A Comment on Techniques used to Estimate Moisture Content of Transformer Insulation System

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Abstract— **Evaluation of moisture content is important as a measure of the insulation undergoing electrical and mechanical stress which may in turn decrease the life expectancy of the transformer. The content of moisture in the insulation is dependent on many factors like; aging, temperature, cellulose material, transformer design, operating conditions, conservator system etc. Moisture content in insulation to transformer age is approximated to vary exponentially and is classified by the presence of moisture as dry and wet. Flow of electrification, dielectric strength and transformer insulation degradation are the main issues due to moisture affecting transformer health. So it is important to study various methods used for the estimation of water content in the insulation material. In the present communication different methods are reported for evaluating this fundamental property of insulating materials. Nevertheless, these test methods differ, depending upon the procedure, design of transformer, different insulating materials used, analyzed on various types of different specimen samples and fluids used for insulation.**

Keywords— *Power Transformer, Solid Insulation, Moisture Content, Dielectric Strength, Water Absorption.*

INTRODUCTION

Power Transformer is a critical and costly electrical component in a power system, and the safe operation of it is of vital importance to maintain the reliability of the power supply. The life of a transformer is usually limited by the life of the cellulose insulation. The rate of insulation life consumption is affected by moisture. Moisture is a byproduct of the aging process of cellulose so that even in a well-sealed unit, moisture will increase over time. The use of various sealing arrangements as well as improper maintenance of the conservator systems may additionally influence this state. Information can be found in the literature [1, 2] stating that decisive factor affecting moisture distribution is temperature distribution. In a transformer water is known to distribute unevenly in the cellulose insulation due to temperature differences [3]. In places with higher temperature, the insulation undergoes aging more rapidly as compared with less heated sites [4-6]. The initiation temperature of the bubble very strongly depends on the water content in the paper [7, 8] and the degree of cellulose aging [9].

The dynamics of the moisture increase changes depending on transformer design and operating conditions (temperature, load, cooling efficiency, etc.). High moisture levels can accelerate the rate of aging of the cellulose, limiting transformer life. In cases where the estimations predict moisture content above 2% actions to precisely evaluate the moisture content are recommended as the dielectric strength of the insulation system starts to decline significantly [10]. Moisture is controlled by maintaining seals to prevent migration into the tank. Excessive moisture can be removed by proper field drying of the transformer. In order to maximize the life of a transformer it is important to know the water content of the cellulose insulation.

The aging of power transformers can be monitored by knowing the water concentration over time which is due to water ingress caused by water formed in chemical reactions involving oxygen and atmosphere which makes the insulation. The paper will age prematurely [11] if the water concentration is high and in the overloaded condition of transformer it fails to work efficiently [12].

CAUSES OF MOISTURE CONTENT

Variation in moisture content generally depends upon transformer construction, thermal load and its age. Especially free-breathing transformers are sensitive to the diffusion of moisture from the surrounding environment, while in hermetically sealed high power transformers it comes from the aging of their solid insulation part. High-power transformers with sealed conservators reveal a small moisture increase during the first period of operation (about 10 years). Then the rate of moistening increases exponentially with age, and the older the transformer becomes, the faster does the moisture content increase. The relation of water content in the insulation to transformer age can be approximated by an exponential function [10].

Water in transformer insulation mainly comes from three sources which are residual moisture left after processing, moisture ingress through seals and the breathing system and moisture produced during the decomposition of cellulose. The moistening effects in transformer speeds up by two principal factors: (i) the acceleration of aging processes developing in the insulation in accordance with the Arrhenius formula (ii) the systematic deterioration of the sealant state, which leads to greater water migration from the surroundings.

Factors Affecting Transformer Health due to Presence of Moisture

According to the CIGRE 349 brochure [1], both thickness of cellulose materials and insulation temperature are the factors most strongly affecting the process of water migration and moisture distribution in the transformer insulation system. Moisture distributes non-uniformly in oil-paper insulation systems of large power transformers. Various negative affects which influence the health of transformer are:

- Distortion of electric field distribution, thereby decreasing its dielectric strength [13]
- reduction in partial discharge initiation level [14, 15]
- reduction of bubbling temperature in transformer insulation [7, 9].
- causes flow of electrification at oil-paper interfaces [36].
- accelerates aging of transformer insulation [34] [40] [16] [17].
- Development of gas bubbles in oil under sudden high temperature events such as emergency overloads.
- Reduction in mechanical strength (approximately half) [18].

To ensure good insulation and safe operation of the oil-filled power transformers in power system it is very important to maintain insulation materials under virtually dry conditions Therefore, different test methods were adopted to investigate and analyze the moisture contents in insulating oils and insulation paper.

VARIOUS METHODS FOR MEASURING MOISTURE CONTENT

The unit for moisture content in paper is typically expressed in percent, which is the weight of the moisture divided by the weight of the dry oil-free paper. It is convinced that since 1920s both the electrical and mechanical strength of paper insulation get decrease due to the presence of the moisture in transformer [17]. Therefore, accurate assessment for the condition of oil-paper composite insulation has important significance [19].

Various approaches have been adopted in literature to test and analyze the moisture content and its migration in insulation systems of oil immersed power transformers. Traditionally testing of insulation was carried out using electrical tests, such as insulation resistance (IR), polarization index (PI) and loss factor (tan δ) which concluded into limited single value outcome providing very little information about transformer insulation. Therefore, they could rarely be correlated with moisture content in the insulation [20].

To overcome the disadvantages of above methods, dielectric response method as a new technique of insulation diagnosis was presented at the commencement of 1980's [21]. The discrimination of moisture from other effects is a key quality feature for the analysis of dielectric response measurements. Dielectric response analysis using mathematical modeling [22] directly measures dielectric properties of insulation systems such as; oil conductivity and water content over a very wide frequency range [23-24]. The highest sensitivity to moisture is possessed by low frequency paper region so it becomes very important to estimate the water content of each characteristic area for reliable measurement. The average water content of the main insulation can be calculated by measuring the dielectric response. In this respect, the first method designed to calculate dielectric response method which was named as the Recovery Voltage Method RVM, failed to give desirable result [23]. To evaluate the accurate moisture content in multilayer oil-paper insulation, the polarization and conduction phenomena were modelled, to describe the accuracy of moisture estimation. Time-domain dielectric response methods such as return voltage measurements (RVM), polarization and depolarization current (PDC) measurements emerged successively [25-26].

Then after, a rigorous mathematical model proposed to predict the moisture migration between air, oil, and insulation accompanied by changing transformer load [27]. Also a new model was presented to simulate the transformer insulation drying using hot-air vacuum process called heat and mass transfer model. Then came a new transient-state model which proposed an analogy relating heat and mass transfer to monitor the moisture in insulting oil [28, 29]. For the evaluation of diffusion, absorption and desorption of moisture during drying and field installation of power transformer, various experimental and mathematical investigations were tested and performed in [30].

Fick's second law presented a one- dimensional mathematical model for simulation of the transient state and moisture diffusion in oil-paper insulation [31, 32] which predicted the moisture content, which varies with time and temperature in both insulating oils and insulation papers.
A numerical method using experimental data to solve the diffusion equation is discussed using an implicit iterative [31] [32]. The analysis and comparison of characteristics of moisture diffusion in oil-paper insulation is done using the stated law. Furthermore, a practical and significant equilibrium time constant is proposed. An equation is obtained for equilibrium time constant as a function of initial moisture content, temperature, and paper thickness.

Coulometric Karl Fischer Titration (KFT) method presented in the IEC standard 60814-1997 [33] is another popular approach and has been adopted in literature [34] [35] [13] to determine moisture content in oil impregnated paper, pressboard and liquid insulation of transformer at different time and temperature during the moisture diffusion experiment. But, the moisture content of cellulose based electrical grade oil impregnated paper and pressboard is slightly difficult to determine as paper insulation becomes inaccessible after oil-filled transformer is energized [36].

As KFT method is not possible on-site, electrical measurements such as; equilibrium oil-paper moisture partition curves [36-37] being simpler and accessible on site operation are preferred in [38] [39] for condition assessment of transformer insulation, including the estimation of moisture content. Moisture equilibrium curves have been well accepted to assess the water concentration of insulation paper. Several classic moisture equilibrium curves include Fabre–Pichon Curves, Oommen Curves, and Griffin's Curves [37] [39] [40]. Moisture content of solid and liquid insulation in Publication [37] introduced another set of moisture equilibrium curves using moisture absorption data at different humidity levels and temperatures. Similar moisture equilibrium curves were illustrated in [40]. Paper [41] presented relationship among various curves by measuring average moisture content, the saturated water vapor pressure and the average temperature of transformers. Different mathematical models are used for description of moisture equilibrium curves in impregnated paper using mineral and vegetable oil were compared in [37-42] and proposed how accuracy can be achieved in measuring the percentage of moisture content. The logarithm of the moisture content in paper is linear approximately to temperature for any moisture content in oil, provided that the moisture in the paper is less than 8% [43]. The higher the moisture content and temperature, the shorter the time is needed for attaining the equilibrium state. However, for practical cases of real transformer insulation systems, which hardly reach the equilibrium state, this correlation becomes much more complex, and therefore the combination of KFT analyses with the use of equilibrium curves may yield relatively large errors. So joint activities based on analyses of the insulation system's dielectric response in both time and frequency domains were carried out by CIGRE to correlate the results of the electrical measurements with moisture content evaluations based on KFT analyses [44-46].

Then use of capacitive sensors came into existence [10] instead of the KFT analyses, which constantly monitor the relative humidity of transformer oil after permanent installation so that degree of moisture migration between oil and cellulose can be estimated. According to [1] the system is said to be in equilibrium if the measured relative humidity of oil remains at a constant level for a long time, but paper [8],[47] defend the problems associated with these sensors that there may be a shift of water absorption curves in a older transformers because the solid insulation becomes less hygroscopic.

There is another approach named as frequency domain spectroscopy (FDS), which introduced in late 90s [24], were also used in literature to estimate the average moisture content in insulation. The FDS method effectively estimates the average water content, but the wetness of various local spots may certainly be larger. Therefore, IEEE standard 62-1995 [48] introduced distinction to classify the insulation moisture as dry, wet and excessively wet. The parameters such as; permittivity, conductivity, dissipation factor which predict the life of insulation totally depend on moisture content, ageing by-products, e.g. acids, and so on [49-51], So FDS was applied for analysis of transformer insulations, particularly to determine the average water content in oil-paper combination [52-54]. Many scientists also reported the correlations between uniformly distributed water content and measured FDS results of oil-paper combination [54-57]. But as per paper [38] FDS can't give a complete steady state for the energized transformers especially for traction transformers in which water content distributed extremely inhomogeneous because of variation in temperature and in loads, impact properties, asymmetry, non-linearity. In this case FDS measurements can also be taken on site to assess the insulation, as the span for transformer out of service to maintenance is usually not long enough to get the moisture equilibrium in oil-paper combination. Also a theoretical model for dielectric medium with an arbitrary distribution of conductivity and dielectric constant was proposed in [38] to investigate the dielectric relaxation behavior of the oil-paper composite insulation with a homogeneous moisture distribution.

CONCLUDING REMARKS

Till date cellulose based papers in combination with oil have been used in transfomers as an insulating material due to its excellent dielectric properties. However, the use of paper has certain disadvantages with regard to its moisture absorption and low thermal stability. So it was desirable to review the elaborate studies, various test methods and procedure conducted over the past 50+ years to determine the moisture content affecting insulation life from view of historical perspective.

This paper has reviewed the various procedure adopted to estimate the moisture content in solid and liquid insulation in transformers but steady state calculation of moisture content of the solid insulation in liquid-filled transformers is still major concern. The future may bring more innovations in determining the water content and improving the performance of cellulose insulation. Understanding the developed techniques for moisture calculation will allow transformer designers to better optimize their equipment and to enable the technologies to be taken into the next generation. Over the next few years, it will be interesting to see how this testing procedure helps in to monitor and decide shape of insulation system of the future transformer industry.

ACKNOWLEDGEMENT

The authors would like to thank I.K.G. Punjab Technical University, Kapurthala for providing fruitful environment to complete this research work.

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