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Study of the distribution of temperatures in the windings of a transformer after suffering a short-circuit.

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Abstract. Power transformers are electrical machines that allow us to transport electric energy, with reduced losses, from generation stations to consumption points. This definition gives us an idea of the number of machines of this type that are used in power distribution systems worldwide. The lifespan of this equipment often exceeds 30 years of operation. Therefore, they can be described as very robust equipment. The main problem that may affect power transformers is the operation at high temperature. This paper summarizes the results of a post mortem study carried out on an 800 kVA distribution transformer. The methodology that is considered for estimating the temperature distribution in the windings of the machine is based on the calculation of the degree of polymerization of the dielectric paper. This parameter is associated with the state of the paper insulation that protects the conductors of the windings. By knowing the value of this magnitude for a new and for an aged paper, and the period of operation of a transformer, the temperature distribution along the height of the windings can be estimated. With these results and the loading regime that a transformer has endured throughout his life, one can draw conclusions for future designs or for similar transformers still in operation.

Key words

Kraft paper, Degree of polymerisation, Activation energy.

1. Introduction

Transformers are one of the most expensive and critical components of electric energy transmission and generation systems [1]. Although transformers are very reliable machines a failure is possible at any age due to many factors as incorrect specification or operation, design or manufacturing errors, bad maintenance, excessive ageing...[2]. Therefore knowing transformers condition is essential to the asset management of large networks [3].

The transformers' life span is determined amongst other parameters by the condition of the solid insulation, particularly at the hot spot [4]. The primary insulation used in liquid filled power transformers is cellulose [6]. The cellulose which is composed of polymerized glucose molecules suffers degradation due to thermal stress caused by electric load losses in the transformer, moisture, oxygen, contamination from conducting particles and mechanical damage or weakening from vibration [5]. The three main processes for cellulose degradation are hydrolysis, oxidation, and pyrolysis [6]. Hydrolysis involves water and acids, which break the cellulose polymer chain. Oxygen dissolved in the oil accelerates the rate of aging of paper. Pyrolysis is decomposition occurring at temperatures above 140°C. Transformer paper operating under normal or overload conditions does not reach this temperature unless a fault develops. The products of cellulose degradation are carbon monoxide (CO), carbon dioxide (CO2), organic acids, water and free glucose molecules. The glucose rings can decompose further into furans [7].

These degradation by-products are soluble in transformer oil. For this reason, analysis of the oil for the degradation by-products (water, dissolved gases, furans) have been used to determine the degree of aging of the cellulose insulation [8]. Nevertheless, these techniques are macro in respect to the entire insulation system where may exist a significant thermal gradient [4]. The hot-spot temperature is one of the most critical parameter to estimate the remaining lifetime of solid insulation [2, 3]. This temperature can be estimated trough thermal model of a transformer taking into account the loading profile of the system, the ambient temperature profile over the year and the setting of the thermostatically controlled cooling system [9]. Other method to determine this hot-spot temperature is taking paper samples from representative parts of the windings and analysing for degree of polymerisation (DP) which is a valid indicator of paper ageing with a value of 200 taken as end of life [10]. It measures the average chain length of the cellulose molecules. However, it is not possible to obtain paper samples from a transformer in service. The DP determination is only possible when a transformer has been removed from service and a detailed post-mortem investigation of the solid insulation is performed [4].

Different authors have carried out a procedure in which paper samples are taken and tested for DP to obtain a map of the solid insulation aging [3-4, 11-13]. For instance, Koch et al. investigated new approaches to determine water in oil-paper-insulated power transformers to conform diagnostic parameters to post mortem investigations as well as, correlations between the furan (2-FAL) concentration in the oil and the average DP [6, 11]. Their aim was to close the gap between the findings during the visual inspection of the active part just before scrapping, the results of the material analysis and parameters which can easily be measured during the life time of the transformer such as water, dissolved gas analysis (DGA) and furans. Susa et al. carried out the condition assessment of a generator transformer by the mapping of degree of polymerization (DP). They also showed the temperature mapping, where the temperature estimation was based on the paper aging kinetics, transformer loading and insulation operating history. Finally, they gave a new equation for the relative aging rate considering all insulation conditions providing possibility of counting transformer loss-of-life more accurately [3, 13]. Prevost et al. also carried out a forensic analysis because the oil analysis had not yield a clear picture of a possible problem in two transformers [4]. Other situation where accurate paper degradation diagnostic could be useful was described by Martins et al. [12]. At the end of 2007, and after a network rearrangement in a region of Portugal, the Pracana substation became redundant. These authors performed a condition evaluation of a transformer to make a decision regarding its transfer to a new substation located in the same region. They carried out a diagnostic based on oil analysis and measures of DP, comparing both.

The combination of the results from service history and post mortem analysis from scrapped and failed transformers help to discover design and material problems specific to a family of transformers which were designed for a specific application and have the same size, voltage class, winding style and cooling system.

All these post-mortem studies have been based on DP which constitutes one of the most important parameters of the insulation condition. The chain length of the cellulose molecules determines the mechanical strength of insulation with cellulose materials. The mechanical strength of the cellulose fibers weakens continuously due to the cellulose's degradation [14]. This paper has taken paper samples from a failed distribution transformer. From these samples, DP calculations have been performed for the three windings of this machine. The basic aim of this analysis was to correlating DP map with the short-circuit. This approach has not been used for any other authors before.

2. Transformer description

The tests were performed with the dielectric paper of a 800kVA three-phase transformer, manufactured in 1986 with an ONAN cooling system. The total weight of the transformer is 2130 kg, with an insulating liquid mass of 390 kg. The connection of the transformer windings is Dy11 type with a ratio of voltages 30.000/400V. The transformer suffered a short-circuit between turns and it had to be removed from service.

Each coil has a height of 50cm and paper samples were taken at different heights in order to calculate DP values. The isolation of the transformer consists of several layers of paper, pressboard and copper. The paper layer uses two strips of kraft paper for insulating windings, one internal and one external. Samples of both types of strips were collected and analysed during the tests in order to see their condition. In Table I are recorded the heights of the points at which paper samples were taken from the windings for further analysis. e_1 means that the sample belongs to the external paper strip and e_2 that the sample belongs to the internal paper strip.

3. Methodology to obtain temperature distribution into the transformer

Firstly, paper samples have been taken out. The next step has obtained the DP mapping in accordance with ASTM D4243 [15]. Once DP results have been obtained the temperature distribution was estimated through cellulose kinetics. Different authors have reported the relationship between DP, time and temperature [16]. In this work, it has been considered the relationship defined by [17] who suggested that the rate of change of DP can be represented by:

$$\frac{dDP}{dt} = -k_1 * DP^2 \tag{1}$$

if k_1 is constant, this equation can be integrated:

$$\frac{1}{DP_0} - \frac{1}{DP_t} = k_1 * t \tag{2}$$

However, if k_1 changes with the time:

$$\frac{dk_1}{dt} = -k_2 * k_1 \tag{3}$$

where k_2 is constant. Integrating and rearranging:

$$\int_0^t \frac{dk_1}{k_1} = \int_0^t -k_2 * dt \qquad k_{1_t} = k_{1_0} * e^{-k_2 * t} \tag{4}$$

Substituting into equation 1:

$$\begin{aligned} &\frac{dDP_t}{dt} = -DP_t^2 * k_{1_0} * e^{-k_2*t} \\ &\int \frac{dDP_t}{DP_t^2} = \int -k_{1_0} * e^{-k_2*t} * dt \\ &-\left[\frac{1}{DP}\right]_{DP_0}^{DP_t} = \left[\frac{k_{1_0}}{k_2} * e^{-k_2*t}\right]_0^t \\ &-\frac{1}{DP_t} + \frac{1}{DP_0} = \frac{k_{1_0}}{k_2} * \left[e^{-k_2*t} - 1\right] \\ &\frac{1}{DP_t} - \frac{1}{DP_0} = \frac{k_{1_0}}{k_2} * \left[1 - e^{-k_2*t}\right] \end{aligned} \tag{5}$$

where k_{10} is the initial rate at which bonds break, k_2 is the rate at which k_{10} changes, DP_t is the insulation DP value at time t, DP_0 is the initial insulation DP value and t is the time in hours.

Assuming that the Arrhenius equation is valid over the temperature range used in the experiments done by [32], the authors have extrapolated this expression to a lower value corresponding with the average operating temperature in power transformers. The Arrhenius equation can be expressed:

$$k = A * e^{-\frac{E_a}{R*T}} \tag{6}$$

where
- k: rate constant
- A: pre-exponential factor
- E_a: activation energy
- R: molar gas constant (8.314 JK-1mol-1)
- T: temperature in Kelvin

The optimised activation energies and preexponential factors for Kraft paper aged in oil obtained through laboratory experiments [32] are:

Table I. - Arrhenius parameters for Kraft paper in oil.

	E_a (J/mol)	**A (h^{-1})**
k_{10}	115200	$9.10*10^8$
k_2	126900	$3.06*10^{12}$

In order to estimate the distribution temperatures it has been assumed that the DP_0 value was 1257. It has been estimated that the transformer was run for 227760 hours so, t=227760h. Finally, DP_t values were obtained following the steps explained previously.

Once the temperature distributions are obtained for the three windings, the final step is to compare them in order to find out any cause of the short-circuit between turns.

4. Results

The summary of the results obtained are shown in Table I. The details of the calculations and measurements made are not given here because the space necessary would be larger than that available for articles in this conference.

As shown in this table, DP values range from 276.9 to 364.4. If these DP values are plotted as a function of height, differentiating each of the coils and also whether it is an external or internal layer, the figures 1, 2 and 3 can be obtained.

By observing these figures it is found that there is the same aging along the entire height of the coil. It is also observed that the deterioration of paper is similar in both the inner and the outer layer, although overall deterioration of the inner layer is slightly higher than the one of the outer layer.

The DP map allows us to estimate the existing temperature distribution in the transformer during operation, Table II, which is also a valuable tool for estimating the remaining life in similar transformers that work under the same load conditions, from the point of view of paper state.

The temperature profile shows that the maximum temperature inside the transformer is 357.7K. Considering this maximum temperature, which represents the most unfavorable conditions, it is possible to estimate the life of others transformers with similar characteristics and operating conditions. By using Eq. 6 and taking into account that the transformer reaches its end of life when the DP of the paper presents a value around 200. In order to calculate the remaining life of the transformer, the time can be obtained from Eq. 5:

$$k_{1_0} = A * e^{\frac{-E_a}{R*T}} = 9{,}1 * 10^8 * e^{\frac{-115200}{8{,}314*357{,}7}} = 1{,}37 * 10^{-8} \ \left(h^{-1}\right)$$

$$k_2 = A * e^{\frac{-E_a}{R*T}} = 3{,}06 * 10^{12} * e^{\frac{-126900}{8{,}314*357{,}7}} = 8{,}99 * 10^{-7} \ \left(h^{-1}\right)$$

$$t\ \text{(remaining life)} = -\frac{1}{k_2} * \ln\left(1 - \left(\left(\frac{1}{DP_{t_2}} - \frac{1}{DP_{t_1}}\right) * \frac{k_2}{k_{1_0}}\right)\right) =$$

$$\frac{-1}{8{,}99*10^{-7}} * \ln\left(1 - \left(\left(\frac{1}{200} - \frac{1}{276{,}9}\right) * \frac{8{,}99*10^{-7}}{1{,}37*10^{-8}}\right)\right)$$

$$\text{t (remaining life)} = 131400 \ (h) = 15 \ (\textit{años}) \tag{7}$$

Table I. Determination of Degree of Polymerization (DP).

Sample	Height (cm)	Coil	Outer layer (e1), inner layer (e2)	Degree of polymerization
1	50	3	e1_1	309.37
2	50	3	e2_1	286.69
3	40	3	e1_2	282.40
4	40	3	e2_2	325.81
5	30	3	e1_3	290.40
6	30	3	e2_3	288.15
7	19	3	e1_4	276.93
8	19	3	e2_4	307.33
9	10	3	e1_5	316.60
10	10	3	e2_5	313.86
11	2	3	e1_6	277.93
12	2	3	e2_6	326.80
13	50	2	e1_7	298.11
14	50	2	e2_7	286.48
15	40	2	e1_8	296.90
16	40	2	e2_8	297.09
17	30	2	e1_9	326.30
18	30	2	e2_9	279.70
19	20	2	e1_10	301.20
20	20	2	e2_10	354.40
21	10	2	e1_11	289.77
22	10	2	e2_11	297.73
23	0	2	e1_12	284.67
24	0	2	e2_12	336.80
25	45	1	e1_13	363.70
26	45	1	e2_13	361.87
27	10	1	e1_14	333.73
28	10	1	e2_14	364.40
29	5	1	e1_15	343.60
30	5	1	e2_15	300.53

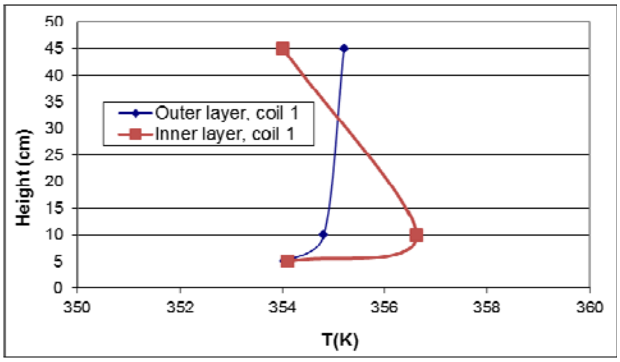

Fig. 1. Temperature distribution in coil1 (it suffered the short-circuit between turns).

Table II. Determination of temperature distribution.

T^a (K)	$(1/DP_t)$ - $(1/DP_0)$	k_{10} $(9.1*10^{8}*e^{(-Ea/R*T)})$	k_2 $(3.06*10^{12}*e^{(-Ea/R*T)})$	$(k_{10}/k_2)*(1-e^{-k2*t})$
356.22	$2.44*10^{-3}$	$1.16*10^{-8}$	$7.53*10^{-7}$	$2.44*10^{-3}$
357.24	$2.69*10^{-3}$	$1.30*10^{-8}$	$8.51*10^{-7}$	$2.69*10^{-3}$
357.44	$2.75*10^{-3}$	$1.33*10^{-8}$	$8.72*10^{-7}$	$2.75*10^{-3}$
355.53	$2.27*10^{-3}$	$1.08*10^{-8}$	$6.93*10^{-7}$	$2.27*10^{-3}$
357.07	$2.65*10^{-3}$	$1.28*10^{-8}$	$8.34*10^{-7}$	$2.65*10^{-3}$
357.17	$2.68*10^{-3}$	$1.29*10^{-8}$	$8.44*10^{-7}$	$2.68*10^{-3}$
357.70	$2.82*10^{-3}$	$1.37*10^{-8}$	$8.99*10^{-7}$	$2.82*10^{-3}$
356.31	$2.46*10^{-3}$	$1.18*10^{-8}$	$7.61*10^{-7}$	$2.46*10^{-3}$
355.91	$2.36*10^{-3}$	$1.13*10^{-8}$	$7.26*10^{-7}$	$2.36*10^{-3}$
356.03	$2.39*10^{-3}$	$1.14*10^{-8}$	$7.36*10^{-7}$	$2.39*10^{-3}$
357.65	$2.80*10^{-3}$	$1.36*10^{-8}$	$8.94*10^{-7}$	$2.80*10^{-3}$
355.49	$2.26*10^{-3}$	$1.07*10^{-8}$	$6.89*10^{-7}$	$2.26*10^{-3}$
356.72	$2.56*10^{-3}$	$1.23*10^{-8}$	$8.00*10^{-7}$	$2.56*10^{-3}$
357.25	$2.69*10^{-3}$	$1.30*10^{-8}$	$8.52*10^{-7}$	$2.69*10^{-3}$
356.77	$2.57*10^{-3}$	$1.24*10^{-8}$	$8.05*10^{-7}$	$2.57*10^{-3}$
356.76	$2.57*10^{-3}$	$1.24*10^{-8}$	$8.04*10^{-7}$	$2.57*10^{-3}$
355.51	$2.27*10^{-3}$	$1.08*10^{-8}$	$6.91*10^{-7}$	$2.27*10^{-3}$
357.57	$2.78*10^{-3}$	$1.35*10^{-8}$	$8.85*10^{-7}$	$2.78*10^{-3}$
356.58	$2.52*10^{-3}$	$1.21*10^{-8}$	$7.86*10^{-7}$	$2.52*10^{-3}$
354.39	$2.03*10^{-3}$	$9.52*10^{-8}$	$6.04*10^{-7}$	$2.03*10^{-3}$
357.10	$2.66*10^{-3}$	$1.28*10^{-8}$	$8.37*10^{-7}$	$2.66*10^{-3}$
356.74	$2.56*10^{-3}$	$1.23*10^{-8}$	8.01E-07	$2.56*10^{-3}$
357.33	$2.72*10^{-3}$	$1.31*10^{-8}$	8.61E-07	$2.72*10^{-3}$
355.08	$2.17*10^{-3}$	$1.03*10^{-8}$	6.56E-07	$2.17*10^{-3}$
355.21	$2.20*10^{-3}$	$1.04*10^{-8}$	6.67E-07	$2.20*10^{-3}$
354.01	$1.95*10^{-3}$	$9.13*10^{-9}$	5.76E-07	$1.95*10^{-3}$
354.81	$2.11*10^{-3}$	$9.97*10^{-9}$	6.35E-07	$2.11*10^{-3}$
356.61	$2.53*10^{-3}$	$1.21*10^{-8}$	7.89E-07	$2.53*10^{-3}$
354.03	$1.95*10^{-3}$	$9.16*10^{-9}$	5.78E-07	$1.95*10^{-3}$
356.13	$2.41*10^{-3}$	$1.15*10^{-8}$	7.45E-07	$2.41*10^{-3}$
354.10	$1.97*10^{-3}$	$9.22*10^{-9}$	5.83E-07	$1.97*10^{-3}$

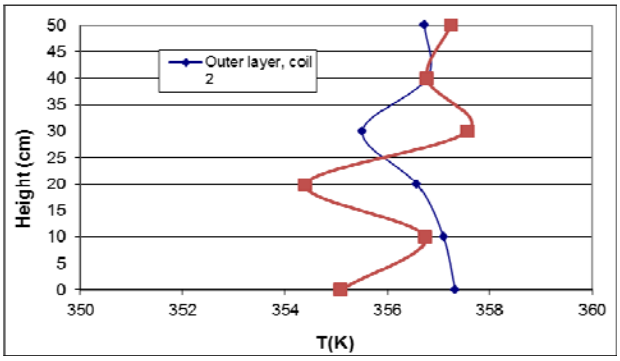

Fig. 2. Temperature distribution in coil2.

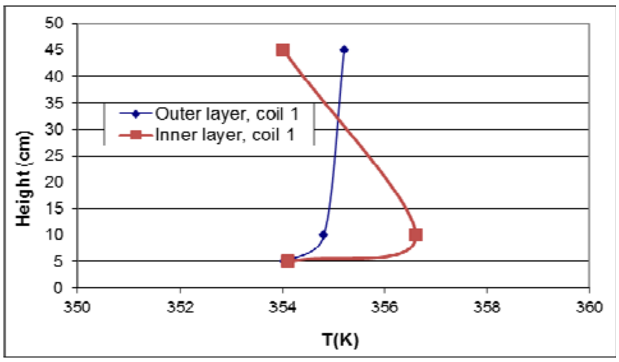

Fig. 3. Temperature distribution in coil3.

5. Conclusions

In this paper the authors have tried to predict the occurrence of a short circuit between turns from the state of degradation of paper insulation in the three windings of a distribution transformer. To achieve this goal the degree of polymerization has been used, which is a direct measure of the state of paper. This technique could be useful to predict potential failures caused by paper degradation in other similar transformers still in operation. The control of the insulation degradation in machines in operation could be performed through indirect methods, as it is the concentration of furans in the oil, which can be carried out with the transformer in service. On the contrary, during operation of the machine is not possible to measure DP values.

The results obtained in this work have shown that for this type of machine, commonly used in distribution networks, it is difficult to predict the occurrence of a short-circuit between turns from the state of degradation of kraft paper.

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