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Assessment of the temperature distribution into a transformer through tensile index

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Abstract. Power transformers are electrical machines which are one of the most critical components in power distribution systems worldwide. Their failure generally is due to the degradation of its insulating system (insulating oil and paper insulation). This deterioration is produced by electrical, mechanical, chemical and thermal stresses which power transformers suffer during their operational lifetime. When dielectric paper has aged severely it loses its tensile strength and its capability to withstand electrical faults decreases considerably. This paper describes an end of life study carried out on a distribution transformer. This analysis has used the tensile index of the dielectric paper to estimate the temperature distribution in the windings of the electric machine. The tensile index is a mechanical parameter 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. These results and the load rate that a transformer has endured during its life can provide useful information for future designs or for similar transformers still in operation.

Key words

Kraft paper, tensile index, power transformer, temperature distribution.

1. Introduction

Transformers represent one of the main equipment of electric energy transmission and generation systems. The failure in-service of these electric machines could lead to the power supply interruption and the capital replacement cost [1, 2]. In order to avoid these problems asset managers must replace aged transformers before failure [3].

Although the expected lifetime of a transformer is considered as around 40 years there is an increasing pressure to prolong power transformer life span because their replacement is expensive and might not be necessary [4-7].

The degradation with the time of the insulating system of a transformer is the main cause of transformers failure. This insulating system consists of cellulosic materials (Kraft paper) and dielectric oil [8]. The oil and other parts of a transformer can be replaced during transformer's life whereas the paper cannot be easily [6]. For this reason, it is considered that paper insulation condition determines the ageing of power transformers.

Different authors have analysed the aging of dielectric paper through the degree of polymerization (DP) which represents the average number of glucose molecules per chain [3, 9]. This parameter is considered to be an indicator for tensile strength of dielectric paper. The paper sampling could not never be carried out during operation and even difficult during active part disassembling in a repair facility [7]. However, it is possible to execute an end-of-life study of a transformer taken out of service. This kind of analysis provide detailed information about the aging status of the transformer. Additionally, it could be possible to estimate the remaining lifetime of transformers wich are identical in their design if loading conditions and maintenance are available [10].

Different authors have published end-of-life studies of scrapped transformers [11-16]. All these works are based on the measuring DP which constitutes one of the most important parameters of the insulation conditions. The chain length of the cellulose molecules determines the mechanical strength which depends on the fiber strength and more importantly, the strength of inter-fiber bonds [8].

This paper has taken paper samples from a failed distribution transformer. From these samples, tensile index (TI) as alternative to degree of polymerization (DP) calculations have been performed for all the windings of the power transformer which were analyzed. The aim is correlate TI map with the temperature distribution into the studied transformer. This approach offers other alternative to the degree of polymerization as a tool to analyze the dielectric paper degradation once a transformer has been taken out service.

2. Transformer description

The study was 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 was 2130 kg, with an insulating liquid mass of 390 kg. The connection of the transformer windings was Dy11 type with a ratio of voltages 30.000/400V. This transformer had been removed from service due to a short-circuit between turns (Figure 1).

Paper samples were taken at different heights in order to calculate TI 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. Table I gathers all the points where paper samples were taken from the windings to determine tensile index. In table I e_1 means that the sample belongs to the external paper strip and e_2 that the sample belongs to the internal paper strip.

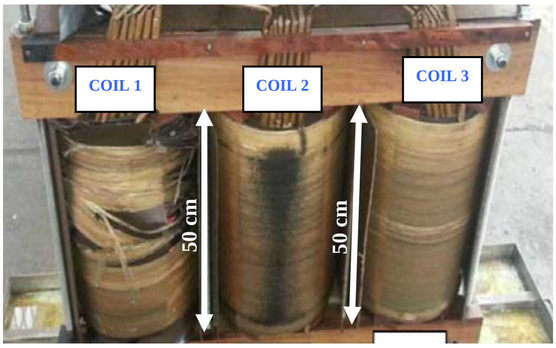

Fig. 1. General view of the studied transformer.

3. Calculation of the temperature distribution into the transformer

Firstly, paper samples were taken out. The next step obtained the TI mapping in accordance with ISO 1924-2 [17]. Once TI results had been obtained the temperature distribution was estimated through cellulose kinetics. In this work, it was considered the relationship defined by [18] who suggested that the relationship between TI, time, temperature and the average chain length (degree of polymerization, DP) can be represented by:

$$TI_t - TI_0 = K_1 \cdot e^{-k_2 \cdot t} + K_2 \cdot \ln\left(e^{k_2 \cdot t} - K_3\right) - K_4 \quad (1)$$

$$K_1 = \frac{k_3 \cdot k_{1_0}}{k_2} \quad (2)$$

$$K_2 = k_4 \cdot K' \quad (3)$$

$$K_3 = k_{1_0} \cdot K' \quad (4)$$

$$K_4 = K_2 \cdot \left(\ln\left(1 - K_3\right)\right) + K_1 \quad (5)$$

$$K' = \frac{DP_0}{DP_0 \cdot k_{1_0} + k_2} \quad (6)$$

where:
TIt is the insulation tensile index value at time t TI0 is the initial insulation tensile index value
t is the time in seconds
DP_0 is the initial degree of polymerization value
k_{10}, k_2, k_3 and k_4 are temperature dependent rate coefficients

Assuming that the Arrhenius equation is valid from the normal operating temperature of power transformers up to the temperatures used in ageing experiments, the coefficients k_{10}, k_2, k_3, and k_4 can be obtained by applying the following equation:

$$k = A \cdot e^{-\frac{E_a}{R \cdot T}} \quad (7)$$

where:
k: rate coefficient
A: pre-exponential factor
E_a: activation energy
R: molar gas constant (8.314 J/mol/K)
T: temperature (K)

Table I. - Description of dielectric samples

SAMPLE	HEIGHT (m)	COIL	OUTER LAYER (e1) INNER LAYER (e2)	GRAMMAGE (kg/m^2)
1	0.50	3	e1	0.12
2	0.50	3	e2	0.12
3	0.40	3	e1	0.12
4	0.40	3	e2	0.12
5	0.30	3	e1	0.12
6	0.30	3	e2	0.12
7	0.19	3	e1	0.12
8	0.19	3	e2	0.12
9	0.10	3	e1	0.12
10	0.10	3	e2	0.12
11	0.02	3	e1	0.12
12	0.02	3	e2	0.12
13	0.50	2	e1	0.12
14	0.50	2	e2	0.12
15	0.40	2	e1	0.12
16	0.40	2	e2	0.12
17	0.30	2	e1	0.12
18	0.30	2	e2	0.12
19	0.20	2	e1	0.12
20	0.20	2	e2	0.12
21	0.10	2	e1	0.12
22	0.10	2	e2	0.12
23	0	2	e1	0.12
24	0	2	e2	0.12
25	0.45	1	e1	0.12
26	0.45	1	e2	0.12
27	0.10	1	e1	0.12
28	0.10	1	e2	0.12
29	0.05	1	e1	0.12
30	0.05	1	e2	0.12

Knowing the values of activation energy (Ea) and preexponential factor (A) (Table II), obtained through accelerated ageing experiments performed in the laboratory, it is possible to calculate the coefficients k_{10}, k_2, k_3 and k_4.
In order to estimate the temperature distributions, samples of new paper were analysed, determining that DP_0 and TI_0 values were 1257 and 553 (kN/m kg), respectively. It was estimated that the transformer had been run for 227760 hours, so t = 227760 h.

Table II. Arrhenius parameters for Kraft paper in oil.

	E_a (J/mol)	A (s^{-1})
k_{10}	115,200	2.53×10^5
k_2	126,900	8.50×10^8
k_3	-43,700	2.17×10^{-5}
k_4	5.54×10^{-2}	4.44×10^{-10}

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

Table III. - Tensile index estimation.

SAMPLE	LOAD (N)	TENSILE INDEX (kNm/kg)
1	649.73	282.37
2	643.82	279.82
3	628.58	273.17
4	637.30	276.97
5	633.93	275.50
6	707.87	307.64
7	651.80	283.27
8	602.50	261.84
9	554.25	240.87
10	522.99	227.29
11	670.02	291.19
12	657.82	285.88
13	658.43	286.15
14	550.01	239.03
15	557.15	242.13
16	646.59	281.00
17	667.36	290.03
18	621.53	270.11
19	695.60	302.30
20	673.99	292.91
21	547.48	237.93
22	667.62	290.14
23	613.13	266.46
24	659.38	286.56
25	750.75	326.27
26	724.27	314.77
27	651.91	271.56
28	522.71	227.17
29	609.09	264.71
30	605.80	263.28

4. Results

The paper samples of the three transformer coils were analysed to obtain the tensile index (Ti_t), according to the ISO 1924-2 standard, as was already explained above. TI_t average values (inner and outer layer) range from 227.17 (kNm/kg) to 326.27 (kNm/kg).
From the analysis of TI_t, it has been obtained that the maximum deviation between inner and outer layer was 8.17%, although in most of the samples analysed (80%) the difference in the value of the tensile strength index between layers was less than 5%.
These results showed that there is higher deterioration at 0.1 m in almost all coils.
From TI_t maps, the temperature distribution throughout the transformer windings was estimated using equations (1)-(7). The estimated temperatures are gathered in Table IV. The maximum estimated temperature in the windings using the tensile index, is 357.35 K. This temperature represents the most unfavourable conditions on the high voltage windings surface.
Considering this maximum temperature, is possible to estimate the remaining life of others transformers that possess similar characteristics and operating conditions. By using equations (1)-(7) and taking into account that the transformer reaches its end of life when the TI_t reduces its value below 50% of TI_0 it would be possible calculate the time that any similar transformer might operate. In order to calculate this remaining life of the transformer, the time can be obtained from equation (1). In this case of study, around the 50% of the TI_t measures possess values below 50% of the initial value of the tensile index, so any similar transformer would have reached its end of life.
The TI_t map allows to estimate the existing temperature distribution in the transformer during operation. For this reason, the tensile index is a valuable tool for estimating the remaining life in similar transformers that work under the same load conditions under the point of view of paper degradation.

5. Conclusions

The aim of this paper has been 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 tensile index (TI), which is a direct measure of the state of paper, has been measured. 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. This method can be carried out with the transformer in service. On the contrary, during operation of the machine is not possible to measure TI 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.

Table IV. - Estimation of temperature distribution.

TENSILE INDEX (TI_t)	k_{10}	k_2	k_3	k_4	K'	K_3	K_1	K_4	K_2	T^a (K)
282.37	$1.13*10^{-8}$	$7.27*10^{-7}$	202679.75	$1.60*10^{-6}$	84427699.95	0.95	3142.49	2734.55	135.08	355.92
279.82	$1.13*10^{-8}$	$7.32*10^{-7}$	202117.20	$1.60*10^{-6}$	83808311.00	0.95	3131.43	2726.59	134.09	355.99
273.17	$1.16*10^{-8}$	$7.48*10^{-7}$	200664.50	$1.60*10^{-6}$	82221943.94	0.95	3102.93	2705.99	131.55	356.16
276.97	$1.14*10^{-8}$	$7.39*10^{-7}$	201489.58	$1.60*10^{-6}$	83120624.56	0.95	3119.11	2717.69	132.99	356.06
275.50	$1.15*10^{-8}$	$7.43*10^{-7}$	201172.42	$1.60*10^{-6}$	82774462.10	0.95	3112.89	2713.19	132.44	356.10
307.64	$1.05*10^{-8}$	$6.70*10^{-7}$	208386.79	$1.60*10^{-6}$	90872724.58	0.95	3255.08	2814.98	145.39	355.25
283.27	$1.12*10^{-8}$	$7.24*10^{-7}$	202881.70	$1.60*10^{-6}$	84650738.99	0.95	3146.46	2737.41	135.44	355.90
261.84	$1.19*10^{-8}$	$7.75*10^{-7}$	198220.40	$1.60*10^{-6}$	79595360.14	0.95	3055.09	2671.23	127.35	356.46
240.87	$1.27*10^{-8}$	$8.27*10^{-7}$	193824.17	$1.60*10^{-6}$	75003601.52	0.95	2969.45	2608.42	120.00	357.00
227.29	$1.32*10^{-8}$	$8.63*10^{-7}$	191049.21	$1.60*10^{-6}$	72192125.75	0.95	2915.66	2568.58	115.50	357.35
291.19	$1.10*10^{-8}$	$7.07*10^{-7}$	204641.48	$1.60*10^{-6}$	86609872.76	0.95	3181.10	2762.28	138.57	355.69
285.88	$1.11*10^{-8}$	$7.19*10^{-7}$	203455.11	$1.60*10^{-6}$	85286051.18	0.95	3157.74	2745.52	136.45	355.83
286.15	$1.11*10^{-8}$	$7.18*10^{-7}$	203514.25	$1.60*10^{-6}$	85351734.76	0.95	3158.90	2746.36	136.56	355.82
239.03	$1.27*10^{-8}$	$8.32*10^{-7}$	193440.90	$1.60*10^{-6}$	74611315.53	0.95	2962.01	2602.92	119.38	357.05
242.13	$1.26*10^{-8}$	$8.24*10^{-7}$	194080.15	$1.60*10^{-6}$	75266329.12	0.95	2974.43	2612.09	120.42	356.97
281.00	$1.13*10^{-8}$	$7.30*10^{-7}$	202385.66	$1.60*10^{-6}$	84103540.82	0.95	3136.71	2730.39	134.56	355.96
290.03	$1.10*10^{-8}$	$7.09*10^{-7}$	204386.60	$1.60*10^{-6}$	86324390.34	0.95	3176.07	2758.68	138.12	355.72
270.11	$1.17*10^{-8}$	$7.55*10^{-7}$	200000.57	$1.60*10^{-6}$	81503196.84	0.95	3089.92	2696.56	130.40	356.24
302.30	$1.06*10^{-8}$	$6.82*10^{-7}$	207158.51	$1.60*10^{-6}$	89460665.32	0.95	3230.78	2797.73	143.13	355.40
292.91	$1.09*10^{-8}$	$7.03*10^{-7}$	205041.52	$1.60*10^{-6}$	87059124.53	0.95	3188.98	2767.92	139.29	355.64
237.93	$1.28*10^{-8}$	$8.35*10^{-7}$	193209.77	$1.60*10^{-6}$	74375354.69	0.95	2957.52	2599.61	119.00	357.08
290.14	$1.10*10^{-8}$	$7.09*10^{-7}$	204412.07	$1.60*10^{-6}$	86352894.04	0.95	3176.58	2759.04	138.16	355.72
266.46	$1.18*10^{-8}$	$7.64*10^{-7}$	199215.40	$1.60*10^{-6}$	80658249.85	0.95	3074.55	2685.39	129.05	356.34
286.56	$1.11*10^{-8}$	$7.17*10^{-7}$	203607.21	$1.60*10^{-6}$	85455059.21	0.95	3160.73	2747.67	136.73	355.81
283.31	$1.12*10^{-8}$	$7.24*10^{-7}$	202890.12	$1.60*10^{-6}$	84660045.71	0.95	3146.62	2737.53	135.45	355.90
326.27	$1.32*10^{-8}$	$8.63*10^{-7}$	191025.62	$1.60*10^{-6}$	72168511.79	0.95	2915.20	2568.24	115.47	354.75
314.77	$1.02*10^{-8}$	$6.55*10^{-7}$	210043.22	$1.60*10^{-6}$	92798825.44	0.95	3287.92	2838.19	148.47	355.06
271.56	$1.16*10^{-8}$	$7.52*10^{-7}$	200315.63	$1.60*10^{-6}$	81843775.05	0.95	3096.09	2701.03	130.95	356.20
227.17	$9.91*10^{-8}$	$6.31*10^{-7}$	212769.11	$1.60*10^{-6}$	96023409.27	0.95	3342.11	2876.24	153.63	357.35
264.71	$1.18*10^{-8}$	$7.68*10^{-7}$	198836.47	$1.60*10^{-6}$	80252429.62	0.95	3067.14	2680.00	128.40	356.38
263.28	$1.19*10^{-8}$	$7.72*10^{-7}$	198532.27	$1.60*10^{-6}$	79927565.97	0.95	3061.19	2675.67	127.88	356.42

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