LABORATORY TECHNIQUES TO ASSESS THE AGING OF ELECTRICAL INSULATING PAPERS

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INTRODUCTION

The solid and oil insulation systems used in power transformers are designed to withstand the continuous and transient dielectric stresses to which transformers are subjected during service. Continuous stresses are those caused by the power-frequency voltage, and transient stresses are due to such things as lightning impulses, short circuits, switching surges, and power-frequency transient overvoltages.

Kraft paper is the basic constituent of the solid insulation. It acts as a dielectric barrier and dissipates. In addition, it must withstand electrical stresses generated in the windings[1]. Kraft paper has a higher dielectric strength than oil[2]. The insulating oil used in conjunction with paper is the liquid dielectric medium, which transfers the heat from the windings to the coolers[2]. In accordance with Standring and Hughes[3], the breakdown in the paper-oil insulation system usually begins with discharges in the oil. Then, the complete breakdown may either be caused by a flashover path passing over the surface of the solid insulation or by a puncture path through the solid.

Compared to metallic materials, solid and liquid insulating materials are subject to a faster deterioration under service operating conditions. It may take many years for the entire aging process to take place. After 40 years of service life, for example, the copper used in a transformer is still in good enough condition to be employed in a new unit. The same thing, however, cannot be said about the insulating materials after as many years in service. Though insulating oil may be reclaimed and gain some additional services life, the dielectric and mechanical properties of Kraft paper cannot be restored.

The dielectric strength of paper decreases with aging, however the measured reduction is not meaningful as shown by the test results obtained from a set of laboratory experiments conducted by Shroff and Stannett[3]. They consider it much more likely that failure occurs because the paper looses its ability to absorb mechanical shocks or because of gas trapped within the solid insulation.

Under service operating conditions, the transformer is permanently subjected to mechanical forces generated by the magnetic field and the winding current.

Since these forces are proportional to the square of the current, extremely high values are reached under short-circuit conditions[5]. The effect of short-circuit forces are cumulative. This means that final failures may not necessarily be caused by a severe fault, but by a culminating effect of one or more factors[6].

When subjected to the short-circuit forces, the aged paper may not withstand them and can eventually rupture. The dielectric strength of the ruptured paper is greatly reduced.

Under this condition, the failure may occur due to a transient overvoltage or even due to the operating voltage[7]. The electrical failure starts from mechanical stresses on the solid insulation.

BASIC PAPER CHARACTERISTICS

The basic constituent of Kraft paper is cellulose, the fiber that forms the framework of the cell walls of plants. Cellulose is a natural polymer composed of glucose units linked to each other by an oxygen atom. This bond is called a beta glycosidic bond because of the type of glucose involved, that is, the beta glucose[8] (Figure 1).

There is a second type of bond in the long linear chain formed by the cellulose molecule. It is the hydrogen bonding between an oxygen atom and the hydrogen of an adjacent hydroxyl group. As oxygen holds more closely the outer electrons than does the hydrogen in the hydroxyl group, there is only a slight polarity[9] and a resultant electrostatic attraction between them. The hydrogen bond between atoms of a same molecule is called intramolecular, and that between adjacent molecules is called intermolecular[10]. Because of the intramolecular bonds, the cellulose chain acquires a certain strength. The intermolecular bonds are responsible for the formation of the plant fiber[11] (Figure 1).

The electrical-grade Kraft paper is not exclusively composed of cellulose. It also contains 5-6% hemicelluloses, 1% lignin[12], as well as minor constituents like pectin, extension, and undetermined constituents[10]. Hemicelluloses are a complex mixture of sugars such as manose, glucose, arabinose, xylose and galactose. Lignin is an aromatic alcohol polymer that provides rigid fiber bonding and structural integrity to plant life[9.12].

The process used in the manufacture of electrical-grade insulating paper is the Kraft process, which is intended to eliminate the lignin. The chemicals used in the Kraft process provide a paper that is very strong and durable[8].

In the late 1950's, thermally upgraded paper was introduced in the U.S. market. This permitted an increase in the average winding-rise temperature of transformers from 55°C to 65°C. Two basic methods were developed to upgrade paper, but the first one (cyanoethylation) is not in use any longer. The second method, which is still in use, consists of adding stabilizers (dicyandiamide, urea, melamine, polyacrylamide and associated substitution products) to the woodpulp during the paper manufacturing process[12].

Kraft paper life can be reduced by three major degradation factors: heat, moisture and oxygen. The aging effect caused by heat is called thermal degradation or pyrolysis of the cellulose molecule. Because of the cleavage of the cellulose molecule, compounds like water, carbon monoxide, carbon dioxide, organic acids and glucose are formed. These reactions occur up to a temperature of 200°C. Above this temperature, other reactions can take place[13].

The cellulose degradation caused by water is called hydrolysis. It is catalyzed by an acid and breaks the glycosidic bond between two glucose residues. Though some intermediate reactions occur, the final result is the splitting of a water molecule to stabilize the glucose residue and recover the acid catalyst, which started the reaction.

Clark[14] conducted a set of laboratory studies, which demonstrated the effect of water on cellulose aging (Figure 2). Paper was aged in contact with oil in sealed nitrogenblanketed tubes. Based on tensile strength test results obtained in these experiments, Clark stated that the mechanical life of paper was reduced by half when the water content was increased 100%. Fabre and Pichon[15] made a similar conclusion based on DP test results obtained from their laboratory experiments. They stated that the life of paper is reduced to half of its original value if the water contents doubles.

Even when water is at low concentrations, it will degrade paper when acids from oil oxidation are present. In a laboratory experiment conducted by Siqueira et al.[16], Kraft paper samples were dried in an oven at 80°C for 16 hours and under vacuum at 105°C for 24 hours. Then they were impregnated under vacuum with insulating oil, and were aged at 155°C for 600 hours in sealed glass tubes failed with a dry nitrogen atmosphere. One of the sets of samples was aged in contact with new uninhibited oil, and the other one was acidic uninhibited oil. Their neutralization numbers were 0.03 mg KOH/g and 0.35 mg KOH/g respectively. Both the oils were previously degassed and dried. The water contents were 17 ppm for the new ou and 13 ppm for the acidic oil. It took six times longer for the paper aged in the new oil to reach a DP of 200 than it did the paper aged in the acidic oil (Figure 3).

The cellulose molecule is also degraded by oxygen. In such a case, water is also produced by the decomposition of glucose rings. So the hydrolysis and oxidation reactions are not independent from each other[12]. The change in the cellulose structure weakens the glycosidic bonds and contributes to chain scission.

Fabre and Pichon[15] state that the paper aged in open test cells in contact with air degrades 2.5 times faster than that aged in nitrogen- or vacuum-sealed cells. As compared with an oxygen-free transformer (<300 ppm of oxygen), the aging rate of paper is five times faster in a sealed unit, and from 40 to 50 times greater for an open transformer[17]. Theoretically speaking, this means that the paper in an open transformer will age 10 times faster than that in a sealed unit operating at the same temperature[18] (Figure 4).

TESTS FOR ASSESSING PAPER AGING

The dielectric strength of paper does not change significantly during its aging. The tensile strength test was chosen in the past to measure the mechanical strength of paper and consequently to assess paper aging. The end-of-life of paper was defined as 50% retention of the initial tensile strength value. Such a definition has a great inconvenience, because 50% retention of the strength of a strong paper may be much higher than that of a very weak paper[19].

From a practical point of view, one of the most important limitations of this test is the size of the paper samples required. Though such samples can be easily obtained during the manufacture of transformers or after failures, it is very unlikely to obtain them from functioning transformers. Also, the initial tensile strength value of the paper is not always available. This obviously prevents the determination of the 50% retention value[8].

Because of these aspects, the physical-chemical test for measuring the viscometric degree of polymerization (DP) of cellulose has been gaining widespread use. To run the DP test, it is not required to have samples with specific dimensions, and the test results are supplied in absolute values rather than in relative ones[8].

The DP test provides information on the integrity of the cellulose chains[20] there is a variation in the molecule lengths, only the average value is obtained. So the DP is the average number of glucose units in the cellulose molecules of a paper sample.

To determine the DP of a paper sample, it is cut into tiny pieces with an area of Imm^2. If the sample is impregnated with oil, it is degreased in a Soxhlet extractor with hexane, chloroform or benzene. The system is heated and the solvent extracts the oil from the paper. The pieces of paper are placed in an appropriate cupriethylene-diamine solution and stirred in a period of time varying from 2 to 18 hours until the samples are totally dissolved. During stirring, the solvent separates the fibers to enable the measurement of the DP of single molecules. After dissolving the sample, that paper and solvent solution is placed in a capillary viscometer. The solution level is raised above the upper mark of the viscometer, and the time taken for the solution to start effluxing from the upper to the lower marks of the viscometer is measured[21]. When the DP is high, the solution is more viscous and takes more time to efflux. The procedure is repeated to measure the flow time of the solvent itself, which is always shorter than the previous measurement. The difference in the two efflux times is used to calculate the DP. The test is easy to perform, has a high reproducibility (2.5% maximum) and requires inexpensive equipment[8].

Since there is no requirement referring to the sample size and dimensions for the DP test, small paper samples can be obtained from several parts of the windings and the leads to the bushings. Approximately 4 g of oil-impregnated paper is required for a DP test to be run in duplicate. Despite these practical advantages of the DP test, there are some shortcomings associated with it. Probably the most important one is the need to take the unit out of service to sample paper from the leads to the bushings, for example. If it is deemed necessary to assess the paper aging of the windings, the unit has to be transported to a repair facility to be untanked and sampled. Unfortunately this limits the number of transformers that can be sampled[8].

The DP test has a good correlation with the mechanical strength properties of paper as measured by the appropriate tests. Lawson and et al.[22] conducted a very informative study on this matter. They made a relative comparison between the mechanical parameters and the DP. They noticed that the double-fold test showed the highest sensitivity for a moderate aging when the DP is higher than 50% of the initial value. However, for severe aging (DP less than 50% of the initial value), the tensile strength test is more sensitive.

The DP test results may very a great deal if the paper samples are collected from different parts of the transformer. This occurs because the influence of the paper degradation agents is not the same all over the solid insulation. Bozzini[23] reported that the paper from the top of the coil of core type transformers is more degraded than that from the bottom. When the unit is contaminated with much water, he emphasizes that the paper from the bottom is more aged. In the two cases, however, the most aged paper was at a central turn. Bassetto and Mak[24] confirmed that the most aged paper was from a middle turn at the bottom of the coil of a transformer contaminated with much water, which had been just mildly loaded during its service life. It has also been found that the outer paper wraps, which are in direct contact with the oil, were more degraded than the inner ones[24.25] even in the case of thermally upgraded paper[26]. This shielding effect was observed in units with both a high[24] and a low[26] water content. In accord with Griffin such an effect is caused by oxygen.

Paper samples collected from the leads to the bushings were less aged than those from any part of the windings of transformers which had not been highly loaded during their service life, but were contaminated with much water[27]. Allan et al.[25] showed that the paper from the leads to the bushings of better maintained units was more degraded than the samples from the windings. The DP increased from the top to the bottom of the windings. Griffin[26] reported that no consistent pattern was observed between the aging of the paper from the leads and from the windings.

As shape and dimensions of paper samples for the DP test are not important, some practical approaches have been developed to obtain paper samples from functional transformers. The simpler way to collect paper from unfailed transformers is to sample the leads to the bushings. In such cases, it is important to know in advance the paper condition of the windings of another unit of the same type and age for a better assessment of the unit sampled. The sampling location must be repaired and should be duly identified to prevent a future sampling on the same location without any previous notice. If not, a mistake in the assessment of the unit aging may occur.

The methods for the DP test[21.28] establish that the paper samples should weigh from 0.05 to 2.25 g. If the paper is impregnated with oil, these values rise from 0.08 to 3.6 g due to the oil absorption. However, if it is deemed necessary to assess the paper aging of the windings of functional units, it is possible to sample an amount of paper which can weigh less than the minimum determined in the standards. This minimum amount of paper can be obtained by collecting tiny paper samples from the windings.

Bassetto and Mak 27developed a paper sampling technique specially suited for obtaining tiny samples (called microsamples) from functional transformers. Microsamples can be collected from the outer paper wraps of HV windings of core type transformers. On average, for 0.55 mm thick sheets of paper, a microsample has an area ranging 30-60 mm^2. Due to differences in sample size, from 15 to 30 microsamples are needed to compose one regular sample with an area of approximately 1200 mm^2. If the area of the composed sample is lower than this value,

It will not be possible to run the DP test in duplicate.

Much care should be taken when collecting microsamples. A 0.05-mm thick, roundended, stainless steel blade is carefully inserted under the outer paper wrap, and the microsample is cut off with a scalpel. To prevent the paper wrap from being completely torn in the future due to short-circuit stresses, the sampling location is painted with insulating varnish. This enables the outer wrap to adhere to the inner ones. First, the location is sprayed with an appropriate oil solvent to facilitate the removal of the oil. Then, both the solvent and oil are sucked out of the insulation by a sheet of absorbing paper. This procedure is repeated until the location is relatively free of oil.

Air-drying insulating varnish is painted on the sampling location with a brush. As paper absorbs the varnish, two or three coats of varnish are necessary to form a protective layer. Special care should be taken to prevent the trapping of air bubbles in the varnish coats. To facilitate the painting and to prevent the trapping of air bubbles, samples should not be taken too close to the spacers between the discs.

Since several pieces of paper are required to make a single sample, it is recommended to skip one or two discs of the coil for collecting the next microsample. If microsamples are taken from the same disc, there should be at least one set of spacers separating them from each other to prevent a significant reduction in the mechanical strength of the paper wrap. For safety, microsamples should not be collected so close to each other. All these parameters, however, refer to power transformers raled up to 138 kV. As the characteristics of the transformers to be sampled may vary widely, the most appropriate locations should have to be assessed at the time of sampling.

Fabre and Pichon[15] conducted extensive research on paper aging. After having correlated DP with the extension-to-break test in laboratory experiments, they determined that paper keeps no mechanical strength for DP values lower than 150. This information was confirmed by Bozzini[23] who stated that the DP in the vicinity of 100-150 possesses properties disappear. Fabre and Pichon[15] also surveyed service-aged transformers. They observed that the DP of paper samples from the more aged units were as low as 150, so they established this value as the end of paper life. Fallou[29] in agreement with Fabre's studies has kept this limit. McNult[30] and Lampe and Spicar[31] consider the DP of 200 as the end of life of paper. Based on the literature and on data obtained from field units, Bassetto and Mak[24] established that a transformer or a voltage regulator has reached the end of its reliable useful life when its insulating paper has a DP around 150. In accordance with them, if there is no other unit available for replacement, the old one can be kept in service. However, this unit should be replaced as soon as possible if the DP of its paper insulation is lower than 100.

Schroff and Stanett[4] correlated DP with the tensile strength test. They noticed that the DP was around 250 when the tensile strength has meached 50% of its initial value. So they adopted such a DP value as the end of paper life. Most of the several DP values considered as the end-of-life of paper are inferior than the 50% reduction of the initial. tensile strength. A correlation between DP and the tensile strength obtained in a recent laboratory study[31] shows that 50% of the tensile strength corresponds to a DP of around 380. As practice has shown, this is a very high value. A paper having a DP of around 200, the tensile strength corresponds to 20% of its initial value, so a DP of 200 is an economical and technically prudent end-of-life criterion. However, it would be interesting to observe the service-aged units in detail when collecting paper samples. Though there are several limit values suggested for the end-of-life of paper, it will be possible to establish a consensus value as more data are obtained. Some key points should be established for DP testing in units of similar design manufacture[9].

Finally, it is worth remarking that the DP test results associated with the history of the short-circuit stresses and the transient overvoltages to which a transformer has been submitted are decisive to determine its service life. Therefore, less mechanically and electrically stressed units can reach lower DP values until they fail due to aging. A few years age, Bassetto and Mak[24] collected a paper sample from an unfailed transformer, which presented a DP value as low as 53.

The thermal degradation of paper gives rise to the formation of several by-products. As some of these are relatively soluble in the oil, the analysis of an oil sample enables the identification and the determination of the concentration of such compounds. The most important ones are the furanoid compounds and the gases carbon monoxide (CO) and carbon dioxide (CO_2). Though the carbon oxide gases are produced from insulating oil aging, furanoid compounds are exclusive from paper degradation, and they can be formed at temperatures as low as 80°C[13].

The study of furanoid compounds was introduced in the electric power industry by the former Central Generating Board (CEGB). United Kingdom. The compounds monitored by CEGB were 2-furfuraldehyde (furfural), 2-furfuryl alcohol, 2-furoic acid, 5-hydroxymethal-2-furfuraldehyde, acetyl furan and 5-methyl-2-furfuraldehyde. Among these compounds, furfural is considered to be the most abundantly detected[32]. The technique commonly used to measure the concentration of furanoid compounds in oil samples is high-performance liquid chromatography (HPLC).

Burton et al.[33] established a correlation curve between the furfural content of the oil and the DP of paper samples from functional transformems. Oommen et al.[34] aged thermally upgmaded and nonupgraded paper in a set of laboratory experiments, and conducted that a simple calibration curve may not exist for different types of paper. Griffin et al.[35] conducted an extensive study based on field data and concluded that the furfuraldehyde content did not correlate with the transformer age.

Several furfural limit values have been established as normal operation levels. Griffin et al.[35] and Dominelli et al.[36] reported recently that the vast majority of the oil samples from the in-service transformems contained less than 100 ppb of furfural. Griffin et al.[35] also informed that the higher levels were reported by other investigators outside the U.S. and Canada. In accord with Griffin et al.[35], such a difference could be partly due to the use of thermally upgraded paper. Laboratory studies[34.35] showed that the amount of furfural produced by the aging of thermally upgraded paper is smaller than

that generated by the regular Kraft paper for a comparable change in the DP. The age, loading, water and oxygen content of the oil, CO and CO_2 concentrations, oil aging condition and the nameplate characteristics of different families of units could be compared to determine normal operating trends and potential problems.

CONCLUSIONS

Because of the simplicity of drawing an insulating oil sample to run tests for furanoid compounds and for CO and CO_2 gases, such a procedure should be implemented on a routine basis to assess any incipient fault condition involving paper. Concerning the DP test, it may be very difficult to deenergize a transformer just to retrieve a paper sample. In view of such a limitation, practical criteria should be adopted to assist in the decision making to run a DP test on paper samples from functional units[8].

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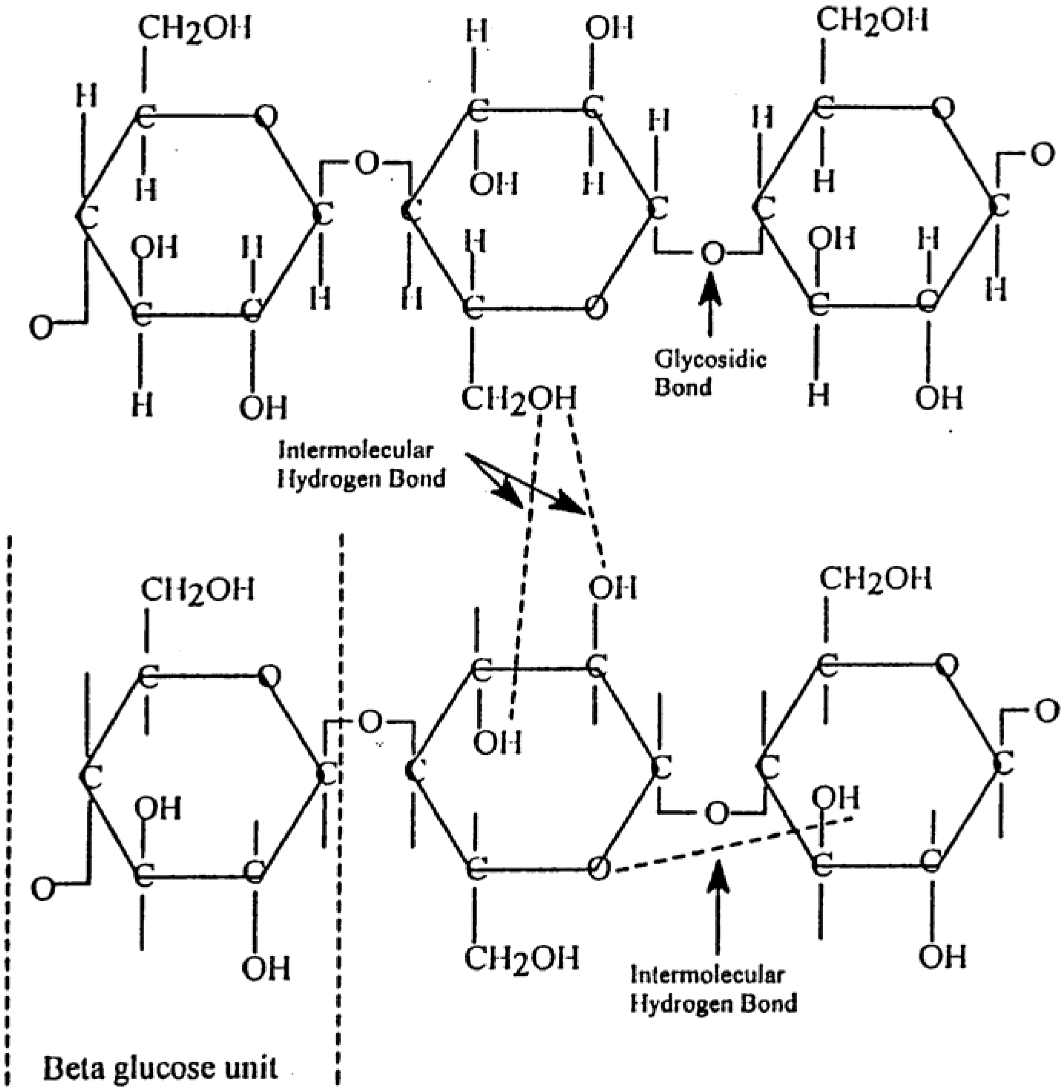

CELLULOSE MOLECULE

FIGURE 1