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High Voltage Electric Power Transformer Condition Monitoring: A Review of Degree of Polymerization Method for Measuring Paper Degradation

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Abstract

The measurement of paper degradation is very often considered the most accurate way of determining the electro-mechanical health of high voltage electric power transformers. Amongst many condition monitoring methods, the degree of polymerization (DP) holds better promise for electric power asset managers. This paper reviews transformer insulation paper degradation measurement techniques, and gives particular attention to degree of polymerization (DP). It discusses the advantages and disadvantages of DP and a future outlook of the transformer condition monitoring industry is also presented.

Keywords: Transformer, condition monitoring, degree of polymerization, paper degradation

1.0 Motivation

The world over, electric power transformers are an important part of power systems. Their utilities range from the evacuation of generated electric power from power stations to distribution of electric power for final energy consumption. Transformers are manufactured in different size specifications ranging from a few KVA to over a few hundred MVA, and usually with a 20 – 35 years design life and an extended service life of about 60 years with appropriate maintenance [1].

The design configuration of electric power transformers is such that the insulation system is critical to its overall reliability and availability. The insulation system of a power transformer consists mostly of hydrocarbon oil and paper and many of these transformers around the world are approaching the end of their design life and this is a major concern [2]. As a consequence of ageing, high operating temperature and the presence of oxygen and moisture, the insulation materials become susceptible to degradation [2-5]. According to Wang et al [1] the insulation degradation consists of hydrolytic, oxidative, and thermal degradation and that the ageing and life of a transformer has been defined as the life of the paper insulation. It becomes important therefore that the degradation of paper insulation in power transformers be monitored to inform Asset Managers in making decisions crucial to the overall reliability and availability of the transformers and hence reduce failures and the attendant cost of transformer unavailability.

2.0 Paper Insulation in Power Transformers

Paper is widely used in various engineering applications due to its physical properties and ease of manufacture and this has resulted in its selection as an electrical insulating material for parts and components in high voltage technology [4] (see Figure 1). Schaible [5] reported that paper insulating materials have been used for the last century to confine electrical currents to specific electrical paths. Paper is made from cellulose with the cellulose fibers dissolved into a solution and cast as a sheet [6]. Certain properties make paper cellulose fibers a choice material for electrical insulation. Table 1 [5], presents the desirable qualities for electrical grade fibers. As already noted [2-5], the operating condition of electric power transformers results in the degradation of cellulose paper insulation, and this ultimately defines the life of the transformer [1]. It is therefore needful for Asset Managers to monitor the degradation of paper insulation in power transformers. This paper attempts to review the various techniques employed in sensing the degradation of paper insulation in electric power transformers.

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Figure 1: Paper insulated coil of a detanked transformer
(Source: [18])

2.1 Paper Degradation Sensing Techniques

The degradation of paper results in the formation of degradation products. In their work, Levchik et al reported that the significant products of the degradation of cellulosic paper (see Figure 2) are furanic compounds (2-Furfural, 2-Furfurol, 5-Hydroxyl methyl-2-furfural, and 5-Methyl-2-furfural), water, CO_2, and CO [7]. Paper degrades by cellulose chains scission i.e breakdown of cellulose chains into smaller chains and the amount of cellulose chains scission is determined by the degree of polymerization (DP), [7]. The degree of polymerization (DP) and the significant products of paper degradation form the key indicators that are measured in order to monitor the degradation of paper insulation in electric power transformers [7].

Several literatures have been written on techniques for sensing paper degradation. Arshad et al [8] highlighted various modern techniques for sensing paper degradation in transformers to include Dissolved Gas Analysis (DGA), Fural Analysis (FA), Interfacial Tension (IFT), Degree of Polymerisation (DP), Recovery Voltage Method (RVM), Frequency Domain Spectrometry (FDS), Polarisation-depolarisation Current (PDC) measurement, Doble Test (DT), Swept Frequency Analysis (SFRA) and Leakage Reactance (LR). The use of Fourier Transform Infrared (FTIR) and Ultra violet visible (UV/vis) as methods for evaluation of oxidative degradation of model paper using the Density Frequency Theory (DFT) approach was reported by Lojewski et al. [9].

Table I: Desirable Qualities for Electrical Grade Fibers

Natural Pulp-(wood, cotton, hemp etc.)	**Synthetic Pulp-(Polymers)**
Chemical Properties -high cellulose content low lignin content for reduced specific conductivity -low hemicellulose content for low p.f. -low ash for low inorganic ion content [low ionic impurities-replace mono with bivalent ions (Ca++, Ba++ for Na+), wash with deionized water to reduce dielectric losses] -high molecular weight for good mechanical properties -low shieve or knot content -blocked hydroxyl groups to lower the dielectric constant of paper to that of the oil -low carboxyl number for lower high temperature losses **Physical Properties** -high density for good electrical strength -low moisture content after oil impregnation -high oil penetration (low density) for low overall dielectric constant -high air resistance (beat pulp to optimize conduction through interfiber bonding and mechanical strength)	**Chemical Properties** -select crosslinking to depolymerizing polymers -select materials with high Tg for thermal stability -optimize mechanical strength through adjustment of molecular weight and molecular distribution -reduce polar group content for better electrical properties -choose chemically inert aromatic polymers with little swelling in oil at service temperatures -Avoid adding hydrogen or halogen groups to the carbons next to the carbon with characteristic functional moiety [6]. **Physical Properties** -minimize fiber to film void content -optimize cross sectional shape of fiber for good mechanical strength -maximize bonding between polymer fibers by heat, mechanical entanglement or chemical means -raise air resistance

(Source: [5])

The molecular weight study of cellulose insulation paper using Gel Permeation Chromatography (GPC) was the subject of intense research work by Hill et al. [10]. It was noted [10] that the average molecular weight of the cellulose chains decreases with age as does the strength of the insulation paper. Accordingly, the time dependence of the molecular weight of the cellulose was investigated to provide information about the rate of main chain bond scission [10]. A comprehensive review of degradation sensing techniques was done by Saha [2]. Saha broadly classified the various techniques into chemical diagnostic techniques and electrical diagnostic techniques. In Saha's review, the use of Near Infrared Spectroscopy (NIR) to accurately determine the moisture content of insulation paper was discussed.

It is worthy of mention that a detailed review of all known degradation sensing techniques has not been attempted in this work. However, being the main mechanism for cellulose degradation, the degree of polymerization (DP) measurement has been selected for detailed review.

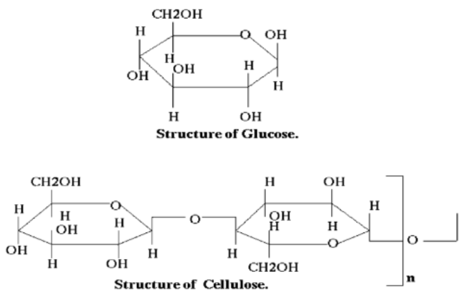

Figure 2: Top- structure of Glucose, bottom – structure of Cellulose
(Source: [2])

3.0 Degree of Polymerisation (DP) Measurement

The degree of polymerization (DP) is simply the number of monomer units in a polymer, and this is the parameter used in determining the quality of cellulose [2]. Kraft paper used in transformer insulation has DP usually between 1000 and 1500 [2-3, 7-8, 11-17]. It has been reported in literature that at a DP of 150-200 the mechanical strength of the paper can be reduced to 20% of its initial value [2-3, 7, l5]. At this point the end of life criterion is indicated for the transformer insulation, and this is because at any lower DP the paper loses all its mechanical strength while its dielectric constant is not greatly affected [2]. Baird et al [3] reported that below a DP of about 200, the tensile strength of the paper remains about 50% or less of the original value and the paper begins to fail.

Traditionally, the degree of polymerization (DP) has been measured using the viscometry method. The use of viscometry to measure DP is outlined in publication IEC 450 which is the equivalent of US Standard ASTM D4243 [2, 15]. This method involves dissolving the Kraft paper in cupric ethylene diamine and then measuring the viscosity. Although there is a mathematical correlation between the measured value of viscosity and the determined value of DP, no attempt has been made to review it in this work. In reviewing the viscometry method, Saha [2] used (DP_v) to denote the viscometric measurement of the degree of polymerization. Saha's review highlighted the advantages and disadvantages of life prediction of transformer insulation from DP_v measurements. Worthy of mention is the fact that DP_v measurements are easy to conduct and the results can be related empirically to insulation condition quite easily. A particular disadvantage was noted that the mechanisms and kinetics of the process are ill defined [2]. Saha's review also pointed out that the rate of degradation was dependent on the type of paper and also on its final chemical treatment and that the rate of degradation increases discontinuously with increasing temperature above about 140^0C [2].

A better method of determining the degree of polymerization is on the basis of the average molecular weight of cellulose. This method is the Gel Permeation Chromatography (GPC). The use of gel permeation chromatography is widely reported in literatures. Hill et al [10] reported the molecular weight study of cellulose insulation using (GPC) and this was justified by the need to investigate the time dependence of the molecular weight of the cellulose to provide information about the rate of main chain bond scission. The use of GPC involves passing the sample cellulose paper through a series of reactions to obtain cellulose tricarbanilate (CTC) which is a derivative of the cellulose in paper, and dissolving the CTC in tetrahydrofuran (THF) and then filtering through a 0.45μm filter just before the GPC measurement [10]. In reviewing the molecular weight study of cellulose done by Hill et al [10], Saha [2] noted that GPC provides the most convenient way to obtain a detailed molecular weight distribution for the polymer. Saha also pointed out a major advantage of the GPC method as it gives the entire distribution for the polymer, and that any small change in molecular weight during the ageing process of an insulation material is easily observable through the chromatogram [2]. It is particularly emphasized that GPC measurement provides accurate information about the change in molecular weight and molecular weight distribution [10] (see Figure 3).

A more recent method of measuring the degree of polymerization is detailed in IEC Standard 60450 [12-13, 16-17]. No attempt is made to present the details of IEC 60450 in this work.

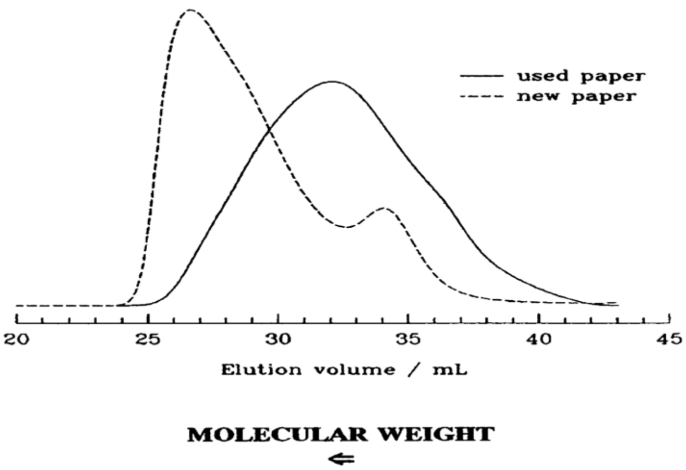

Figure 3: GPC Chromatograms of Molecular weight Distribution of New and Used Insulation Paper
(Source: [10])

4.0 Future Trends

A major practical drawback of DP is that its estimation is not possible without collecting cellulose samples from the operating transformers [3]. This drawback has however created a window of opportunity for more research work aimed at developing non-destructive methods of assessing the degradation of paper insulation in power transformers. Baird et al [3, 18] have worked remarkably to develop one such method. They have reported the successful development of a non-destructive spectroscopic method for measuring the degradation of paper insulation in electric power transformers (see Figure 4). They have called this spectroscopic method TRANSPEC™ and they configured it for examining paper in such a way that it can operate even when the paper is loaded with oil and water. TRANSPEC™ combines the application of Ultraviolet-visible (UV/vis) and Near Infrared (NIR) spectroscopy and multivariate statistical analysis (MVSA) to enable the accurate measurement of DP, and it has the advantage of providing additional information which relate to the water content of the paper and the condition of the oil [18].

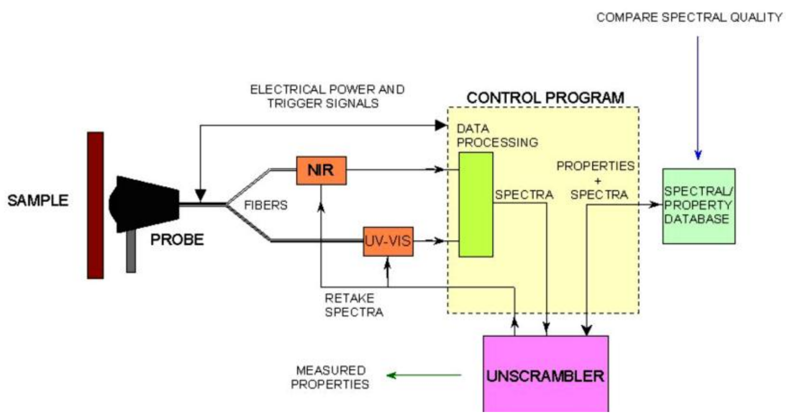

Figure 4: Spectroscopic measurement system
(Source: [18])

A field trial of this method has been demonstrated (see Figure 5) and some opportunities for improvement have been noted [18].

Figure 5: A field assessment of transformer condition using TRANSPEC^{TM}
(Source: [18])

5.0 Conclusion

A review of the various techniques for sensing paper degradation in electric power transformers has been presented. Particularly, emphasis has been placed on the measurement of the degree of polymerization of the cellulosic paper as a major indicator of the condition of paper insulation in electric power transformers. Viscometry which involves dissolving the cellulosic paper in cupric ethylene diamine solution and then measuring the viscosity was presented as a traditional method for measuring DP. The advantages and disadvantages of the viscometric method were presented as highlighted in literatures. The use of Gel Permeation Chromatography which is a more accurate method of measuring DP than Viscometry was discussed. The fact that GPC gives a better molecular weight distribution of the paper cellulose over its degradation span was particularly emphasized. It was noted that new Kraft paper used for electrical insulation have values of DP ranging from 1000 to 1500. When DP value drops to between 150 and 200, the paper is said to have reached its end of life. Beyond this value the paper loses its mechanical strength and this will lead to transformer failure.

6.0 References

[1] M. Wang, A.J. Vandermaar & K.D. Srivastava, "Review of Condition Assessment of Power Transformers in Service" *IEEE Electrical Insulation Magazine*, DoI:10.1109/MEI.2002.1161455, Vol. 18, No. 6; pp 12 – 25, 2002

[2] T. K. Saha, "Review of Modern Diagnostic Techniques for Assessing Insulation Condition in Aged Transformers," *IEEE Transactions on Dielectrics and Electrical Insulation,* Vol. 10, No. 5; pp 903-917, October 2003

[3] P. J. Baird, H. Herman & G. C. Stevens, "Non-Destructive Measurement of the Degradation of Transformer Insulating Paper," *IEEE Transactions on Dielectrics and Electrical Insulation,* Vol. 13, No. 1; pp 309-318, February 2006

[4] E. Tuncer, G. Polizos, I. Sauers & D. R. James, "Electrical Insulation Paper and Its Physical Properties at Cryogenic Temperatures," *IEEE Transactions on Applied Superconductivity*, Vol. 21, No. 3; pp 1438 – 1440, June 2011

[5] M. Schaible, "Electrical Insulating Papers: an Overview," *IEEE Electrical Insulation Magazine*, DoI: 10.1109/MEI.1987.290616, Vol. 3, No. 1; pp 8 – 12, January 1987

[6] P. Basappa, S. Jang & J. Kim, "Electrical Breakdown Studies on Electro-active Paper," *IEEE Transactions on Dielectrics and Electrical Insulation* Vol. 14, No. 5; pp 1125-1132, October 2007

[7] S. Levchik, J. Scheirs, G. Camino, W. Tumiatti & M. Avidano, "Depolymerization Processes in The Thermal Degradation Of Cellulosic Paper Insulation In Electrical Transformers," *Polymer Degradation and Stability,* Elsevier Science Limited, Great Britain; pp 507-511, 1998

[8] M. Arshad & S. M. Islam, "Significance of Cellulose Power Transformer Condition Assessment," *IEEE Transactions on Dielectrics and Electrical Insulation,* Vol. 18, No. 5; pp 1591-1598, October 2011

[9] T. Lojewski, P. Miskowiec, M. Missori, A. Lubanska, L. M. Proniewicz, & J. Lojewska, "FTIR and UV/vis as methods for evaluation of oxidative degradation of model paper: DFT approach for carbonyl vibrations" *Carbohydrate Polymer,* 82 (2010), 370-375; Available from Elsevier Science Limited

[10] D. J. T. Hill, T. T. Le, M. Darveniza & T. Saha, "A study of degradation of cellulosic insulation materials in a power transformer, part 1: Molecular weight study of cellulosic insulation paper," *Polymer Degradation and Stability* 48 (1995) 79-87; Available from Elsevier Science Limited

[11] E. O. dos Santos, A. M. S. Silva, W. D. Fragoso, C. Pasquini, & M. F. Pimentel, "Determination of degree of polymerization of insulating paper using near infrared spectroscopy and multivariate calibration," *Vibrational Spectroscopy,* 52 (2010), pp 154–157; Available from Elsevier Science Limited

[12] I. Höhlein and A. J. Kachler, "Aging of Cellulose at Transformer Service Temperatures. Part 2. Influence of Moisture and Temperature on Degree of Polymerization and Formation of Furanic Compounds in Free-Breathing Systems," *IEEE Electrical Insulation Magazine*, Vol. 21, No. 5; pp 20-24, September/October 2005

[13] A. J. Kachler and I. Höhlein, "Aging of Cellulose at Transformer Service Temperatures. Part 1: Influence of Type of Oil and Air on the Degree of Polymerization of Pressboard, Dissolved Gases, and Furanic Compounds in Oil," *IEEE Electrical Insulation Magazine*, Vol. 21, No. 2; pp 15-21, March/April 2005

[14] J. Gielniak, A. Graczkowski and H. Mościcka-Grzesiak, "Does the Degree of Cellulose Polymerization Affect the Dielectric Response?," *IEEE Transactions on Dielectrics and Electrical Insulation,* Vol. 18, No. 5; pp 1647-1650, October 2011

[15] R.J.Heywood, A.M.Emsley and M.Ali, "Degradation of cellulosic insulation in power transformers. Part 1 : Factors affecting the measurement of the average viscometric degree of polymerization of new and aged electrical papers," *IEE Proc.-Sci. Mens. Technol.,* Vol. 147, No. 2; pp 86-90, March 2000

[16] M. G. Ese, K. B. Liland and L. E. Lundgaard, "Oxidation of Paper Insulation in Transformers," *IEEE Transactions on Dielectrics and Electrical Insulation,* Vol. 17, No. 3; pp 939-946, June 2010

[17] Lars E. Lundgaard, Walter Hansen, Dag Linhjell, and Terence J. Painter, "Aging of Oil-Impregnated Paper in Power Transformers," *IEEE Transactions On Power Delivery*, Vol. 19, No. 1; pp 230-239, January 2004

[18] P. J. Baird, H. Herman, and Gary C. Stevens, "On-Site Analysis of Transformer Paper Insulation Using Portable Spectroscopy for Chemometric Prediction of Aged Condition," *IEEE Transactions on Dielectrics and Electrical Insulation,* Vol. 15, No. 4; pp 1089-1099, August 2008.