Condition of the Solid Insulation System of Power Transformers

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Abstract: Operating power transformers the reliability and operational risk is strongly dependant on the load. Different kind of stress can be distinguished, normally a combination of electrical and thermal stress is present as well as the influence of humidity in the insulation system has to be considered. The so called multistress load results in an accelerated ageing process and the degradation of the insulation system. The condition of the mineral oil can be determined by sampling and analyzing the oil by the means of DGA and chemical-physical analysis. The solid insulation system mainly consists of transformerboard. The condition determination of the cellulose can be done by sampling, which is quite expensive and difficult. New dielectric methods which operate on the effect of response function have established in the last years. In this paper the focus should be directed on the mechanism of cellulose ageing and dielectric measurements.

Keywords: Transformer, Technical Diagnosis, Lifetime, Condition Evaluation

Introduction

Power transformers represent very important equipment in production and distribution of electric power. Since the liberalization of the electric energy market the cost pressure to the utilities raised and enforced to change the management strategy in several business segments. Taking a look to the technical and economical aspects of operating a distribution grid the length of life in correspondence to the drop out risk of electric power equipment is coherence.

For the estimation of the technical condition of a power transformer following parameters have to be considered: life cycle characteristics, overload times, maintenance strategies and measures. The coherence between life cycle characteristics and temperature excursions of the oil-paper insulation system due to overloads is described by the Law of Montsinger [1], which is also manifested in the “loading guide for oil-immersed transformers” [2].

Technical Diagnostics

Applying modern diagnosis methods dielectric parameters can be measured and give conclusions to the condition of the transformer insulation system. For example one of the most important parameters for the condition evaluation is the oil diagnostic. But also the water content of paper and transformer oil has to be observed very carefully because the deterioration of the transformer board. New methods for determining the water content were developed by the means of dielectric response measurements as Polarization Depolarization Current (PDC) or Frequency Domain Spectroscopy (FDS).

Other methods to determine the humidity of the cellulose material were very expensive: paper samples have to be taken out and the humidity can be measure by weighing or Karl Fischer Titration. Usually the furanic compounds were determined by oil analysis and a recalculation to the degree of polymerization (DP) is done. The DP value can also be determined directly by the means of viscosimetric measurement.

Using diagnosis and monitoring systems over the whole lifetime period the condition of the power transformer can be evaluated; maintenance strategies and the volume of measures can be adapted flexible to minimize the life cycle costs and the risk of long servicing and fall out time. The reinvestment can be delayed for several years and the point of renewal can be appreciated much better.

The basis for a condition evaluation of electrical power equipment is the knowledge about the characteristics of the insulation system and their behavior. According to the definition and terminology of maintenance [3] following measures can be distinguished: inspection, extended inspection, overhaul and servicing. The condition of a transformer is dependent on the operation condition and the number and amount of the maintenance measures and their intervals.

Aging of Cellulose

The main part of the electric insulation system of a transformer consists of oil impregnated paper. The electric and mechanical strength of the paper depends on the operating condition of the transformer and different chemical and physical processes which cause aging. The degradation of the cellulose material is influenced by the effects of oxygen and water in oil.

Degradation of the paper can cause the fail of the transformer by several mechanisms: the brittle paper can break away from the transformer windings and block ducts; water is a product of degradation and builds up in the paper, reducing its resistivity; in the extreme, local carbonizing of the paper increases the conductivity to cause overheating and conductor faults. [4]

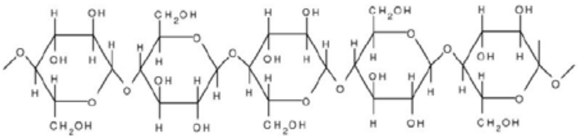

Figure 1: Structure of cellulose molecule [5]

In Fig. 1 the chemical structure of the cellulose molecule is shown. In reaction with water the cellulose molecule is split up and the process of depolymerization goes on, the number of glucosic units is reduced. The length of the cellulose molecule gives an objective information about the paper condition and so for the electrical breakdown strength of the transformer insulation system. To determine the degree of polymerization (DP) there were two possibilities: by chemical analysis of the oil or by chemical analysis of the paper.

Furan Analysis

By the means of furan analysis the DP is determined in a chemical analysis of the transformer oil. According to the standard [6] the 2-Furfural can be measured and with response to the curve in Fig. 2 the DP can be derived. New paper has a DP of more than 1000, after factory drying this value will drop to 800 to 1000. Paper under normal operating condition has a DP of more than 400, aged paper more than 200 and paper with a DP lower than 200 is aged extremely. The accuracy of the furan analysis is very high and most utilities apply this method to determine the condition of their equipment as state of the art.

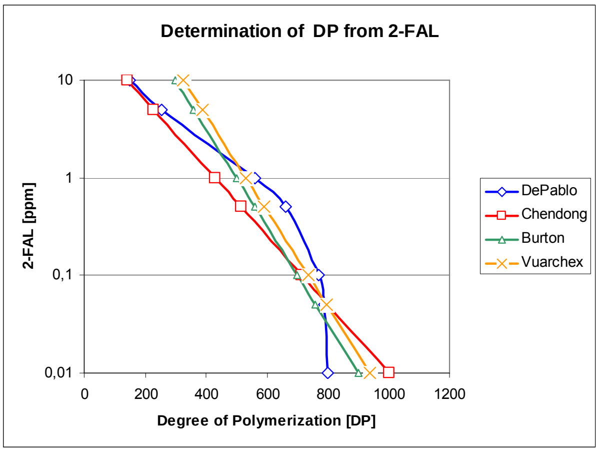

Figure 2: Determination of 2 FAL [7]

DP Determination with viscosimetric measurement

The degree of polymerization of cellulose can be determined directly by viscosimetric measurement according to IEC 60450 [8]. Paper test specimens have to be taken out of the transformer and to be prepared according to this standard by crushing and drying the cellulose fibers and resolving in the CUEN solvent. Then the average viscosity is measured with a viscosimeter and from this result the DP can be determined by the relation of intrinsic viscosity and limiting viscosity number. In Fig. 3 a viscosimeter is shown.

Figure 3: Viscosimeter [5]

The advantage of this method is that the results were very reliable and the DP of several points in the transformer can be determined exactly. The disadvantage of this method is that paper test samples have to be extracted from the inner of the transformer and the method for DP determination needs quit a big experience for the chemical engineers. Normally this method is not applied for transformers in operation, but it delivers good results to determine the electrical and mechanical residual strength of paper insulation.

Thermal Degradation

High load of a transformer means high ohmic losses and a rise of the temperature in the windings and the insulation system. With the rise of the operating temperature the degradation processes of the paper-oil insulation system is accelerated according to the law for thermal aging, the parameters for aging of paper-oil systems were determined a long time ago by Montsinger [1]:

$$Thermal\ Aging = 2^{\frac{\upsilon - 90°C}{8°C}} \quad \ldots (1)$$

In Figure 4 an example shows the thermal degradation of paper oil-insulation systems according to the Montsinger Law. Assuming an average lifetime for a power transformer of 50 years the estimated lifetime for higher load is calculated and displayed in this graphic. This means if the average operating temperature of the transformer over the whole lifespan is increased for 8°C a 50% reduction of lifetime can be expected.

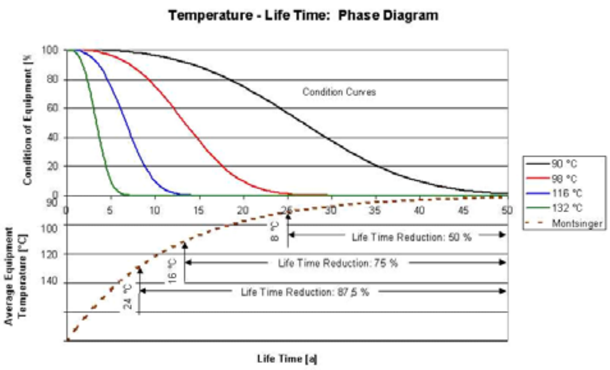

Figure 4: Transformer lifetime in dependance of thermal load [9]

Influence of oil moisture

Due to the fact that most transformers operate with open systems the paper-oil insulation system “breathes” with air. Newer transformers were encapsulated hermetically. Different physical processes cause the absorption of the air humidity in the transformer insulation system, in the mineral oil and the paper. Water molecules in oil and paper accelerate the depolymerization of paper on the one hand and minors the quality of mineral oil concerning the electric strength parameters (breakdown voltage etc.) on the other hand.

For this reason the content of water in oil is an important parameter which can be determined by chemical analysis or dielectric measurements. The chemical analysis is done by the Karl-Fischer titration (KF). The fundamental principle behind KF titration is based on the Bunsen reaction between iodine and sulfur dioxide in an aqueous medium. It is most applied for the moisture determination in oil and a standard test in chemical oil analysis.

Moisture determination with dielectric response methods PDC and FDS

Since new test equipment for the well known dielectric response method for electric insulation systems were developed the moisture of oil can be determined by dielectric measurements. The Polarization and Depolarization Current (PDC) Method on the one hand and the Frequency Domain Spectroscopy (FDS) on the other hand enable to measure the content of water in the whole insulation system of a transformer.

At the PDC analysis a DC Voltage is applied to the test object and the current is measured. The whole response spectroscopy of the insulation system can be recorded with one measurement. The determination of the humidity is done by comparing with reference values respectively reference curves.

But how good is the correlation of PDC results and the reality? To clarify this question a test series with different paper qualities was done. The test samples were weighed under dry condition than stored in a climate chamber with defined climatic condition (temperature and air humidity) and then weighed again. For the determination of the weigh a chemical balance with high accuracy was used, so that the weighing resulted in a traceability calibration process. The sorption of water in the paper shows a hysteresis character according to Fig. 5, for this reason the impregnation duration had to take appropriate duration.

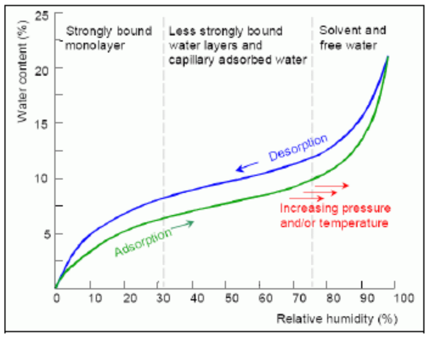

Figure 5: Sorption of humidity in paper [5]

For the PDC measurement a PDC Analyzer 1MOD [10] was used, a test voltage of 2kV was applied for a duration of 1200 seconds. The result of the moisture determination with PDC is shown in Fig. 6. The polarization and the depolarization current were compared to the reference curves in the system and resulted in a moisture content of 4.9%. The calibrated weighing method resulted in a moisture content of 4.554%, which means a good correspondence of both methods.

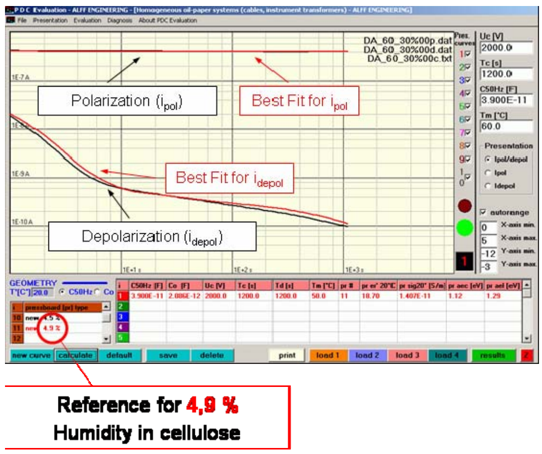

Figure 6: Determination of water content with PDC analysis [5]

The second dielectric method which should be mentioned in this paper is the FDS, where an AC voltage with variable frequency is applied and the dissipation factor tan δ is measured. In opposite to PDC the FDS displays the result in frequency domain and the tan δ is measured directly without necessary transformation from time domain.

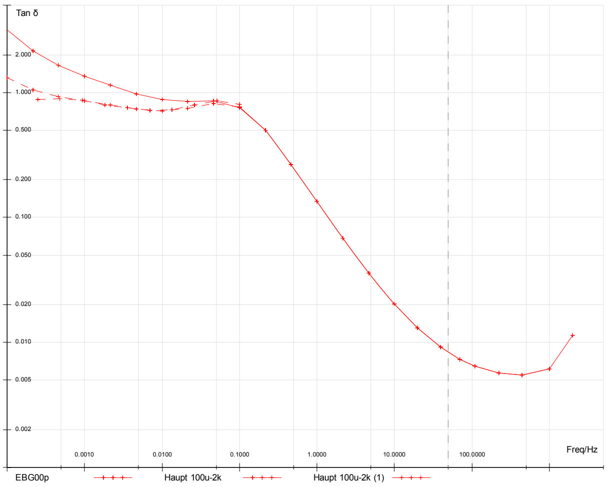

Figure 7: Comparison of FDS (continuous line) and PDC (dotted) measurement

A new combined method was developed to join the advantages of FDS and PDC method; the duration of measurement can be shortened significant [11]. The determination of the moisture content can easily be done with the FDS device DIRANA [12] with comfortable software.

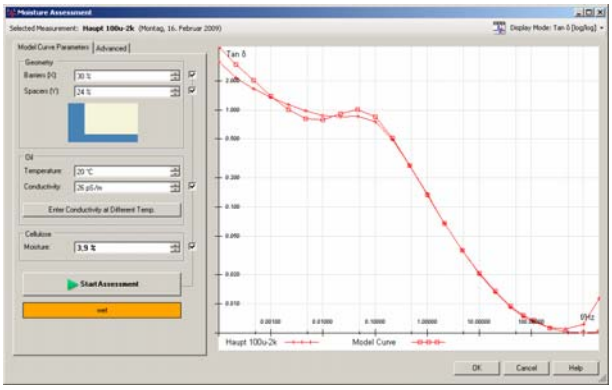

Figure 8: Determination of water content with FDS analysis

Summary

Beside the classical oil analysis there were new methods to determine the condition of the electric insulation system of transformers. The aging of the insulation system is influenced dominant by the water content of mineral oil. For this reason the moisture determination with chemical analysis and dielectric measurements were essential.

The mechanical paper condition is linked directly with the electrical breakdown strength. For this reason the structure of the paper gives useful information about the transformer condition. The appearance of the paper molecule can be determined by analysis of the furanic compounds or by measurement of the degree of depolarization (DP). The DP measurement with a viscosimeter requires an extraction of paper test samples out of the transformer. For this reason the furanic analysis is applied more often and the expressiveness of both methods equals.

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