Postmortem estimation of temperature distribution on a power transformer: Physicochemical and Mechanical approaches

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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, 3, 4]. Therefore knowing transformers condition is essential to manage large networks [5, 3].
The transformers' life span is determined amongst other parameters by the condition of the solid insulation, particularly at the hot spot [6]. The primary solid 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 [7]. The three main processes for cellulose degradation are hydrolysis, oxidation, and pyrolysis [8-10]. 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 (CO_2), organic acids, water and free glucose molecules. The glucose rings can decompose further into furans [11].
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 [12-14]. Nevertheless, these techniques are macro in respect to the entire insulation system where may exist a significant thermal gradient [6]. The hot-spot temperature is one of the most critical parameter to estimate the remaining lifetime of solid insulation [4, 5]. 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 [3, 15-20]. 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 [2, 21]. 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 postmortem investigation of the solid insulation is performed [6].
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 [5-6, 22-26]. For instance, Koch et al. investigated new approaches to determine water in oil-paper-insulated power transformers to conform diagnostic

parameters to postmortem investigations as well as, correlations between the furan (2-FAL) concentration in the oil and the average DP [10, 23-24]. 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 furanes. 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 [5, 26]. 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 [6]. Other situation where accurate paper degradation diagnostic could be useful was described by Martins et al. [25]. 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 and compared them.

The combination of the results from service history and postmortem 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 postmortem studies have been based on DP which constitutes one of the most important parameters of the insulation condition [2]. 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 degradation cellulose's [27, 28]. Moser et al. established that both tensile strength index and DP decrease exponentially during ageing at constant temperature [29] Therefore, it is possible evaluate the aging of paper through the tensile strength index. In this work paper samples were taken from a failed distribution transformer to determine DP and tensile strength index (TS). Later, the distribution temperature was obtained through DP and TS results. The two temperature distributions were compared in order to show the suitability of tensile analysis for a postmortem study. The main reason to use tensile strength index instead of DP is that the first one could be carried out more quickly. Additionally, TS test is much more reliable than DP test. This new approach can serve to obtain additional information about the cause of the turn-to-turn shortcircuit fault suffered by this transformer.

2. Transformer description

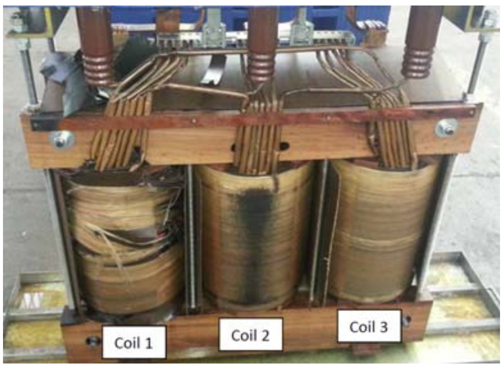

Fig. 1. Transformer studied: State of the three windings.

The tests were conducted using the isolation paper of a three-phase transformer with a rated power of 800kVA at 50Hz and manufactured in 1986 with a ONAN cooling system .The total weight of the transformer is 2130kg, with a mass of liquid insulating equal to 390 kg. The connection of the transformer windings is Dy11 type, with a voltage ratio 30.000/400V.

The transformer suffered a short circuit between turns in one of the coils and had to be withdrawn from service after 26 years of operation. This type of distribution transformers are not monitored, so there are no measures that indicate the progress of the dielectric system degradation. Fig. 1 shows the damage that the fault causes in the transformer.

3. Methodology to obtain temperature distribution into the transformer

This work has followed the methodology shown in Fig. 2 in order to demonstrate the suitability of TS for temperature distribution evaluation in postmortem studies:

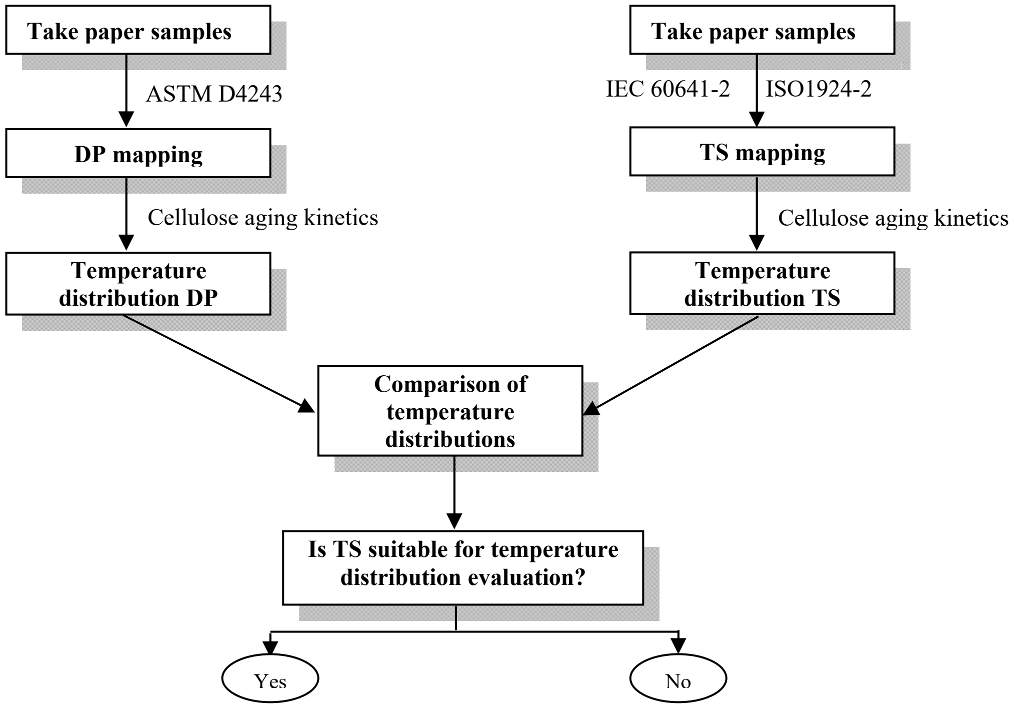

Fig. 2. Methodology applied in this work.

3.1.- Samples collection

Each coil has a height of 50 cm and paper samples were taken at different heights in order to calculate the tensile index and the degree of polymerization. This allowed us to observe the degradation distribution along the coils. In Fig. 3, the two layers of paper for insulating the phases can be observed, inner and outer strips. Paper samples were taken from both layers and were analyzed during the tests to see their real state. In Table 1 below, the heights of the points at which the paper samples were taken from the coils for further analysis are recorded. e1 means that the sample comes from the outer strip of paper. e2 means that the sample comes from the inner strip of paper.

Fig. 3. Transformer studied: Detail of the inner and outer paper layers.

Table 1
Samples analyzed: height, coil number and type of layer.

Sample	Height (cm)	Coil	Outer layer (e1), Inner layer(e2)
1	50	3	e1_1
2	50	3	e2_1
3	40	3	e1_2
4	40	3	e2_2
5	30	3	e1_3
6	30	3	e2_3
7	19	3	e1_4
8	19	3	e2_4
9	10	3	e1_5
10	10	3	e2_5
11	2	3	e1_6
12	2	3	e2_6
13	50	2	e1_7
14	50	2	e2_7
15	40	2	e1_8
16	40	2	e2_8
17	30	2	e1_9
18	30	2	e2_9
19	20	2	e1_10
20	20	2	e2_10
21	10	2	e1_11
22	10	2	e2_11
23	0	2	e1_12
24	0	2	e2_12
25	10	1	e1_13
26	10	1	e2_13
27	5	1	e1_14
28	5	1	e2_14
29	45	1	e1_15
30	45	1	e2_15

3.2.- DP and TS mapping

Once paper samples were collected, in the next step DP and TS values were measured in accordance with ASTM D4243, IEC 60641-2 and ISO1924-2 [30-32].

The ASTM D4243 test method describes a standard procedure for determining the average viscometric degree of polymerization (abbreviated DP_v) of new or aged electrical papers. The determination is made by measuring the intrinsic viscosity of a solution of the paper in an appropriate solvent (cupriethylene–diamine). The degree of polymerization (or the degree of condensation) of a particular cellulose molecule is the number of anhydro-b-glucose monomers, $C_6H_{10}O_5$, in the cellulose molecule.

In IEC60641-2 the tests methods for pressboard and presspaper for electrical purposes are described. ISO1924-2 details the determination of tensile properties of paper. Tensile force is measured under standardized test conditions to cause failure of test pieces 15 mm × 250 mm cut from both directions of the material. This value represents quite well the current state of paper samples. The tensile strength index, in kN m/kg, is calculated by the formula: *TS =F/(wxb)*. Where *F* is the force, in kN; b is the width of the specimen, in m; and *w* is the grammage of the specimen, in kg/m^2.

3.3.- Temperature distribution

Once DP and TS results have been obtained the temperature distributions were estimated through cellulose kinetics. Different authors have reported the relationship between DP, time and temperature [13, 27]. In this work, it has been considered the relationship defined by Heywood [33] who suggested that the rate of change of DP can be represented by:

$$\frac{1}{DP_t} - \frac{1}{DP_0} = \frac{k_{1_0}}{k_2} * \left[1 - e^{-k_2 * t}\right] \quad (1)$$

where k_{1_0} is the initial rate at which bonds break, k_2 is the rate at which k_{1_0} 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.
Heywood also proposed in his thesis a model which relates the average chain length (DP) with the fibre strength:

$$TS_t - TS_0 = K_1 * e^{-k_2 * t} + K_2 * \left(\ln\left(e^{k_2 * t} - K_3\right)\right) - K_4 \tag{2}$$

Where

$$K_1 = \frac{k_3 * k_{1_0}}{k_2} \tag{3}$$

$$K_2 = k_4 * K' \tag{4}$$

$$K_3 = k_{1_0} * K' \tag{5}$$

$$K_4 = K_2 * (\ln(1 - K_3)) + K_1 \tag{6}$$

$$K' = \frac{DP_0}{DP_0 * k_{1_0} + k_2} \tag{7}$$

TS_t is the insulation tensile strength index value at time t, TS_0 is the initial insulation tensile strength index value and t is the time in hours.

Assuming that the Arrhenius equation is valid from the normal operating temperature of power transformers up to the temperatures used in aging experiments [27], the constants k_{10}, k_2, k_3, and k_4 can be obtained by applying the following equation:

$$k = A * e^{-\frac{E_a}{R*T}} \tag{8}$$

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

Knowing the values of activation energy (E_a) and pre-exponential factor (A), obtained through accelerated aging experiments performed in the laboratory, it is possible to calculate the constants k_{10}, k_2, k_3, and k_4.

Table 2
Arrhenius parameters for Kraft paper in oil.

	E_a (J/mol)	**A (h^{-1})**
k_{1_0}	115200	$9.10*10^{8}$
k_2	126900	$3.06*10^{12}$
k_3	-43700	$7.82*10^{-2}$
k_4	$5.54*10^{-2}$	$1.60*10^{-6}$

In order to estimate the temperature distributions, samples of new paper has been analysed, determining that DP_0 and TS_0 values were 1257 and 553 (kN/mKg), respectively. Taking into account the date in which the transformer was connected to the distribution network, the total period of operation considered is 227760 hours so, t= 227760 h. The data obtained on the mapping stage for each sample give DP_t and

TS_t. With all these data and the Eqs. (1)-(2) the temperature distribution on each coil of the transformer can be obtained. In the next section of this paper a comparison between these results is performed.

4. Results

With the paper samples taken from the three coils of the transformer, the degree of polymerization (DP) was analysed in a viscometric environment, following the ASTM D4243 standard, as it was already explained above. The summary of the results obtained for the DP in each winding of the transformer is shown in Table 3. As seen in this table, the values of DP range from 276.9 to 364.4. The results reported in the table show that the degree of aging along the entire height of the coil is quite homogeneous. Similarly, one can also observe that the deterioration of the paper is similar in both the inner and the outer layer, although overall deterioration of the inner layer is somewhat less than the outer layer.

In like manner, the paper samples of the three transformer coils were analysed by obtaining the tensile strength index (TS), according to the ISO1924-2 standard, as already explained above. The summary of the results obtained for the tensile index are shown in Table 3. TS values range from 227.1 to 326.2. These results showed that, like the DP map, aging along the entire height of the coil is quite similar. Unlike what happened in the map of DP in the case of TS exists higher deterioration at 10cm in almost all coils. Moreover, from the TS point of view, there are no clear differences between the outer and the inner strips, except at the coil that suffered the short circuit.

From DP and TS maps, the temperature distribution throughout the transformer windings was estimated using Eqs. (1)-(2). In Figs. 4-9, the estimated temperatures for each point are shown, considering the two methodologies, differentiating each coil and the inner from the outer layer.

In the coil 1, where the short-circuit appeared, the greatest differences between the temperature estimate performed by both methods are seen, these being reasonably low. The estimate carried out by the DP method provides lower values for all points in the inner layer and for two of the three points analysed in the outer one. In the samples taken at 10 and 45cm, the highest differentials are shown with 3.3K and 2.1K, respectively. In the coil 2 the two methods are closer than in the previous case, differences varying between 1.3K and 0.018K. The coil 3 also shows similar temperature distributions for both methodologies, fluctuating between 1.9K and 0.2K.

The maximum temperature estimated from DP in the windings is 358.5K. And the temperature profile obtained from the tensile index shows that the highest temperature in the surface of the coils is 358.2K, which is slightly lower than the maximum temperature obtained from the map of DP. These maximum temperatures represent the most unfavourable conditions on the high voltage winding surface.

Table 3
Determination of DP and TS.

Sample	Eflux time of the solution (s)	Specific viscosity [η_s]	Concentration [c] (g/dl)	[η] * c	Intrinsic viscosity [η]	Degree of polymerization [DP]	Grammage (kg/m^2)	Tensile index (kNm/Kg)
1	203.46	0.41	0.16	0.36	2.32	309.37	0.12	282.37
2	184.52	0.28	0.12	0.25	2.15	286.69	0.12	279.82
3	192.08	0.33	0.14	0.30	2.12	282.40	0.12	273.17
4	194.00	0.34	0.13	0.31	2.44	325.81	0.12	276.97
5	193.13	0.33	0.14	0.30	2.18	290.40	0.12	275.50
6	189.63	0.39	0.13	0.28	2.16	288.15	0.12	307.64
7	187.02	0.29	0.13	0.27	2.08	276.93	0.12	283.27
8	184.10	0.27	0.11	0.25	2.31	307.33	0.12	261.83
9	204.61	0.41	0.16	0.37	2.37	316.60	0.12	240.85
10	179.12	0.24	0.09	0.22	2.35	313.86	0.12	227.29
11	184.50	0.28	0.12	0.25	2.08	277.93	0.12	291.19
12	193.21	0.34	0.12	0.30	2.45	326.80	0.12	285.88
13	181.73	0.26	0.11	0.24	2.24	298.11	0.12	286.15
14	168.57	0.16	0.07	0.16	2.15	286.48	0.12	239.03
15	194.41	0.34	0.14	0.31	2.23	296.90	0.12	242.13
16	179.20	0.24	0.10	0.22	2.23	297.09	0.12	281.01
17	178.22	0.23	0.09	0.22	2.45	326.30	0.12	290.03
18	176.13	0.22	0.10	0.20	2.10	279.70	0.12	270.11
19	179.47	0.24	0.10	0.22	2.26	301.20	0.12	302.30
20	184.25	0.27	0.10	0.25	2.66	354.40	0.12	292.91
21	194.88	0.35	0.14	0.31	2.17	289.77	0.12	237.93
22	186.23	0.29	0.12	0.26	2.23	297.73	0.12	290.14
23	177.82	0.23	0.01	0.21	2.14	284.67	0.12	266.46
24	180.22	0.25	0.09	0.23	2.53	336.80	0.12	286.57
25	196.70	0.36	0.12	0.32	2.73	363.70	0.12	326.27
26	198.87	0.37	0.12	0.34	2.71	361.87	0.12	227.17
27	192.31	0.33	0.12	0.30	2.50	333.73	0.12	271.56
28	179.19	0.24	0.08	0.22	2.73	364.40	0.12	283.31
29	179.95	0.24	0.09	0.23	2.58	343.60	0.12	264.71
30	181.73	0.26	0.01	0.24	2.25	300.53	0.12	263.28

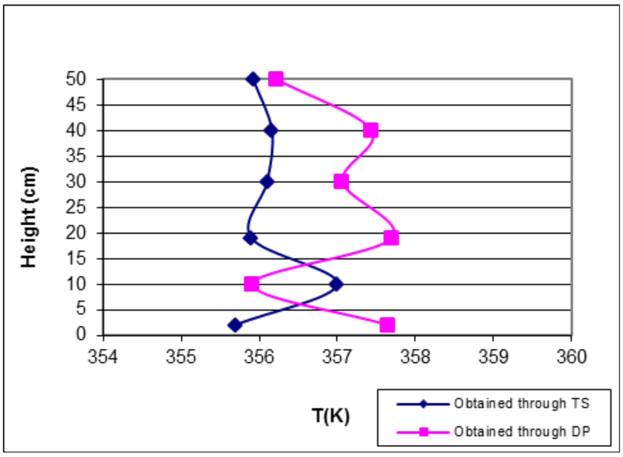

Fig. 4. Comparison of temperatures obtained through DP and TS (outer layer, coil 3).

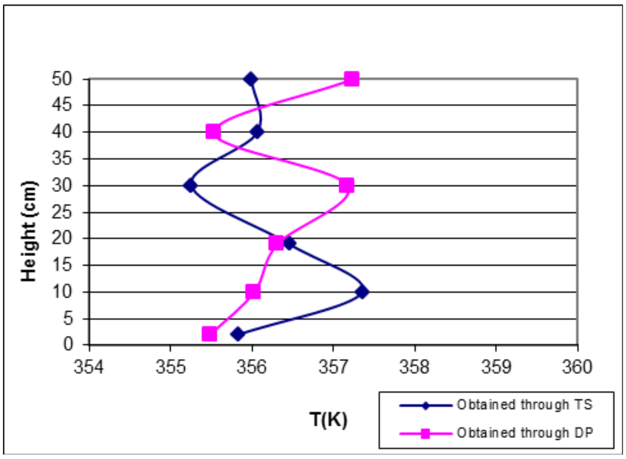

Fig. 5. Comparison of temperatures obtained through DP and TS (inner layer, coil 3).

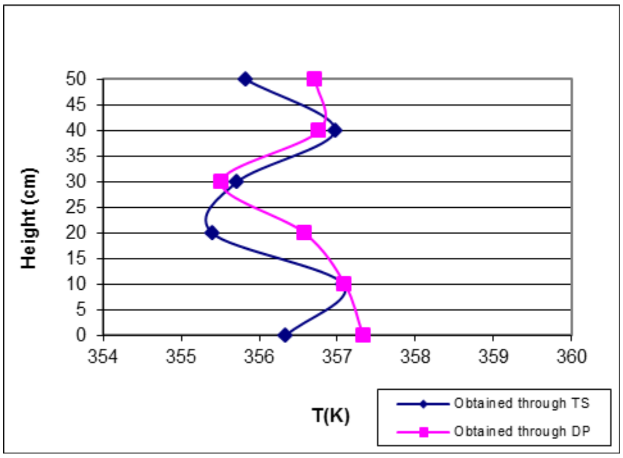

Fig. 6. Comparison of temperatures obtained through DP and TS (outer layer, coil 2).

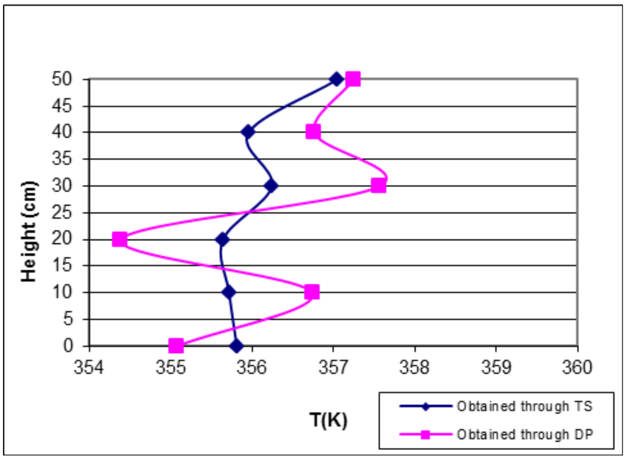

Fig. 7. Comparison of temperatures obtained through DP and TS (inner layer, coil 2).

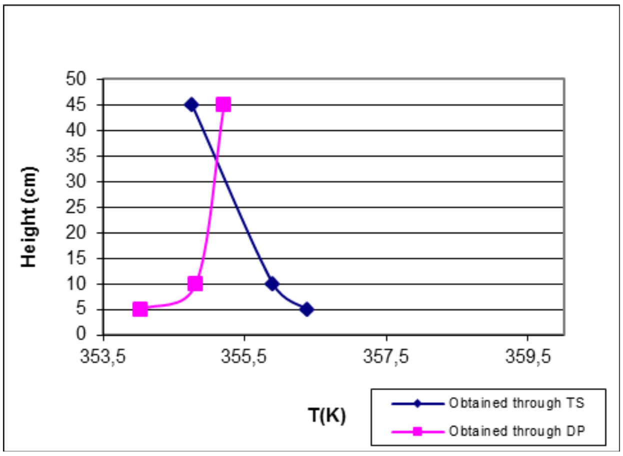

Fig. 8. Comparison of temperatures obtained through DP and TS (outer layer, coil 1).

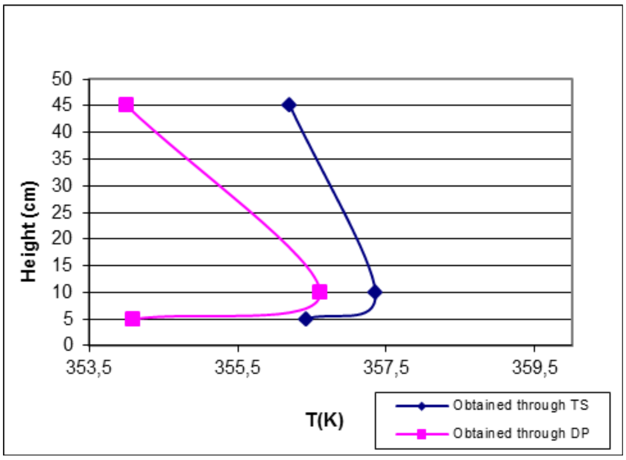

Fig. 9. Comparison of temperatures obtained through DP and TS (inner layer, coil 1).

5.- Conclusions

This work has carried out a postmortem temperature estimation of a distribution transformer. The study involved the evaluation of paper condition in the surface layer of the high voltage coils that insulates the machine. Two properties of the paper have been analyzed, providing information about its level of degradation. The first is the degree of polymerization and the second is the tensile strength index. Previous postmortem studies had only used the degree of polymerization for determining the status of the dielectric paper. The aim of this study was to test the suitability of the tensile strength index to perform postmortem studies. To do so the temperature distribution is obtained from the tensile strength index along the transformer windings. Once obtained this temperature distribution, it is compared with that determined from the degree of polymerization of the same paper samples.

The comparison of the two temperature distributions showed that the maximum difference for the same point is less than 3.3K. There are some points where the values obtained from DP and TS were almost coincident. The two methods have proven valid for postmortem study of transformers, the tensile strength index being a more reliable and repeatable indicator. The test giving the tensile stress is carried out more quickly than the one serving to obtain the degree of polymerization. While the first one may take 10 minutes per sample, the second one usually takes a few days per sample, and it is also much more laborious to obtain. Furthermore, the paper sample required to perform the degree of polymerization test is very small compared to the one required by the standard in the case of the tensile test, where the samples size must be 15x250mm. This sample size is very difficult to obtain in postmortem studies, because the paper is very weathered and is very fragile. The latter would be the main disadvantage of this type of test.

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