

Transformer health indices calculation considering hot-spot temperature and load index

Key words: health index, hot spot temperature, transformers, dielectric oil

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This article presents a method that considers the study of the hot spot temperature in the calculation of a health index describing the condition of power transformers in service.

Introduction

The state of a transformer depends on many parameters, which should be taken into account to determine its actual condition. In recent years, it has been defined what is known as health indexes of transformers, which is a practical tool to assess the overall status of these electrical devices. Data from field inspection, laboratory tests, and observations during operation of the transformer are combined. All these results in an index that provides fairly objective and quantitative information as to the condition of the transformer [1].

Most health indices proposed combine electrical testing, oil testing, visual inspection as well as additional information such as the age of the transformer, loading, and environmental conditions. The condition of the transformer is estimated through a weighted sum of the indices associated with each diagnostic parameter. The parameters considered by various authors in the calculation of health indices are listed in the following paragraphs.

The actual age, the life expected by the manufacturer, and the environmental conditions of the transformer location are taken into account in determining the health index [2]. The winding temperature is also used [3], this information being used to estimate the machine elapsed life, which is based on empirical formulae.

The load history of the transformer could be useful for the health index calculation. Aside from the average load, the peak loads in certain periods should be considered. For example, we need to know the peak load in each month over the past 12 months [4]. The formula proposed by [1], only considers the last four measures of the "track record", outweighing the most recent. Each researcher has proposed a different way of dealing with these data.

Although some researchers [1], [4] do not distinguish between power factor values recommended for transformers of different capacities, it would be appropriate to establish a classification. Another group of data considered for transformer condition evaluation are the electrical resistance of the windings, the leakage reactance, the ground isolation and the state of the bushings, focusing on oil leaks, the state of porcelain, and the level and color of the oil [4].

The physical and dielectric properties of oil are the most common variables monitored by managers of

transformer assets. They include dielectric strength, acidity, moisture, dissipation factor, and in the vast majority of cases, the color and the interfacial tension of oil. When using the data of the dielectric strength, it must be taken into account the standard used, since the distance between the electrodes may be different. For dissipation factor, it is necessary to consider the temperature at which it was measured. Along with the previous variables, the furans concentration and the dissolved gasses in oil, form part of the typical analysis performed to the transformers oil. Regarding oil, other parameters to be checked are the level and possible leaks.

The general condition of a transformer could be based on visual inspections, a check of the condition of the seals, sound, vibration, ground, foundation or animal protection [4]. The state of the tank and the refrigeration system should be also observed.

The tap changer is usually evaluated separately. Various researchers [1], [3], [4] have weighted a split of 60% on the general data of the transformer and 40% on the tap changer evaluation. Tap changers need to be checked for oil quality, dissolved gasses and the general condition. Finally, the status of the protection equipment could be taken into account; for example, overload, lightning, pressure, as well as other parameters.

As noted, considerable data are necessary, and many of them depend on the subjective judgment of the technician performing the evaluation, such as the state of the foundations, the bushings or the tank. Furthermore, the researchers often explain vaguely the criteria used to evaluate such factors. This can result in different health indexes for the same transformer, depending on the technician who performed the evaluation.

This article proposes adding to the parameters used in determining the health index of a transformer [1]-[7], the temperature distribution along the windings depending on the load, which would provide a more accurate measure of the state of a transformer.

Basic Health Index

The first step in this work was to select a basic health index. This should be based on clearly defined quantitative values and measurements routinely performed by managers of transformer assets. The basic health index chosen was the one proposed in [2], which consists of four subindexes, three of them analyze aspects such as paper, dissolved gases and oil quality, while the fourth evaluates transformer aging. This article proposes an alternative calculation for the subindexes considering the paper condition and transformer ageing.

The subindex that evaluates the state of the insulating paper consists of two factors, the first of which takes into account the content of gases composed of carbon-oxygen and the second factor considers the content in 2FAL dissolved in oil. The weights assigned to both factors are 30% and 70%, respectively.

The subindex that evaluates transformer aging increases with the time of operation following an exponential function described by (1). This subindex depends on the initial factor, $HI(0)$, an aging coefficient, B , and the year in which the initial factor and the current state of the transformer are considered, t_1 and t_2 . Thus,

$$Aging = HI(0) \cdot e^{B(t_2 - t_1)} \quad (1)$$

The factor $HI(0)$ indicates the state in which the transformer starts its operation. This value is usually 0.5 [2]. When a transformer reaches its end of life, this factor has a value close to 6.5. With these values and the expected life, t_{exp} , given by the manufacturer, B can be calculated from (2):

$$B = f_L \cdot \frac{\ln(6.5/0.5)}{t_{exp}} \quad (2)$$

where f_L is the load factor as given in Table 1.

Table 1. Load factor as a function of percent load [2]

Load (%)	Load factor (f_L)
0 – 40	1
40 – 60	1.05
60 – 70	1.1
70 – 80	1.25
80 – 150	1.6

Analyzing these two subindexes proposed in [2], it can be observed that there are certain problems in their calculation. For example, in the case of the subindex that evaluates the state of the insulating paper, it has been shown that in old transformers, it is not very accurate, since the concentration of furan and carbon-oxygen compounds are no longer a reference of the degradation degree, which compromises subindex reliability [10]. In the case of the subindex observing transformer aging, this considers very large load intervals, leading to a load factor (f_L) that is relevant to any variable that can be determined or measured from the operating point of the machine.

An improvement of the health index presented previously will be introduced by taking into consideration the effect of the hot spot temperature in the windings into the subindex assessing the degradation of the paper insulation, and also, in the subindex that assesses the aging condition of the transformer.

Methodology for Improving the Accuracy of the Health Index

In the available literature on health indices there are no references that take into account the exact calculation of the hot spot temperature in the windings, which ultimately is the most unfavorable condition for insulating paper degradation.

The operation of power transformers is characterized by efficiency. A low efficiency means a loss of power that becomes heat. Power transformers are characterized by an optimum load where losses are minimal and the performance maximum. Thus, in any operating point where the load exceeds the optimum one the losses will increase, and accordingly, the temperature inside the transformer increases. The temperature increase favors the degradation of dielectric materials in the transformador, oil and paper. Specifically, it is the paper insulation that suffers greater deterioration with increasing temperature. In this sense, it seems necessary to predict as accurately as possible the location and temperature of the hot spot affecting the paper that covers the windings, as it will be at that point where greater degradation occurs.

The groundwork for introducing this concept in health indices is described in the following methodology:

- The hot-spot temperature is determined by software based on the finite element method, in which it is necessary to define the winding geometry, a fluid-thermal model that considers a transformer under load, and the characteristics of the materials making up the winding.
- Subsequently, the heat source is modified, i.e. the level of current through the conductors of the winding. Thus, the heat produced when different currents circulate in the windings is calculated. These values are in a range from the optimal load to full load.
- As a result of the previous step, an equation relating the load index with the hot spot temperature is obtained. Therefore, the rate of aging of the insulation system can be related to the load index at which the transformer operates.
- The load factor f_L proposed in [2], can be calculated more accurately using the above equation. This variable would correspond to any value of current demanded and it would serve to obtain the aging coefficient, defined by the basic health index.
- The hot-spot temperature would be introduced in the expression proposed by [8], which will allow us to know the degree of degradation of dielectric paper by observing its degree of polymerization.
- This last degree of polymerization will provide an alternative measurement of the state of the paper,

different to the subindex proposed in [2]. This would be useful when the transformer has been in operation for more than 30 years, where the furans dissolved in the oil are no longer a reliable indicator of the state of the paper.

In order to find out the maximum working temperature of a three-phase power transformer according to its load index, a thermal fluid study has been carried out. A section of the low voltage winding (LVW) of the transformer has been chosen, since it is the worst area regarding high temperatures. The LVW section has been selected for two reasons:

- It withstands greater current than the high voltage winding (HVW), which leads to higher copper losses and generates more amount of heat.
- It is the innermost part of the transformer, and therefore, it has more difficulty in cooling.

For these reasons, the highest temperature occurs in the LVW.

Geometric and Numerical Model

A core-type three phase distribution transformer has been chosen to check the previously defined methodology. The primary and secondary windings are delta- and wye-connected, respectively. The voltage ratio is 66/6.3 kV. The rated power is 14 MVA, cooling is ONAN. As illustrated in Figure 1, each phase of this transformer consists of three windings: low voltage winding (LVW) in the inner part, on-load tap winding in the outer part, and the high voltage winding (HVW) located between the two previous ones. The height of the windings is 1,056 mm. In the numerical study, the LVW is the only winding analyzed, based on the fact that hot-spots have a higher probability to be in this winding (inner location and higher currents). For that reason, a more detailed description of this winding is given in next few paragraphs.

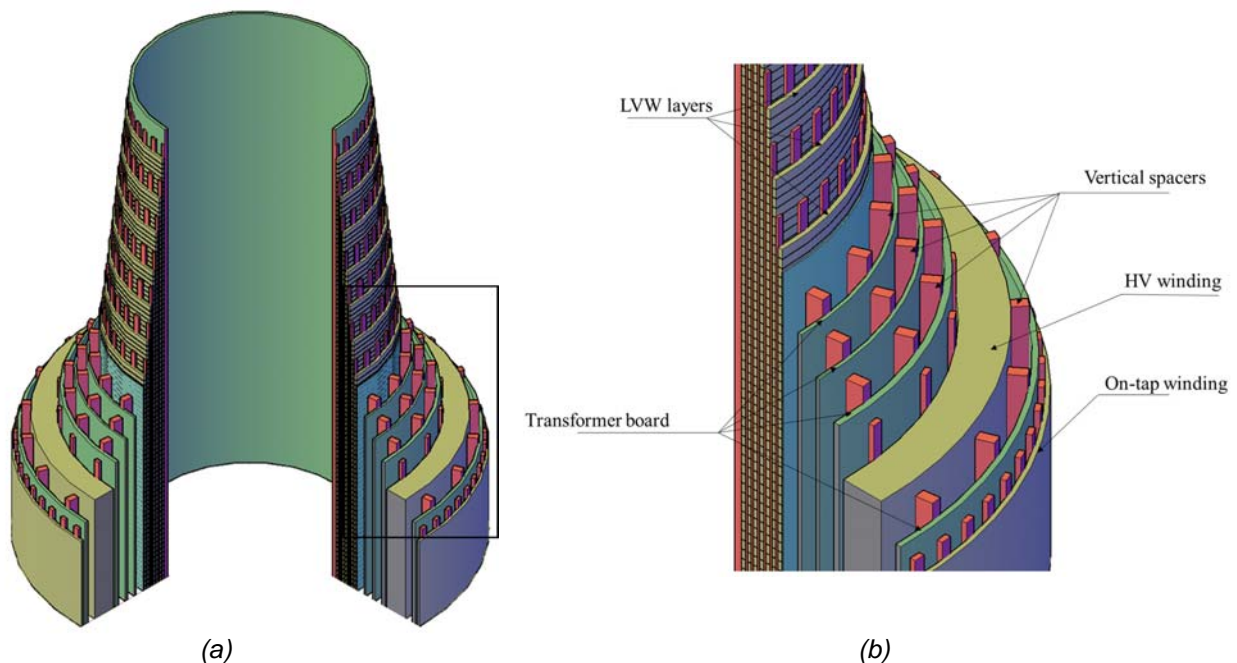


Figure 1. One phase of the 3 phase distribution transformer studied; (a) 3D geometry, and (b) main components.

Figure 2 provides the 15-degree section of one phase both cross sectional and 3D views. Each phase is constructed by repeating this section along the 360 degree circumference. Also, this 3D figure shows, by means of labels, different parts of the windings and the cooling ducts.

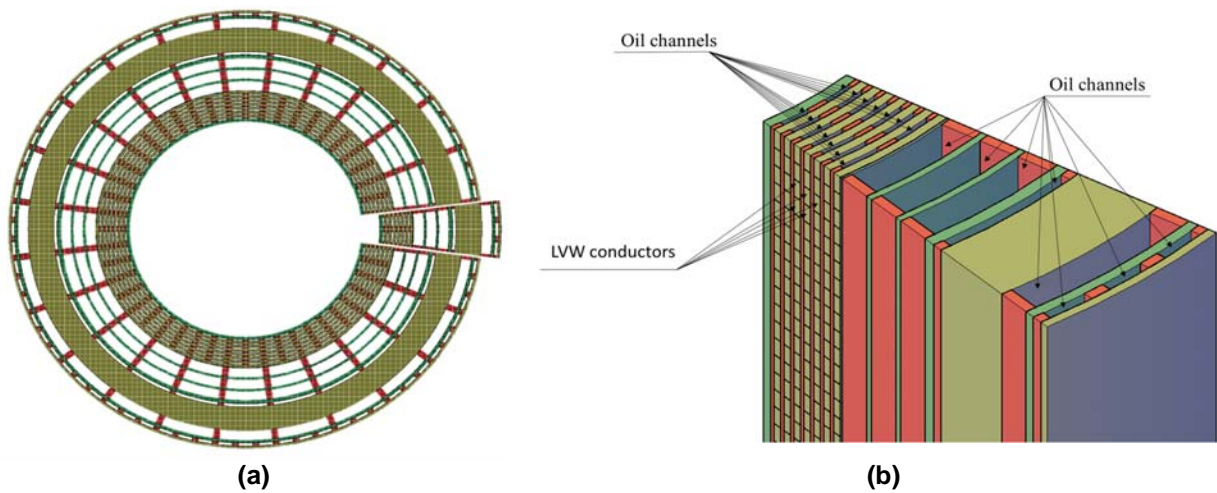


Figure 2. 15-degree section of one phase of the distribution transformer studied, (a) cross section and (b) 3D geometry.

Figures 1 and 2 show the design of one phase of the 3 phase transformer. The inner part consists of a cylinder of transformer board, 6 mm thick and 450 mm inner diameter. This is surrounded by the LVW consisting of 7 concentric layers, each layer having 11 copper turns that are wrapped with 0.3 mm thick paper. The layers are separated from each other and the inner cylinder by 48 vertical oil channels. The channels are formed using 3 mm thick wood spacers that are spaced every 7.5 degrees.

The HVW and LVW are radially separated by means of three vertical channels, 20 mm separation and spaced every 15 degrees. These ducts are made using three cylinders of transformer board and 4 mm thick wood spacers. The separation between the last cylinder and the HVW consists of 24 vertical oil ducts, 6 mm separation and spaced at 15 degree intervals. The outer HVW is made with 1397 turns divided into 112 coils with 24 vertical oil channels, 20 mm wide and spaced every 15 degrees. These channels are formed using cylinders of transformer board, 6 mm thick and 24 vertical wooden spacers. The on-tap load winding is separated from the last cylinder using 48 wooden vertical spacers, 6 mm thick.

The LVW is the only part of the geometry that is numerically analyzed. Initially, a 15-degree section of the winding was considered and the three outer oil channels (Figure 3b). Then, the fluid-thermal symmetry of the 7.5-degree radial plane, shown in Figure 3a, allowed to reduce the computational cost by simulating only half of the 15-degree section.

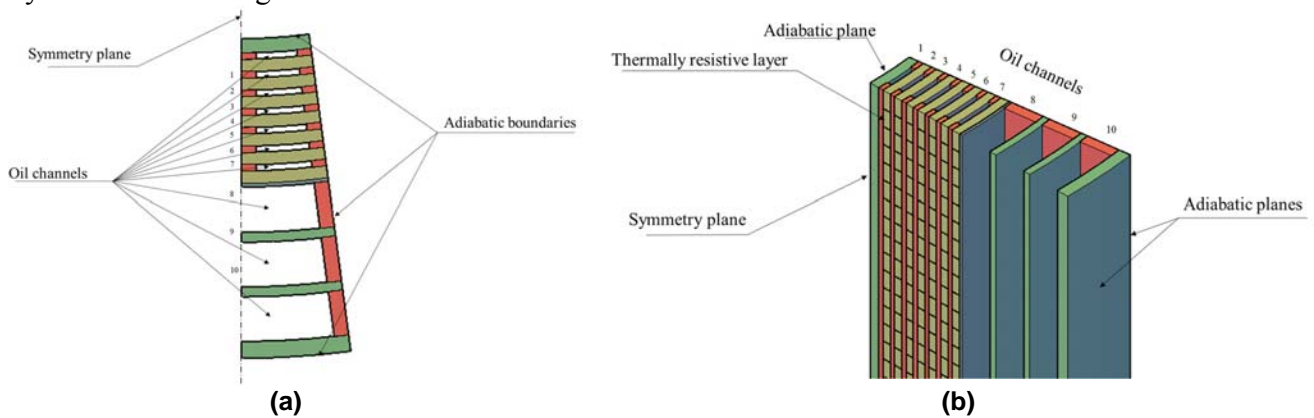


Figure 3. LVW geometry that is numerically analyzed; (a) plane view and (b) 3D view.

The simulation of the geometry shown in Figure 3 was performed using the static heat transfer and fluid dynamics module in COMSOL Multiphysics® 5.0. Details of the model and its validation can be found in [9] but a brief outline of this model is as follows:

- Navier-Stokes equations for incompressible fluids and energy equation are the governing equations that are numerically solved.
- All exterior vertical walls of the geometric model are considered as adiabatic surfaces, including that of the symmetry plane. Also, the upper horizontal plane is also considered as a adiabatic surface.
- Heat transfer by convection between the bottom horizontal plane and the oil is considered.
- The initial temperature of the solid components and oil are considered.
- No-slip condition is taken into account in the surfaces of the vertical ducts. Also, heat transfer by convection between these surfaces and the oil is considered.
- Bouyancy forces are considered in the oil that is inside the channels.
- Wrapping paper is defined mathematically as a thin thermally resistive layer.
- A uniform volumetric heat source is applied in the copper conductors.

Tables 2 and 3 summarize the properties of the materials considered in the numerical model:

Table 2. Properties of the oil

Property	Units	Standard	Mineral oil
Viscosity, 40°C	mm ² /s	ISO 3104 ASTM D 445	7.6
Density, 20°C	kg/dm ³	ISO 12185 ISO 3675 ASTM D 1298	0.877
Breakdown voltage (2.5 mm)	kV	IEC 60156	40 - 60
Acidity	mgKOH/g	IEC 62021 ASTM D 974	0.01
Tan delta (90°C and 50 Hz)		IEC 60247	0.001
Flash point	°C	ISO 2719 ASTM D 92	144
Moisture content	mg/kg	IEC 60814	< 20

Table 3. Physical properties of solid materials

	ρ [kg/m ³]	k [W/(m K)]	C_p [J/(kg K)]
Copper	8,700	400	385
Paper	930	0.19	1,340
Cardboard	1,150	0.25	2,093.5
Wood	418.5	0.15	2,720

Calculation of Load Indexes and Associated Performance

For each load, a transformer produces different losses, and therefore, different hot spot temperatures in the windings. These points corresponds to maximum temperature occurring in the winding insulation system.

According to the electrical machines theory [11], the maximum performance, η_{max} , of a transformer is achieved when the copper losses, P_{Cu} , match the iron losses, P_{Fe} . This can be expressed by (3), knowing that P_{Fe} is the power measured in the no-load test, in this case equal to 10kW. Therefore, at maximum

performance, the copper losses in the primary winding, P_{Cu1} , and in the secondary winding, P_{Cu2} , will add 10 kW (4), thus,

$$P_{Cu} = P_{Fe} = 10 \text{ kW} \rightarrow \eta = \eta_{\max} \quad (3)$$

$$\text{and } P_{Cu1} + P_{Cu2} = 10 \text{ kW}. \quad (4)$$

The calculation of P_{Cu1} and P_{Cu2} at maximum performance, is based on the measurement of the ohmic resistance of the windings and the turns ratio. The values obtained for P_{Cu1} and P_{Cu2} were 4220W and 5780W, respectively.

Obviously, the value required for our simulation is the second one, P_{Cu2} , which corresponds to the LVW. Comparing both values, it can be observed that P_{Cu2} is approximately 30% higher than P_{Cu1} .

Considering that P_{Cu2} corresponds to the three LV windings, it is possible to calculate the power to be applied on the section of 7.5° at maximum performance, $P_{Cu\text{-section}}$. It will be necessary to divide these losses between 3 (phases) and between 48 (the simulated section is the forty-eight part of a winding):

$$P_{Cu\text{-section}} = \frac{P_{Cu2}}{3 \cdot 48} = 40 \text{ W} \cdot \quad (5)$$

These losses correspond to a load index that allows the transformer to achieve the best possible efficiency, $C_{\eta\max}$. It is known that the load index, C , is equal to the ratio between the apparent power, S , and the rated one, S_n . Thus, $C_{\eta\max}$ (6) can be calculated taking into account the results of the no-load test ($P_{Fe}=10000\text{W}$) and the shortcircuit test ($P_{Cu-n}=86727\text{W}$), thus,

$$C_{\eta\max} = \sqrt{\frac{P_{Fe}}{P_{Cu-n}}} = \sqrt{\frac{10000}{86727}} = 0.34 \cdot \quad (6)$$

That is, this transformer will work at optimal efficiency, when operating at 34% of the rated power. If the transformer works at higher load index, the copper losses would be also higher and, therefore, the efficiency would be worse. Assuming that the transformer operates in a load index range [0.34 to 1], the highest losses would occur at the rated power, (Load Index = 1). These losses in the windings can be obtained from the short-circuit test, in the LVW (P_{Cu2-n}) and in the HVW (P_{Cu1-n}). Thus, P_{Cu2-n} has a value of 50500W. Therefore, within the load range mentioned previously, P_{Cu2} would vary between 5780 W (Load Index = 0.34) and 50500W (Load Index = 1).

As a result of increased load index, the copper losses and the LVW temperature will increase, adversely affecting the dielectric paper lifespan, especially in the hotter areas of the winding (hot spot).

The variation of this temperature (hot spot temperature, HST) with the load index is what is intended to be obtained by running a parametric simulation in the range mentioned [0.34 to 1]. In other words, in the range of P_{Cu2} [5780-50500W].

The parametric simulation has considered five values of P_{Cu2} : the two already calculated (0.34, 1) and three more (0.58, 0.75, 0.88) obtained by dividing the range of losses in four equal parts. Table 4 shows the aforementioned five values of P_{Cu2} and their corresponding load indexes.

In order to calculate the load indexes associated with these three intermediate P_{Cu2} values, it is again necessary to use the classical theory of electrical machines [11]. If the voltage of the secondary winding is considered constant, the load index could be also determined with the ratio between the actual current, I_2 and the rated one, I_{2-n} , (7). This last relationship can be used in the ratio between P_{Cu2} and P_{Cu2-n} to obtain the load indexes as a function of copper losses, (8), thus,

$$C = \frac{S}{S_n} = \frac{I_2}{I_{2-n}}, \quad (7)$$

$$\frac{P_{Cu2}}{P_{Cu2-n}} = \frac{3 \cdot R_2 \cdot I_2^2}{3 \cdot R_2 \cdot I_{2-n}^2} = \frac{I_2^2}{I_{2-n}^2} = C^2 \rightarrow C = \sqrt{\frac{P_{Cu,2}}{P_{Cu2-n}}}. \quad (8)$$

Finally, considering (7) and (8), it is possible to obtain the transformer performance depending on the load index by means of (9), thus,

$$\eta = \frac{P_{output}}{P_{input}} = \frac{P_{output}}{P_{output} + Losses} = \frac{S \cdot \cos \varphi}{S \cdot \cos \varphi + P_{Fe} + P_{Cu,2}} = \frac{C \cdot S_n \cdot \cos \varphi}{C \cdot S_n \cdot \cos \varphi + P_{Fe} + C^2 \cdot P_{Cu-n}}. \quad (9)$$

Table 4. Load indexes, copper losses and performances

	C				
	0.34	0.58	0.75	0.88	1.00
P_{Cu2}	5780	16960	28140	39320	50500
$P_{Cu-section}$	40	118	195	273	351
η	0.9958	0.9952	0.9944	0.9937	0.9931

Results

After performing the numerical analysis, considering the values of $P_{Cu-section}$ in Table 4 and $\cos\varphi=1$, the hot-spot temperatures, T_{HS} , and the oil outlet average temperatures, $T_{avg outlet}$, were obtained. These values are shown in Table 5. Also, the temperatures distribution and the location of the hot-spot in the case of the rated power ($C=1$) are shown in Figure 4.

Regarding to the location of the hot spots, it should be noted that it does not depend on the losses considered; it is always located on the same position: on the top of the geometry, in the middle of the third layer of the LVW, in the plane of symmetry. This coincidence is justified by the fact that the location of hot spots will depend only on the model and on the type of geometry considered.

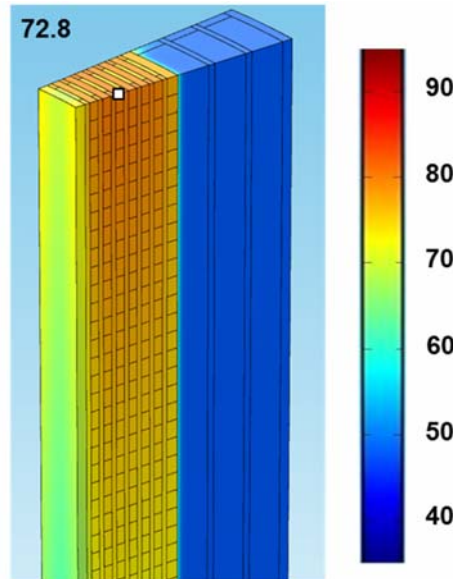


Figure 4. Temperature distribution ($^{\circ}C$) and location of hot-spot in the model.

Concerning temperatures, it can be seen that the higher temperatures of the oil are located in the ducts that

are near to the hot-spot. That is, the oil of the channels 3 to 5 reaches temperatures closer to the hot-spot than the oil of the rest of the ducts. On the other hand, it is clear from the analysis of the evolution of the hot-spot with the load index that the higher the index, the higher the hot-spot. In fact, the difference between the extreme cases, optimal and full load, is about 25°C.

Table 5. Oil outlet average temperatures in cooling ducts, $T_{avg outlet}$ (°C), and hot-spot, T_{HS} (°C) in relation to Load Index (C).

C	$T_{avg outlet}$ in each channel										T_{HS}
	1	2	3	4	5	6	7	8	9	10	
0.34	46.1	47.0	47.4	47.4	47.1	46.5	44.9	35.9	35.1	35.0	47.9
0.58	52.6	54.8	55.3	55.4	55.2	54.7	52.9	36.3	35.1	35.0	57.1
0.75	56.6	59.8	60.4	60.4	60.3	59.9	58.3	36.5	35.1	35.0	63.3
0.88	59.7	63.7	64.4	64.3	64.1	63.9	62.6	36.7	35.1	35.0	68.4
1	62.2	67.0	67.7	67.6	67.3	67.1	66.2	36.9	35.1	35.0	72.8

Finally, it is possible to mathematically relate the hot spot temperature with the load index by calculating the trend line, as shown in Figure 5. In this figure, it is also shown the evolution of the transformer performance versus the load index, as well as the mathematical equation of this trend line, which is clearly downward.

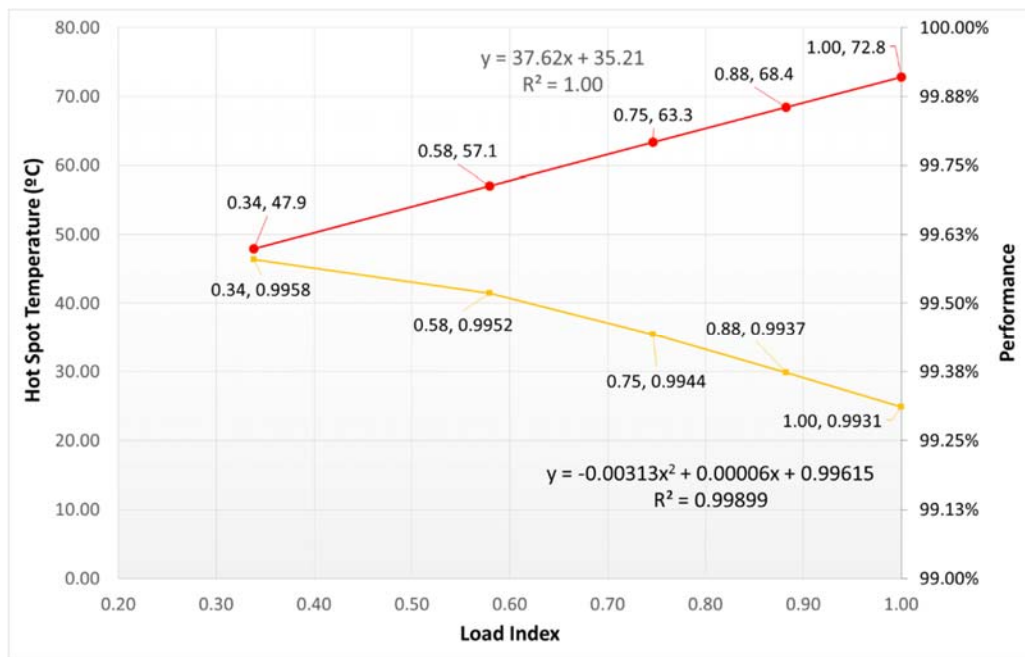


Figure 5. Hot spot temperature (°C) and performance (%) as a function of the load index.

Using the Hot Spot Temperature in Health Indices

From the equation shown in Figure 5, the hot-spot temperature can be obtained for any load index. This could help to assign a more distributed load factor (f_L) than the one proposed by [2]. Table 6 shows these values which could serve to calculate in a more accurate way the aging factor, B, thereby improving the contribution of aging subindex within the health index considered.

Table 6. Hot spot temperature, load index and load factor

T_{HS} (°C)	Load Index	Load Factor (f_L)
35.2	0	1
39.0	0.1	1
42.7	0.2	1
46.5	0.3	1
50.3	0.4	1.05
54.0	0.5	1.075
57.8	0.6	1.1
61.5	0.7	1.175
65.3	0.8	1.25
69.1	0.9	1.275
72.8	1	1.3

The knowledge of the hot-spot temperature can also help to improve the subindex observing the quality of dielectric paper. This subindex is based on the gas content in the dielectric oil, focusing on carbon-oxygen compounds and furan compounds. However, after analysis of the historical records of oil testing in a fleet of industrial transformers, it was found that these compounds are not related to the condition of dielectric paper when the machines have been in operation for more than 30 years. In this sense, the knowledge of the hot spot would serve to determine the degree of polymerization of the paper using the method proposed by [8], (10), thus having an alternative for the determination of this subindex when the transformer has been in operation for long time,

$$\frac{1}{DP_0} - \frac{1}{DP_t} = k \cdot t \rightarrow k = A \cdot e^{-\frac{E_a}{R \cdot T_{HS}}}, \quad (10)$$

where:

- k is the rate constant,
- A is the pre-exponential factor (128 kJ/mol),
- E_a is the activation energy ($4.1 \cdot 10^{10}$ hours⁻¹),
- R is the gas constant (8.314 J/mol/ K),
- t is transformer life (hours),
- T_{HS} is the hot spot temperature (K),
- DP_0 is the initial polymerization degree, and
- DP_t is the degree of final polymerization.

The temperature in (10) is the hot spot temperature, T_{HS} , obtained from the numerical model. Previously, the transformer asset manager had to calculate the average load index at which the transformer worked during the period of time considered. In this the new DP_t associated with the dielectric paper could be determined.

Conclusions

This article has modified a known health index which in addition to the usual variables also considers the operating time and the load index of the transformer. Based on this new health index, the hot-spot temperature in the windings is taken into account when assessing the status of a transformer. This temperature is determined by a fluid-thermal simulation of transformer windings under load. After determining the highest temperature of the winding at rated load, it is calculated at lower loads. Thus, a function is obtained which allows relating the load level to the rate of aging of the insulation system. The higher the load index the

higher the temperature of the hot spot in the windings, and consequently, the dielectric paper and oil is exposed to increased thermal stress.

In addition, this article proposes the calculation of the degree of polymerization of the paper using the known expression that relates temperature with the degradation rate. This parameter is used to determine alternatively the subindex assessing the state of the insulating paper, since in fleets of transformers in operation for more than three decades, the furan compounds cease to be a reference of the degree of degradation of paper.

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