Investigation on Degradation of Power Transformer Solid Insulation Material

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Abstract: **Power transformers are vital parts of electric energy transmission and generation systems. Numerous power transformers in the European power grid have reached an age of 30 years or even more and are possibly close to their end of life. Because of economic reasons it is demanded to keep current assets as long as possible in service without taking the risk of a failure. The DP (degree of polymerization) value is an indicator for the mechanical stability of Kraft paper insulation. The ageing process depends on the transformer's operation temperature and is accelerated by the presence of moisture and acids in the insulation system. During the decomposition reaction of cellulose chains furanic compounds and water is generated.**

In this paper investigation results from samplings of solid insulation material and their correlation to the concentration of furfurals in oil are presented. These investigations have been carried out during scraping of power transformers that have been put out of service due to failure or replacement. The distribution of the DP value over the insulation system shows a non-uniform ageing of the paper material.

I. INTRODUCTION

A transformer's life span is determined amongst others by the insulation system's mechanical resistance to withstand short circuit current forces. Electric load losses in the transformer cause thermal stress in the active part. This leads to aging and decomposition of both liquid and solid insulation material, oil and celluloses.

Cellulose is composed of polymerized glucose molecules that break up into smaller chains under thermal stress. The average number of glucose molecules in each cellulose cluster is determined by the degree of polymerization (DP) and is an indicator for tensile strength of Kraft paper. But paper sampling from the insulation system is impossible during operation and even difficult during active part disassembling in a repair facility.

Aging of solid insulation is always in combination with aging of transformer oil. Oxidation is the predominant mechanism leading to formation of carboxylic acids in oil. Recent publications suggest that low molecular weight acids that are more reactive than high molecular weight acids originate from degradation of paper [7]. Water is a side product of both solid and liquid decomposition reactions and accelerates aging by autocatalysis.

An established source for diagnostics are transformer oil samples that can be obtained during normal operation. From model investigations it is well known that the concentration of furanic compounds in transformer oil and the DP value of insulation paper are correlated to each other as furanic compounds are a product of decomposition of cellulose. Furanic compounds are relatively stable and can be identified in transformer oil by chromatographic methods. This can be used as an indicator for degradation of solid insulation. Recent work shows that the correlation is heavily influenced by various factors like temperature or moisture content [1].

In this investigation a population of 15 GSU and substation transformers from various major German power utilities has been inspected during scraping after the transformers have been put out of service. From 11 power transformers meaningful oil reports with determination of furanic compounds for at least some past years were available. A method for acquiring solid insulation samples and calculation of DP mean average has been developed.

II. KRAFT PAPER SAMPLING FROM POWER TRANSFORMERS

The calculation of the DP mean average of a winding requires constant observation of DP values along the length of the winding. For example, if there are too many samples from the upper area of the winding, where it is easier to gain samples in practice, low DP values will be emphasized too strong as there is usually the highest thermal stress.

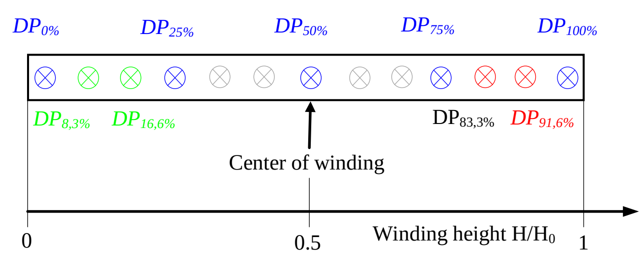

Fig. 1: Calculation of DP mean average from non-equidistant samples (red) over winding height by adding calculated DP values (green)

If it was possible to take samples at any axial position of the winding, one would be starting in the center of the winding, using equidistant samples to top and bottom for calculation of DP mean average (Fig. 1). If three-phase transformers are investigated, samples should be taken from the transformer's center limb, as the highest thermal stress is expected within the middle phase (Fig. 3).

From the arithmetic mean $x_{m,i}$ with N single values x_k of the axial sampling series i as an empiric estimate

$$\mu_{m,i} \approx x_{m,i} = \frac{1}{N} \cdot \sum_{k=1}^{N} x_k \tag{1}$$

one gets with corresponding samples from top and bottom

$$\mu_{m,i} \approx x_{m,i} = \frac{1}{N} \cdot \left(x(0.5) + \sum_{H=0}^{<0.5} x(1-H) + x(H) \right) \tag{2}$$

To a sample from position H there is always a corresponding sample from position 1 – H, H is the normalized winding height. So the number of samples from above the center of the winding equals the number of samples from below the center. In practice, the corresponding sample H from the lower part of a winding is sometimes not available. So this sample has to be calculated from its neighbors:

$$x(H_1 + k \cdot \Delta H) = x(H_1) + k \cdot \frac{x(H_2) - x(H_1)}{M+1} \quad with \;\; k = 1, \ldots, M \tag{3}$$

The DP mean average of a winding is calculated from the mean of each sampling series with a total number of S axial series:

$$\mu_{Winding} \approx x_{Winding} = \frac{1}{S} \cdot \sum_{k=1}^{S} x_{series,k} \tag{4}$$

The investigated power transformers are listed in Table 1. Fig. 2 shows the total process of Kraft paper sampling on a 31.5 MVA substation transformer that was built in 1958 and had been in service for almost 50 years.

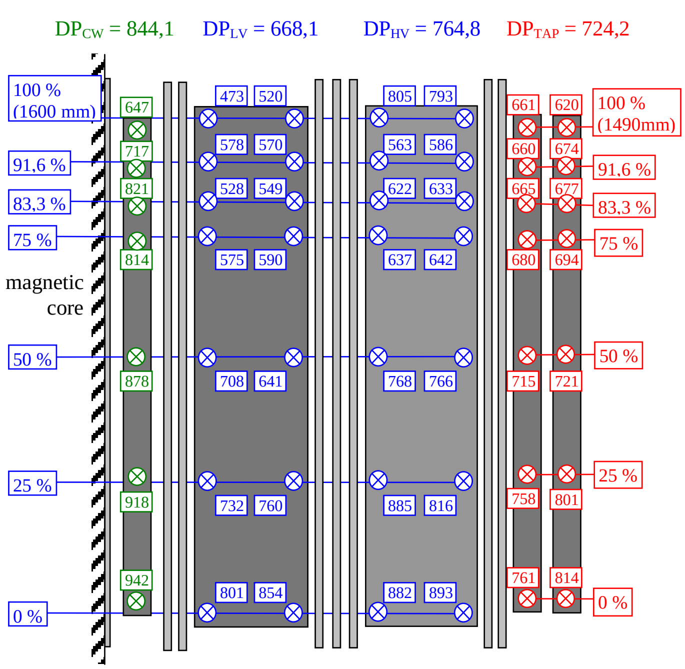

Fig. 2: Winding construction of a 31.5 MVA 110/20 kV substation transformer with location and DP value of paper samples

The degree of polymerization of paper was measured according to IEC 60450. [9]

TABLE I
INVESTIGATED POWER TRANSFORMERS

Built in	End of service	Voltage [kV]	Rated power [MVA]	Type	DP mean average
1958	2008	105/22.5	31.5	Substation	719
1964	2006	110/22	23	Substation	880
1964	2006	115/10.7	62.5	GSU	543
1967	2007	220/66/	100	Substation	690
1970	2005	107/10.5	110	GSU	250
1970	2005	235.8/21	380	GSU	219
1970	2005	400/21	360	GSU	456
1971	2007	236/21	225	GSU	484
1971	2007	115/6.6	33.3	GSU	190
1971	2007	115/6.6	9	GSU	319
1973	2007	110/21	385	GSU	506
1973	2006	105/22	40	Substation	793
1976	2007	110/110	200	Substation	720
1988	2007	400/120	300	Substation	942
1992	2006	400/27	650	GSU	929

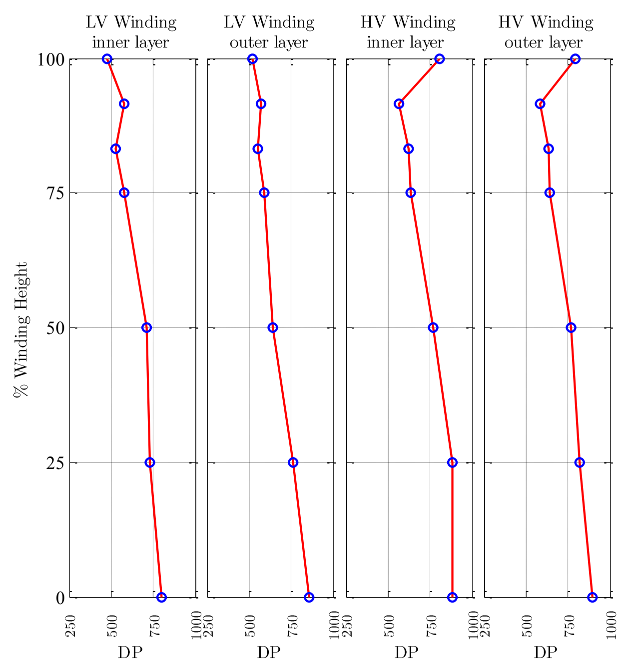

Fig. 3: Distribution of DP over winding height, HV and LV winding

III. ANALYSIS OF FURFURAL CONCENTRATION AND DEPOLYMERIZATION OF KRAFT PAPER

Under normal transformer service temperature, degradation of cellulose runs by hydrolysis with further oxidation of the products. With Glucose and Pentose as intermediate steps Furfural (2-FAL) is the reaction product, Fig. 4.

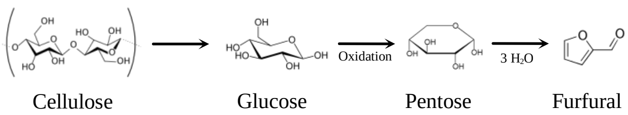

Fig. 4: Degradation of cellulose

It is assumed that all winding systems with their Kraft paper proportion and all other insulation material contribute in the same manner to the formation of furfurals solved in transformer oil. So the determined DP values are weighted with the insulation paper's mass:

$$DP_{total} = \frac{DP_{Tap} \cdot m_{Paper,Tap} + DP_{HV} \cdot m_{Paper,HV} + DP_{LV} \cdot m_{Paper,LV} + DP_{Leavings} \cdot m_{Leavings}}{m_{Paper,Tap} + m_{Paper,HV} + m_{Paper,LV} + m_{Leavings}} \quad (5)$$

If the construction documentation is not available, the paper masses cannot be determined. Taken into account, that mainly the HV and LV winding contribute to the paper mass, other windings are neglected. Furthermore it is assumed that paper mass is similar in HV and LV system. With allowing certain error, the DP mean average is calculated as

$$\overline{DP} = \frac{1}{2} \ DP_{HV} + DP_{LV} \quad . \quad (6)$$

New insulation paper has a DP value of 1300 to 1100, after transformer vacuum drying this is reduced to about 950 [5] and is reduced further during operation. The relation of tensile strength σ and DP value is given by equation

$$\frac{\sigma}{\sigma_0} = 0{,}1 + \frac{5}{3} \cdot \left(\frac{DP}{DP_0}\right) \text{ [6].} \quad (7)$$

Starting with $DP_0 = 950$, and the initial strength σ_0, the tensile strength is reduced to 50% of σ_0 at a degree of polymerization $DP = 228$. Reaching a DP value of 150 to 200, celluloses is expected to be defective.

Fig. 5: LV winding of a 110 MVA GSU transformer, DP mean average < 200

There are three reaction mechanisms in degradation of paper: Oxidation, hydrolysis and thermolysis, where thermolysis is predominant at temperatures above 120°C, what is usually limited to local defects. At service temperatures with moisture or oxygen present activation energy is reduced and causes degradation even at 70°C. Recent publications suggest that low molecular weight acids that are more reactive than high molecular weight acids originate from degradation of paper [7].

The decomposition of Kraft paper is an autocatalytic process that is accelerated by water and carboxylic acids that are generated by the reaction itself [1], an approach to prolonged power transformer life would be the reduction of water in the solid insulation system and the removal of acidic compounds from oil.

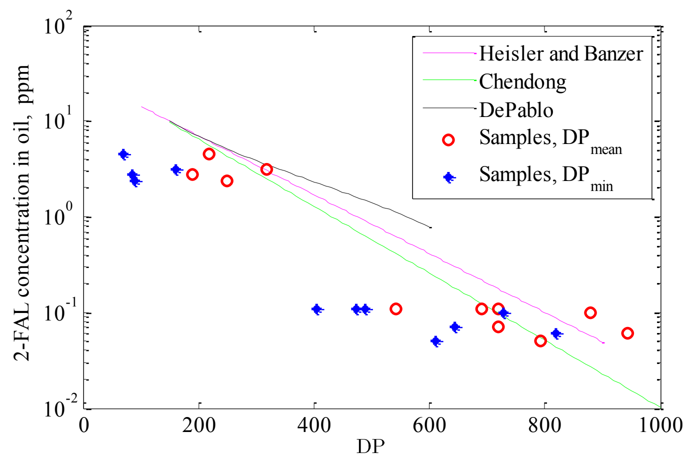

Fig. 6: Correlation of 2-FAL concentration in transformer oil and mean and minimum DP value from Kraft paper samples

Different correlations between DP value and concentration of 2-FAL have been proposed in [2],[3] and [4]. These correlations are shown in Fig. 6 in combination with the DP mean average and minimum DP value from sampling during transformer scrapings presented in this paper.

Samples with low mean DP value seem to be correlated to slightly lower concentrations of 2-FAL than stated in literature. The dispersion in the correlation of 2-FAL and mean DP value is reduced with higher concentrations of Furfural respective with lower DP values. However, more investigations with transformers taken out of service with concentrations of 2-FAL between 0.1 and 1 ppm need to be done for more information about medium range DP values.

The correlation between concentration of 2-FAL and degree of polymerization is disturbed if there is oil replacement or oil reclaiming as the furanic compounds in oil are removed. As most furanic compounds are present in the solid insulation material there will be a balancing process in the period of some months until equilibrium is reached again. Another source of aberration in the correlation can be the modified distribution of furanic compounds in insulation oil and solid insulation caused by advanced aging of mineral oil or increased water content [8].

Compared to the DP mean average the lowest degree of polymerization that was found can be less than 50% of the mean value. In accordance with temperature distribution in power transformers under load, the lowest DP values have been typically observed in the uppermost 25% of the winding.

Especially with paper samples from GSU transformers that have been constantly under high load during their life cycle DP values significantly lower than 200 have been observed although there was no clue for accelerated aging caused by defects (Fig. 5). According to common technical rules, these transformers have reached their end of life. Distribution or step-down transformers that are under medium or intermittent load show a much higher degree of polymerization even after a long period of service.

IV. Conclusions

From artificial accelerated aging experiments with Kraft paper and oil the correlation between 2-FAL concentration in oil and DP value of Kraft paper has been investigated in different publications. A similar behavior has been observed at transformer insulation aged under normal service conditions that have been inspected after their end of life.

With higher concentration of 2-FAL it seems that the correlation to DP values has a reduced dispersion within the investigated power transformer population. However the analysis of furfural concentration should be used as a tool for trend analysis in paper decomposition as the formation of furanic compounds is influenced by various factors.

Decomposition of paper over the height of a winding is not uniform. Usually the lowest DP values can be found within 75% and 100% of the winding's height, according to the typical thermal profile of a power transformer.

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