods for evaluating the various parameters of transformer paper insulation are discussed, providing crucial insights for the power industry.

Keywords: power transformer, cobb test, density, thermal conductivity.

INTRODUCTION

Electrical insulation plays a vital role in the proper operation of electrical equipment. Power equipment inherently operates with energy losses, leading to temperature increases. Therefore, it is crucial to dissipate the heat generated by these losses, especially under high load conditions. Failure to manage this heat can result in premature aging and eventual failure of the equipment [1]. Paper, pressboard, and transformer board are all made of plant-based cellulose and are often used as solid insulation in transformers. For several years, insulation made from cellulose mixed with mineral-based oil was the principal insulation technique for transformers. Because of its high dielectric strength and low dielectric loss, cellulose insulating paper, cloths, and tapes are widely used. As a result, impregnated paper is now acknowledged by many as the fundamental insulating material in the electrical sector. Insulation materials like pressboard and paper, made from pure cellulose, have an exceptional ability to be impregnated with insulating liquid, significantly enhancing their insulating characteristics. These solid insulators are very simple to make and cover around coils, and they may be produced in different sizes to satisfy other needs [2].

Dry paper's hygroscopicity—its propensity to absorb moisture—is the main drawback to utilizing it as insulation. Drying the paper and treating it (impregnating it) with a liquid—such as varnish, oil, or resins—is necessary to lessen this issue. These treatments serve to

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limit moisture intrusion while preserving the paper's dielectric property by finishing the gaps between the fibers and improving its insulating qualities. Today, artificial insulation materials are utilized to insulate sections where the temperature during operation is expected to be high, as well as complete transformers engineered to run at elevated temperatures. These materials include synthetic polymers like Aramid paper [3]. Despite the impregnation, paper may retain moisture from outside air or liquid. In liquid-filled transformers, dry paper progressively collects moisture from the insulating liquid. Moisture will reach an equilibrium state between the paper and oil, with the paper retaining significantly more moisture than the oil. Moisture in insulation increases dielectric loss and lowers the optimum dielectric strength of the pressboard or paper. Paper has the capacity to absorb a significant volume of water—up to several hundred liters in big power transformers. Koestinger et al. [4] provided an example: "For a 300 MVA transformer, with 10,000 kg of insulation at a 3% moisture level, this represents 300 liters of water. The amount in the oil is typically negligible (for a 300 MVA transformer with 60,000 kg of oil and 10 ppm H2O at 30□, it represents 0.6 liters of water)." To find the most effective techniques, years of extensive research have been conducted on the challenging problem of reducing the moisture content in an oil-paper insulating system. The insulation of a power transformer undergoes monitoring according to standards set by IEC and ASTM. These standards comprise various tests such as breakdown voltage, moisture absorption, pH value, Cobb value, density, ash value, and thermal conductivity.

INSULATION PAPER STUDIES

This section focused on the behavior of insulation paper and the rate at which it degrades when ester oil is present. It also looked at how insulation paper affects the transformer's thermal performance and how long ester-filled transformers endure [5]. The tensile strength of paper was investigated by C.P. McShane et al. [6] in 2001 at different temperatures when ester oil was present. They clarified that by quickly absorbing moisture from the insulating paper, ester oils improve the thermal stability of paper. C.P. McShane et al. [7] [8] investigated the physical characteristics of aged kraft paper in mineral oil and ester-based liquid in 2002 and 2003. They observed that, in contrast to mineral oils, the pace at which paper ages is slower when esters are present. M. Hemmer et al. [9] investigated the behavior of several kinds of insulating papers by immersing them in plant-bases liquids in 2003. They promoted the use of liquids made from plants as a more ecologically friendly technique. K.J. Rapp et al. [10] and T.A. Prevost [11] clarified in June 2005 and May 2006, respectively, that the esters' greater capacity for water is the reason for the paper's slower rate of deterioration. This phenomenon causes water to migrate to the esters, thus keeping the paper dry, reducing aging, and prolonging the paper's lifespan. D. Martin et al. [12] demonstrated in 2007 that the AC impulse withstands voltage of insulation paper immersed with esters is higher than that of insulating paper treated with mineral oil. J. Dai et al. [13] [14] investigated surface tension and viscosity and discovered that pressboard impregnation with esters at elevated temperatures results in an identical level of impregnation as mineral liquid impregnation. In

November 2010, Maria Augusta et al. [15], and in June 2011, L. Yang et al. [16], applied thermal stresses on papers impregnated with mineral liquid and ester-based liquid at different temperatures. They discovered that the degradation rate of insulation paper is slower for transformers filled with ester oil. In 2011, H.M. Wilhelm et al. [17] addressed dissipation factor, acidity, and viscosity as crucial indicators for determining the aging of natural esters. They noted that variations in acidity and viscosity occur due to hydrolysis and oxidation of the ester, respectively. In October 2011, Liao Ruijin et al. [18] explored the aging behavior of ester liquids in the existence of insulating papers. They advocated for ester liquids over mineral liquids for power transformers. M. Augusta et al. [19] demonstrated in 2012 that the viscosity and cooling capacity of ester liquids are greater than that of mineral liquid. They also noted that natural esters outperformed synthetic esters. Dongjin Kweon et al. [20] investigated the thermal performance of insulation paper in transformers filled with mineral and ester-based liquids using hot spot and optical measurements. They concluded that designing ester-filled transformers did not necessitate decreased loading or improved cooling procedures. In July 2012, J. Hao et al. [21] studied the frequency dielectric response of pressboard impregnated with ester-based liquids and recommended the usage of ester-based liquids for better transformer insulation durability. In 2012, J. Van Hest et al. [22] tested ester-impregnated paper under operational circumstances to see how air affected both windings and insulating paper. They also discussed the development of gel in natural ester-filled transformers. Concurrently, Junru Xiang et al. [23] noted that natural esters extract more water from paper because of their increased water consumption via hydrolysis, resulting in less paper deterioration. M.L. Coulibaly et al. [24] in 2013, investigated whether acids produced in esters were more tolerant against cellulose because ester fluids have a higher degree of polymerization compared to mineral oil. Meanwhile, X. Yi et al. [25] investigated creepage discharges in paper treated with ester liquid and concluded that ester liquids are superior to transformers. A. Abubakar et al. [26] in 2014, investigated the absorption properties of treated Kraft paper in mineral liquids and ester-based liquids. They clarified that although the thickness of the paper and the chemical makeup of the oil utilized determine moisture absorption, the rate of absorption is inversely correlated with paper thickness.

PAPER INSULATION TESTING EQUIPMENTS

Thickness Gauge Meter

Bending stiffness of paper can be decided by evaluating thickness. The dominating method for assurance of paper thickness is to gauge the distance between two parallel plates under a given load. In current research work, a microprocessor based motorized thickness micrometer is used to measure the thickness of fresh, modified, and aged paper samples by thickness profile assessment [27].

To measure the thickness, a sheet of paper which is to be tested, is bolstered at consistent motion using a nip amid two probes of spherical shape. The tests in this way pursue the paper thickness profile & separation among probes is constantly noted. Thickness average can be

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determined from the profile & and known as auxiliary thickness (µm). The procedure mentioned in ISO R-534 is followed for measurement of thickness. The technique can be utilized both on single & heap of few sheets.

Weighing Machine

Grammage is defined as weight of the substance/test piece to the per unit area. It is measured in g/m^2. Paper weight is also an important factor while selecting the paper as solid insulation because it directly affects the transformer weight. So, it must be low as it can be. It is designed for measuring the weight of the substance/test piece.

For precise GSM measurement, a specimen sample of paper, board, or other sheet material is stored in the top/ring. This sample is used to measure the grammage of fresh, aged, and updated paper samples. The screen that is given displays the digital readout of the GSM.

Bursting Strength Measurement

Blasting quality or impacting quality is estimated as the most extreme hydrostatic weight required to cracking the test by continually expanding the weight connected through an elastic stomach of roundabout shape. It tells how much weight a paper can endure before crack. The kind, quantity, and size of filaments in the sheet, their preparation method, their degree of pulverization and refinement, the formation of the sheet, and the addition of materials are the main factors that determine blasting quality.

The diaphragm was clamped with its outside edge under the lower clamping plate and was renewed less than six weeks prior to test. The test piece was first clipped immovably over the stomach without slippage amid the test between two annular, unpolished (matt), plane surface with 30 mm inner diameter. Run the machine with the goal that the weight may increments at a uniform rate of roughly 0.75 kg/cm2 every second until the point that paper piece blasts. The weight (kg/cm2) at which test piece burst was noted from pressure gauge. The procedure mentioned in IS: 2758 is followed for calculation of bursting factor [28].

Tensile Strength Measurement

The stress and strain curve depicted in Figure 1 can be used to describe tensile strength (TS). The direction in which the paper moves during manufacturing is known as machine direction (MD), and the direction perpendicular to the machine direction is known as cross machine direction (CD). Compared to CD, paper in MD is less flexible but stronger. MD is typically used to measure paper that comes from dismantled transformers. There are two methods for measuring TS: long and zero span measurement.

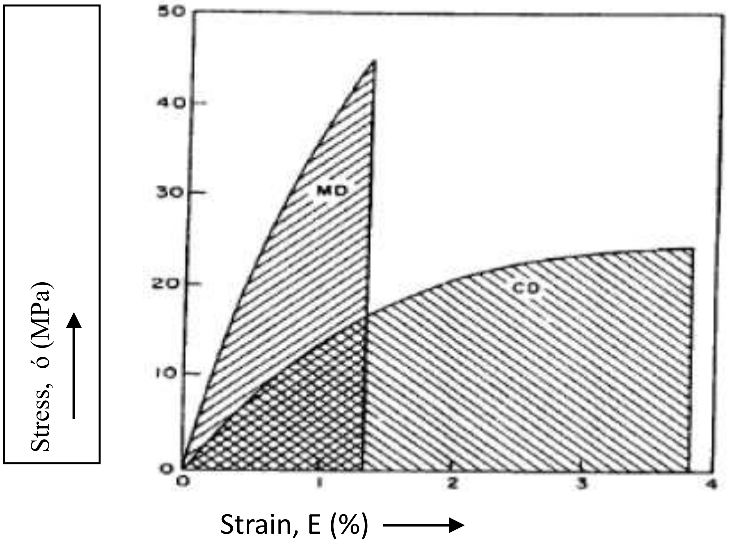

Figure 1 The two directions of stress and strain behavior are MD (machine direction) and CD (cross machine direction).

The pliable properties of paper tests are estimated by bracing a paper strip between two grasps and applying a ductile load until the point that the strip breaks according to the method referenced in ISO-1924 [29]. Tightly hold one end of every strip in upper clasp in the wake of setting the strip freely in the lower cinch and checking its arrangement. At that point apply an starting stress of 0.23 kg to each strip before clamping. With the mechanical assembly in which sample is cinched vertically, this is helpfully done by incidentally flipping an appropriate load to the lower jutting end of the strip before fixing the lower brace. Closely firmly cinch the two finishes of the strip and apply the heap. The heap applied on the stationary jaw was detected by a sensor associated with load cell, which specifically shows the heap in digitalize form in kg.

Tear Resistance Measurement

Tearing resistance is a proportion of the power expected to tear the paper. Mostly, it is less machine direction (MD) than in cross direction (CD). Ballistic kind of tear-analyzer, like; Elmendorf type tear resistance tester (as shown in Figure 2) is used to measure the tear resistance of fresh, modified, and aged paper samples.

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(a) Overview (b) Actual view

Figure 2 Elmendorf type tear resistance tester

Clamp the test piece's outer and center tongues firmly in place using a fixed clamp. To continue the tear, release the pendulum and observe the required load. One test piece at a time or in packs of two or more may be used for the test, if the reading is between 25% and 70% of the instrument's capacity. For both the machine and the cross direction, the tearing resistance is measured independently.

The machine is furnished with two braces, the one settled and the other carried on an area molded pendulum, suspended from a segment by methods for a frictionless bearing situated close to the zenith of the part. On discharging the pendulum, the middle tongue is exposed to the heap of pendulum recorded through a spring stacked contact pointer on the circumferential scale set apart on the pendulum [30].

Cobb Tester

The opposition from water entrance is examined by amount of water consumed by a paper or a board when one of its countenances is set in contact with this fluid. The mass of water absorbed by a one square meter sample of paper, board, or corrugated under conditions in each amount of time is known as the Cobb value. The test period is indicated along with the findings, which are reported in g/m^2.

The sample first gauged accurately to 1 mg and put it on the elastic support sheet with the surface to be examined highest. Thereafter the barrel was put on samples & cinched adequately firmly to keep any spillage of water among it and test piece. At that point water was filled the barrel to a profundity of 1 cm and stopwatch began quickly. Total 60 seconds were selected for the test as per mentioned in ISO 535 [31].

Oil Absorbency Measurement

Oil absorbency analyzer is utilized to evaluate the rate of oil absorption through a sheet of paper. This test involves applying oil to a predetermined spot on one side of a paper pack. After a definite time, interval, the oil poured off, the top sheet is blotted and the increase in weight through absorption of the oil is determined by direct weighing.

This test strategy comprises of estimating the time for which castor oil drop creates a uniform translucent spot on the underside of the test specimen by permeation through the specimen. The test is conducted using viewing box as per described in TAPPI standard T-402 [32]. According to IEC Publication 296 and mineral oil standards, the oil is used and first kept in a sealed container at the reconditioning temperature. Each test uses a total of 100 cm^3 of oil, however following the first test, there was enough oil to top it off to the necessary level. The Indian standard ISO-535 [31] has information on the methodology used to assess oil absorption.

Breakdown Voltage Tester

Dielectric breakdown strength is the maximum potential distinction at which failure happens under recommended conditions in insulation material placed between two anodes. It is usually expressed in kilovolts per unit of thickness. This test strategy is most regularly used to decide the dielectric breakdown voltage through the thickness of a test piece (punctured). It might likewise be utilized to decide dielectric strength along the interface between paper specimens. An electrical breakdown of paper can be measured with a rising AC voltage under prescribed condition as mentioned in accordance with IEC Publication no. 243.

The voltage was applied uniformly to the test electrodes from zero until breakdown occurs. Breakdown esteems got in protecting fluid, for example, mineral oil may not be practically identical with those acquired in air. The idea of the protecting fluid and the level of past use may influence test esteem. So the breakdown voltage test was also completed using air as surrounding medium at ambient temperature [33].

Muffle Furnace

Muffle furnace is used for determining the ash content of fresh, modified, and aged paper samples. The paper sample is taken about 5 g of the sheet in small portions and placed in already weighed crucible. Then paper samples are heated up suspiciously using Bunsen burner to make sure that paper burns quietly till completely charred. Shift the crucible in electric muffle furnace at 800+25°C & heated again till all carbonaceous substance burnt off. Cool down the crucible in a desiccator, weigh up & repeat the procedure till constant weight is not received. The difference in the weight of paper sample before and after the burnt off is calculated and predicted in percentage (%). The procedure followed for measurement of ash content of paper samples is described in ISO Standard IS:2144 [34].

Measurement of Paper Density

Paper density is one of the important parameters of cellulose paper for judging its electrical performance. Paper density is its mass per unit volume. As per Indian Standard IS: 9335 (2nd Part) [35], indicates it is expressed in grams per cubic centimetre g/cm^3.

Every sample of fresh and aged paper is examined to assess its thickness and grammage. The apparent density of each test piece is determined by dividing the paper's weight by its caliper, and the average of these densities is determined as the outcome. Grams per cubic centimeter is the unit of measurement for apparent density.

Measurement of Paper Moisture Content

Moisture is defined as presence of water content in the insulation. The adapted specimens are gauged and warmed to a consistent load to remove dampness. The distinction between two gauging gives the dampness content. Generally, it is measured in %. In transformer, there are several sources of moisture; good drying process should result in less than 0.5% moisture in paper, leakage of gasket/joints, insufficient maintenance. The thermal degradation of paper with increase in temperature also generates water content. This water content further degrades more. Dampness is unequivocally consumed by paper inside the transformer and it is hard to evacuate. So, water content in transformer insulation is a persistent concern. The amount of moisture in paper is a very important parameter to know, as it directly affects the (a) aging rate of the winding insulation (b) bubbling temperature (limits the amount of overloading of a transformer) (c) breakdown voltage of barriers near bottom of winding. Weighing container, thermo-meter, drying oven, chemical balance, desiccators are the various major accessories used for measurement of moisture content.

Fresh & aged samples of paper are examined in terms of water content present in them as per the procedure mentioned in the Indian Standard IS: 1060 (Part 1) [36]. Firstly, small specimens are placed in the drying oven without removing them from the weighing bottle. Then stopper of the bottle is removed, heated for about 1 hour at 103 + 20C, closed again the bottle in the oven, cooled to normal temperature and loose the stopper for a moment to adjust any change in air pressure and weigh. The procedure is repeated until the distinction in weight between two progressive weighing is not greater than 0.1 % of specimen weight.

The final moisture content is calculated as % of actual weight of material as pursues:

Moisture content (%) $= W1 - W2$

$W1$ = actual weight (g) of specimen prior to dry

$W2$ = weight (g) of dehydrated specimen

Thermal Conductivity:

A material's thermal conductivity is a measurement of how easily heat flows through it. Watts per meter kelvin is the unit used to test thermal conductivity. Low thermal conductivity materials can function as a barrier to stop heat from entering through radiation, convection, or conduction.

Thermal conductivity (K) = $\mathbf{Q\ .\ t\ \ (T\,2\ - T\,1\ )\ .A}$

Where, Q - Total heat generated (W), t - Thickness of panel (m), A - Surface area of the panel (m^2), T2-T1 - Difference in temperature in □ [36].

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CONCLUSION

This paper discusses comprehensive testing methods for critical parameters of paper insulation in transformers, essential for ensuring long-term functionality and reliability. Given that sampling paper insulation from an operational transformer is impractical, validating these parameters before use is crucial. The focus on breakdown voltage, tensile strength, Kubb test, paper density, thermal conductivity, and moisture content is particularly valuable for both academic research and the power transformer industry. By thoroughly testing these parameters, the quality and reliability of paper insulation in transformers can be ensured, thus supporting the longevity and efficiency of transformer operations. This paper provides valuable insights and methodologies that will serve as a reference for both academic research and practical applications in the power transformer industry.

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