CALCULATION OF POWER TRANSFORMERS HEALTH INDEXES

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Abstract **– In order to prevent possible defects of power transformers and to avoid losses which occur after taking them out of service, it is important to know the state of their insulation systems. For this purpose, health index is used, which quantifies the global state of power transformers.**
To determine power transformers state, a multitude of factors are taken into consideration and a number of tests are conducted, in order to evaluate their global state as accurate as possible.
In literature, Health index is calculated based on the model of twenty-four diagnostic factors. In this paper, expanding the list with three factors (loss factor at very low frequency, conductivity factor and polarization index) is a new model proposed. The health index was determined using special software, which has the values of the twenty-seven diagnostic factors as entry data.
Using the health index, the condition of a power transformer can be assessed. This factor allows the estimation of remaining transformer lifetime, taking into account some of the most important characteristics of its insulation system.
The health index is strongly influenced by the dielectric losses which occur inside electro-insulating components volumes, but also by the conductivity factor and the polarization index.

Keywords: *health index, power transformer, failure, life assessment.*

1. INTRODUCTION

Power transformers are designed to function safely for 20-35 years. In practice, the transformer life may be higher than 60 years if proper maintenance is performed.
Generally, it is not economic for an old transformer to be subjected to rigorous inspections and thorough testing. A promising strategy for lifetime increase is to establish monitoring priorities and develop a strategy for their maintenance [1]. This is why insulation systems monitoring and diagnosis has become an important part in transformers monitoring.
Different methods of monitoring and diagnosis are used, based on a wide variety of physical, electrical, mechanical, thermal and optical effects. They allow the state assessment, provide information on ageing and recommend measures to improve insulation quality and lifetime assessment [2].
Lately, more and more is discussed about using the health index to evaluate transformer states and develop more effective maintenance policies [3, 4]. In order to calculate the health index, diagnostic factors (related to both transformers and load tap changer status) are proposed. Considering the usefulness of measurements done with modern equipment, taking into consideration three other parameters obtained by non-destructive electrical measurements is proposed in this paper, respectively conductivity factor, loss factor at 1 mHz and the polarization index.
The paper also includes a health index calculation based on the test results of a transformer insulation system (dissolved gas analysis, oil quality, furans content, turns ratio, leakage reactance, winding resistance, bushings state, load tap changer general state, dielectric loss factor at 1 mHz and conductivity factor) using 27 state elements and was conducted a simulation on health index variation with the variations of polarization index and loss factor of transformer oils.

2. HEALTH INDEX

Health index (*HI*) is a size which can be used to evaluate the general condition of a power transformer. This size is calculated using some of the most representative elements of diagnosis (or state) that characterize the operation and status of the transformer and is converted into a quantitative index that provides information about its health status. In [3], a relation for calculating the health index is proposed, namely:

$$HI = A_1 \cdot \frac{\sum_{i=1}^{n-3} c_i \cdot DI_i}{\sum_{i=1}^{n-3} 4 \cdot c_i} + A_2 \cdot \frac{\sum_{i=n-3}^{n} c_i \cdot DI_i}{\sum_{i=n-3}^{n} 4 \cdot c_i}, \qquad (1)$$

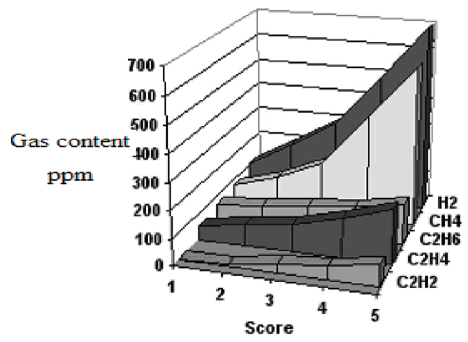
where c_i is the rating given to each state element, DI_i is the value of the diagnostic index (i.e., the score given to each state factor from Table 1), n is the number of considered diagnostic factors, A_1 and A_2 are the corresponding weights of n-3 factors that describe the transformer state, respectively the load tap changer.
Next, the calculation model of diagnostic index (*DI*) is shown for several diagnostic factors proposed for calculating the health index.

2.1. Dissolved gas analysis

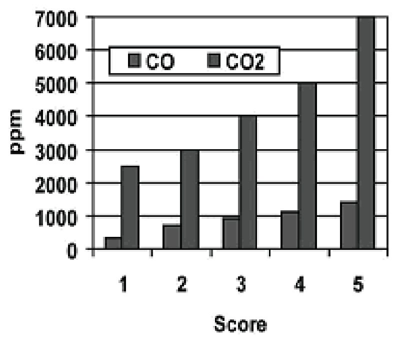
Dissolved gas analysis (DGA) is a safe and valuable technique to detect transformers incipient failure states. Using DGA, it is possible to distinguish the existence of internal arcs, poor electrical contacts, hot spots, partial discharges, overheating of oil, cellulose paper, wires, etc. [1]. Maximum allowed levels for gas in oil were established in IEEE, IEC, Dornenburg, Bureau of Reclamation, etc. [3].

	Diagnostic factors	c_i	DI_i
1	Dissolved gas analysis (DGA)	10	4,3,2,1,0
2	Load history	10	4,3,2,1,0
3	Global loss factor	10	4,3,2,1,0
4	Infrared thermography	10	4,3,2,1,0
5	Oil quality	6	4,3,2,1,0
6	Overall transformer condition	8	4,3,2,1,0
7	Furans content	5	4,3,2,1,0
8	Turns ratio	5	4,3,2,1,0
9	Leakage reactance	8	4,3,2,1,0
10	Winding resistance	8	4,3,2,1,0
11	Core-to-ground connection	2	4,3,2,1,0
12	Bushing condition	5	4,3,2,1,0
13	Main tank corrosion	2	4,3,2,1,0
14	Cooling equipment	2	4,3,2,1,0
15	Oil tank corrosion	1	4,3,2,1,0
16	Foundation	1	4,3,2,1,0
17	Grounding	1	4,3,2,1,0
18	Gaskets, seals	1	4,3,2,1,0
19	Connectors	1	4,3,2,1,0
20	Oil leaks	1	4,3,2,1,0
21	Oil level	1	4,3,2,1,0
22	Conductivity factor k_c	10	4,3,2,1,0
23	Polarization index k_p	10	4,3,2,1,0
24	Loss factor tgδ at f = 1mHz	10	4,3,2,1,0
25	Dissolved gas analysis of LTC	6	4,3,2,1,0
26	LTC oil quality	3	4,3,2,1,0
27	Overall LTC condition	5	4,3,2,1,0

Table 1: Diagnostic factors used to calculate the health index.



a)



b)

Figure 1: Score given to dissolved gas [3].

Based on that, gas analysis factor F_g is defined:

$$F_g = \frac{\sum_{i=1}^{7} n_i \cdot p_i}{\sum_{i=1}^{7} p_i}, \qquad (2)$$

where n_i = 1…6 is the score (note) given to gas i and p_i – its weight factor. For p_i, the following values are considered: 1 – for CO and CO_2, 3 – for CH_4, C_2H_6 and C_2H_4, 5 – for C_2H_2 and 2 – for H_2. Score n_i corresponding to gas i is chosen depending on gas concentration (content) (fig. 1) [3]. If the gas content exceeds the maximum value (fig. 1), the awarded score will be 6. Sizes n_i and p_i allow the calculation of gas analysis factor F_g.

Depending on F_g values, a rating code is given to the insulation system, noted with A, B, C, D or E. According to [3], A is given for the best state (F_g < 1.2) and E for the worst ($F_g \geq 3$) (Table 2). The ratings corresponding to gas analyses A, B, C, D and E are numbers 4, 3, 2, 1 and 0, used as diagnostic indexes (DI_g) in formula (1). The rating values of state element c_i in (1) are given according to statistics on the considered element influence on transformer failure. Thus, for dissolved gas analysis is given a 10, for furans content – 5, for oil level – 1, etc. [3].

2.2. Oil quality

An important part of extending the life of a power transformer consists in insulating fluid recondition. A series of physical and chemical tests, such as water and oxygen content, interfacial tension, acidity index, loss factor, dielectric strength, etc. indicate the oil state [1]. Transformer moisture leads to lower (worse) dielectric characteristics of the insulation system. Interfacial tension between the electro-insulating liquid and water quantifies the attraction forces between molecules at the separation interface between two different environments.
Using relation (2) and the values of ratings n_i and weight factors p_i (Table 3), oil quality factor F_o is determined. Based on F_o values, a rating code is given to oil quality (A, B, C, D, E), similar to dissolved gas analysis, thus determining diagnostic index DI_o [3].

Description	State	State score
$F_g < 1.2$	Good	A
$1.2 \le F_g < 1.5$	Satisfactory	B
$1.5 \le F_g < 2$	Poor	C
$2 \le F_g < 3$	Very poor	D
$F_g \ge 3$	Dangerous	E

Table 2: Transformer condition assessment using F_g [3].

2.3. Furans content

Furans content analysis allows the assessment of solid component states of the power transformers insulation systems (PTIS) and oil-impregnated paper.
This test is recommended to be performed when the transformer is overheated, has a high CO and CO_2 level or has more than 25 years of service. To calculate the health index (*HI*), the first two columns of Table 4 are used.
If the oil has been replaced or renewed, then this test does not provide real information regarding the degradation of cellulose paper. In such cases, you can use transformer age found in the third column of Table 4 to determine *HI*. In [3], information is given about the analysis of other elements that determine the health state of a transformer (windings, partition insulators, lead tap changers, etc. – Tables 5 and 6).

2.4. Conductivity factor

Conductivity factor is calculated based on absorption/resorption currents, using:

$$k_c = \frac{i_a(30) - i_r(30)}{i_a(60) - i_r(60)}, \qquad (3)$$

where $i_{a,r}$ (30, 60) represent the values of absorption/resorption currents measured at 30 and 60 s from the applied voltage start [8]. Conductivity factor k_c values allow the estimation of the oil's total electrical conductivity, respectively of its degradation state.

2.5. Polarization index

The polarization index is also calculated using absorption/resorption currents:

$$k_p = \frac{i_a(60)}{i_a(600)}, \qquad (4)$$

where i_a (60) and i_a (600) represent absorption current values measured at 60 s and 600 s from the applied voltage U start [6].
Noting that water is the main contaminant of power transformers insulation systems and that is highly polar ($\varepsilon_r = 81$), k_p is strongly influenced by the water content inside the insulation system [6]. In table 8, diagnostic index DI_p values are presented.

2.6. Loss factor at *f* = 1 mHz

The importance of this factor stems from the fact that, at low frequencies, the existence of degradation products can be more clearly highlighted due to intensified orientation and interfacial polarization, ionic conductivity growth, increased dispersion processes (at low frequencies) and "ionic dipoles" forming processes (due to alternating displacements of ions having opposite signs). Consequently, the loss factor values can be determined using the relation:

$$tg\delta = \frac{\varepsilon_r'' + \dfrac{\sigma}{\omega \cdot \varepsilon_0}}{\varepsilon_r'}, \qquad (5)$$

where ε_r' and ε_r'' represent the real and imaginary part of the complex relative permittivity, σ is the dc conductivity, ω is angler frequency and ε_0 is vacuum permittivity [5]. Diagnostic index DI_{tg} values are presented in table 9.

3. EXPERIMENTS

To determine the values of k_c, k_p and tgδ, a series of tests were done on NYNAS oil samples, thermally accelerated aged at T = 155 °C for time intervals τ between 0 and 750 h (Table 10).
The 3 state elements k_c, k_p and tgδ show an important variation with ageing time (Table 10); this is the reason for taking them into account regarding transformer evaluation.

3.1. Experimental set-ups

The experimental set-up used to measure absorption/resorption currents for liquids is presented in Figure 2. The measurements were realized at voltage U_0 = 300 V, for 7200 s. To measure the loss factor tgδ, a NOVOCONTROL dielectric spectrometer

3.2. Results

Size / U_n	$U_n \leq 69$ kV	69 kV < U_n < 230 kV	230 kV ≤ U_n	Score (n_i)	p_i
Dielectric strength (kV/mm) (2 mm)	≥ 45	≥ 52	≥ 60	1	3
	35 – 45	47 – 52	50 – 60	2	
	30 – 35	35 – 47	40 – 50	3	
	≤ 30	≤ 35	≤ 40	4	
Interfacial tension (dyne/cm)	≥ 25	≥ 30	≥ 32	1	2
	20 – 25	23 – 30	25 – 32	2	
	15 – 20	18 – 23	20 – 25	3	
	≤ 15	≤ 18	≤ 20	4	
Acid number	≤ 0.05	≤ 0.04	≤ 0.03	1	1
	0.05 – 0.1	0.04 – 0.1	0.03 – 0.07	2	
	0.1 – 0.2	0.1 – 0.15	0.07 – 0.1	3	
	≥ 0.2	≥ 0.15	≥ 0.10	4	
Water content (ppm)	≤ 30	≤ 20	≤ 15	1	4
	30 – 35	20 – 25	15 – 20	2	
	35 – 40	25 – 30	20 – 25	3	
	≥ 40	≥ 30	≥ 25	4	
Oil colour	≤ 1.5			1	2
	1.5 – 2.0			2	
	2.0 – 2.5			3	
	≥ 2.5			4	
Dissipation factor at 50 Hz (%) (25 ^oC)	≤ 0.1			1	3
	0.1 – 0.5			2	
	0.5 – 1.0			3	
	≥ 1.0			4	

Table 3: Insulating oil parameters evaluation based on IEEE C57.106-2006 [3].

Diagnostic index DI_f	Furans content [ppm]	Transformer life [years]
4	0 – 0.1	< 20
3	0.1 – 0.25	20 – 40
2	0.25 – 0.5	40 – 60
1	0.5 – 1.0	> 60
0	> 1.0	…

Table 4: Values of the diagnostic index DI_f corresponding to furans content test [3].

Diagnostic index $DI_{tr,\,lr}$	Turns ratio deviation (ΔTR) [%]	Leakage reactance deviation (ΔX) [%]
4	ΔTR ≤ 0.1%	ΔX < 0.5%
3	0.1% < ΔTR ≤0.5%	0.5% ≤ ΔX < 1%
2	0.5% < ΔTR ≤ 1%	1% ≤ ΔX < 2%
1	1% < ΔTR < 2%	2% ≤ ΔX < 3%
0	ΔTR ≥ 2%	ΔX ≥ 3%

Table 5: Diagnostic index $DI_{tr,\,lr}$ corresponding to turns ratio and leakage reactance [3].

Diagnostic index DI_{wr}	Winding resistance deviation (ΔR) [%]
4	ΔR < 1%
3	1% ≤ ΔR<2%
2	2% ≤ ΔR <3%
1	3% ≤ ΔR<5%
0	ΔR ≥ 5%

Table 6: Evaluation of the winding resistance test [3].

Diagnostic index DI_c	k_c	State
4	$k_c \geq 1.4$	Good
3	$1.4 > k_c \geq 1.3$	Satisfactory
2	$1.3 > k_c \geq 1.2$	Poor
1	$1.2 > k_c \geq 1.1$	Very poor
0	$k_c \leq 1.1$	Dangerous

Table 7: Diagnostic index DI_c corresponding to the conductivity factor.

equipped with a special measurement cell was used. The tests were done at voltage of U = 1 V and frequency $f = 10^{-3} \ldots 10^{6}$ Hz [5].
It was considered that the tested oil was identical to the one used in a transformer in service, which has known diagnostic indexes DI_i values. Using (1), health index HI calculation software was done, using 2 versions: V1 – with and V2 – without taking into consideration quantities k_c, k_p and tgδ.
Taking into consideration only the state elements proposed in [3], respectively 1…21 and 25...27 from table 1, health index value was calculated, amounting to HI_1 = 0.757.

Diagnostic index DI_p	k_p	State
4	$k_p \geq 2$	Good
3	$1.25 \leq k_p < 2$	Satisfactory
2	$1.1 \leq k_p < 1.25$	Poor
1	$1 \leq k_p < 1.1$	Very poor
0	$k_p < 1$	Dangerous

Table 8: Diagnostic index DI_p corresponding to polarization index.

Diagnostic index DI_{tg}	*tgδ*	State
4	*tgδ* ≤ 2	Good
3	2< *tgδ* ≤5	Satisfactory
2	5< *tgδ* ≤ 20	Poor
1	20 < *tgδ* ≤ 100	Very poor
0	*tgδ* > 100	Dangerous

Table 9: Diagnostic index DI_{tg} corresponding to dielectric loss.

τ	k_c	k_p	tgδ at f = 1mHz
0 h	1.41	2.665	1.53
150 h	1.379	1.466	1.94
450 h	1.35	1.366	4.01
600 h	1.055	1.096	123
750 h	1.0072	1.0032	134.6

Table 10: Sizes k_c, k_p and tgδ experimentally determined.

HI	State	Expected lifetime
0.85–1	Very good	> 15 years
0.7–0.85	Good	> 10 years
0.5–0.7	Satisfactory	< 10 years
0.3–0.5	Poor	< 3 years
0–0.3	Very poor	End-of-life

Table 11: Expected lifetime estimation using *HI* [3].

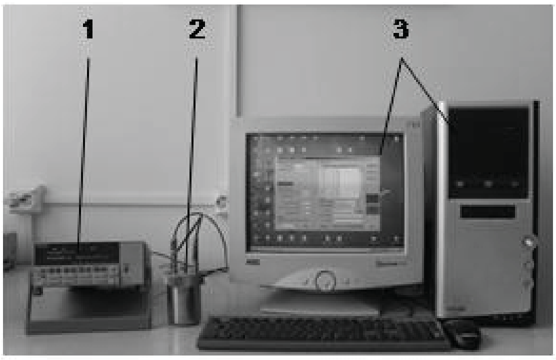


Figure 2. Experimental set-up used for measuring absorption/resorption currents on liquids :
1 – Electrometer Keithley 6517, 2 – IRLAB measurement cell, 3 – PC.

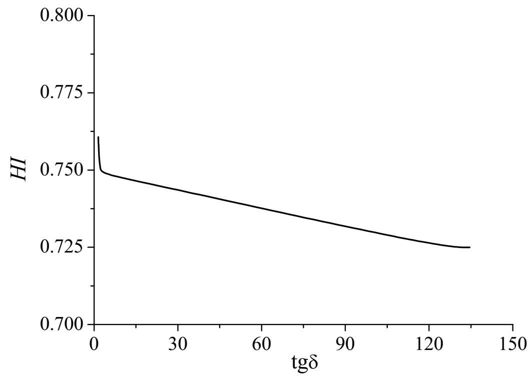


Figure: 3 Health index *HI* variation with loss factor tgδ (f = 1 mHz).

Adding quantities k_c, k_p and tgδ, it resulted HI_{21} = 0.760 (k_c, k_p and tgδ were chosen according to state A) and HI_{22} = 0.689 (k_c, k_p and tgδ were chosen according to state E). Next, different transformer states simulations were made, considering that k_c, k_p and tgδ values changed (Fig. 3 and 4). It can be seen (Fig. 3) that health index decreases with loss factor increase, and for tgδ = 30, $HI \approx 0.74$, which corresponds to a remaining lifetime of at least 10 years, according to Table 11.
In Figure 5, health index *HI* variation with polarization index k_p is presented. k_p decrease leads to lower *HI* values, water content increase inside the insulation system being assigned to oil degradation.
In Figures 5 and 6, variations of health index calculated with 24 and 27 diagnostic factors, (with winding resistance deviation values) are presented, respectively with the leakage reactance deviation of the power transformer. It can be said that using 27 factors offers a more realistic result regarding *HI* (Figs. 5 and 6, curves 2 and 3). For example, curve 2 was made using 27 factors (k_c, k_p and tgδ were chosen according to state A), while curve 3 (27 factors) with sizes k_c, k_p and tgδ according to state E.

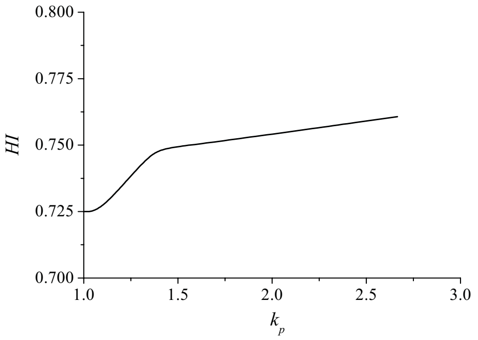


Figure 4: Health index *HI* variation with polarization index k_p.

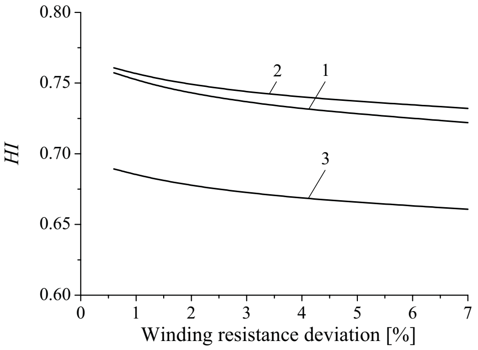


Figure 5: Health index *HI* variation with winding resistance values: *HI* calculated with 24 factors (1), *HI* calculated with 27 factors – k_c, k_p and tgδ chosen for state A (2), *HI* calculated with 27 factors – k_c, k_p and tgδ chosen for state E (3).

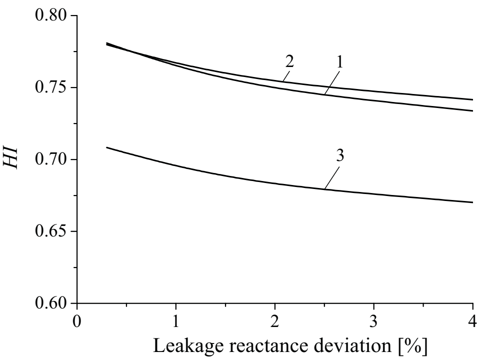


Figure 6: Health index *HI* variation with leakage reactance values: *HI* calculated with 24 factors (1), *HI* calculated with 27 factors – k_c, k_p and tgδ chosen for state A (2), *HI* calculated with 27 factors – k_c, k_p and tgδ chosen for state E (3).

4. CONCLUSIONS

This paper presents a study regarding power transformers health index.

Using the health index, the condition of a power transformer can be assessed, therefore its remaining lifetime. This factor allows the estimation of remaining transformer lifetime, taking into account some of the most important characteristics of its insulation system. The health index is strongly influenced by the dielectric losses which occur inside electro-insulating components volumes, but also by the conductivity factor and the polarization index. Moreover, using a number of 27 diagnostic factors allowed a more precise determination of health index *HI*.

Acknowledgment

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