An Approach to Determine the Health Index of Power Transformers

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An Approach to Determine the Health Index of Power Transformers

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Abstract **This paper describes a realistic Health Index formulation method for power transformers using readily available data. The method considers practical limitations on obtaining data, and the possible constraints on the parameters. It also utilizes IEC, IEEE, and CIGRE criteria for condition parameters.**

This Health Index calculation considers not only typical test results such as dissolved gas analysis (DGA), oil quality, furan, and power factor, but also other parameters such as tap changer and bushing condition, physical observations, load history, maintenance work orders, and age. The calculation includes condition ratings, weighting factors, and assigned scores for specific condition parameters. By using a multi-criteria analysis approach, the method combines the various factors into a condition-based Health Index.

I. Introduction

Power transformers have the single highest value of equipment in substations, comprising almost 60% of the total investment. Most power utilities are highly motivated to assess the actual condition of their transformers, because there is an increasing demand for improved financial and technical performance. To achieve the optimal balance among capital investments, asset maintenance costs, and operating performance, there is a need to provide economic and technical justifications for engineering decisions and capital replacement plans.

Health Indices (HI) represent a practical method to quantify the results of operating observations, field inspections, and site and laboratory testing into an objective and quantitative index, providing the overall health of the assets. Asset HI is a powerful tool for managing assets and identifying investment needs and prioritizing investments into capital and maintenance programs [1, 2].

Several studies discuss different condition assessment and life management techniques for power transformers by measurement or monitoring of parameters such as partial discharge, dissolved gas analysis, moisture, oil quality (dielectric strength, acidity, color, and interfacial tension), frequency response analysis, recovery voltage method, tap changer tests, bushing condition, online partial discharge measurement, and other methods [3-10]. Utilities may conduct some of these tests periodically to evaluate the condition of the power transformers, but there is no recommended method available by standards or individuals to quantify the condition of the asset considering all available data. This paper describes a practical HI calculation method using available data by considering standard recommendations from [3] to [9] and Kinectrics' experience in analyzing data from different utilities.

II. Parameters and Tests

According to the latest CIGRE WG 12 report, the main subsystems of a transformer that are exposed to degradation are [4]:

- Dielectric (major / minor insulation, leads, windings)
- Magnetic circuit (core, clamping)
- Tap changers (LTC)
- Mechanical parts (bushing, tank, cooling, etc.)

The most applicable methods currently used as a routine test, diagnostic method, or monitoring technique are: dissolved gas analysis (DGA), oil quality, furfural, power factor, tap changer monitoring, load history, and maintenance data.

A. Dissolved Gas Analysis

IEC 60599 provides a coded list of faults detectable by dissolved gas analysis and IEEE Std C57.104 introduces a four-level criterion to classify risks to transformers, for continued operation at various combustible gas levels [6, 11]. Therefore, theoretically, by means of dissolved gas analysis (DGA), it is possible to distinguish internal faults such as arcing, partial discharge, low-energy sparking, severe overloading, and overheating in the insulation system.

Practically, DGA data by itself does not always provide sufficient information from which to evaluate the integrity of a transformer system. Normal operation will also result in the formation of some gases. Information about the history of a transformer in terms of maintenance, loading practice, previous faults, manufacturer data, and so on are an integral part of the information required to make an evaluation. In fact, it is possible for some transformers to operate throughout their useful life with substantial quantities of combustible gases present [6].

Several classic interpretation techniques have been developed for DGA of power transformers in the past 30 years such as Rogers, Durenburg, Duval Triangle, and modified Durenburg

[5, 6, 11, 12]. Most of these methods are based on the gas ratio, i.e. $\frac{C_2H_2}{C_2H_4}$, $\frac{CH_4}{H_2}$, and $\frac{C_2H_4}{C_2H_6}$.

Table I compares the recommended alarm level of gases from different references. The numbers are relatively close, except the IEEE thresholds for acetylene and carbon dioxide.

TABLE I
COMPARISON OF GAS LIMIT RECOMMENDATIONS [PPM]

Gas	Dorenburg	IEC	IEEE	Bureau of Reclamation
H_2	200	100	100	500
CH_4	50	75	120	125
C_2H_6	35	75	65	75
C_2H_4	80	75	50	175
C_2H_2	5	3	35	7
CO	500	700	350	750
CO_2	6000	7000	2500	10000

Considering the different recommendations, Tables II and III introduce a ranking method developed using the DGA data. The DGA factor is described in Equation (1):

$$DGAF=\frac{\sum_{i=1}^{7} S_i \times W_i}{\sum_{i=1}^{7} W_i} \tag{1}$$

Where S_i is the score of each gas based on Table III and W_i is the proper weighting factor. The rating code starts with A as the best condition to E, which represents the worst situation. This type of coding is employed for the remaining factors.

TABLE II
TRANSFORMER RATING BASED ON DGA FACTOR

Rating Code	Condition	Description
A	Good	DGAF<1.2
B	Acceptable	1.2 ≤ DGAF<1.5
C	Need Caution	1.5 ≤ DGAF<2
D	Poor	2 ≤ DGAF<3
E	Very poor	DGAF ≥ 3

TABLE III
SCORING AND WEIGHT FACTORS FOR GAS LEVELS [PPM]

	Score (S_i)						
Gas	1	2	3	4	5	6	W_i
H_2	≤ 100	100-200	200-300	300-500	500-700	>700	2
CH_4	≤ 75	75-125	125-200	200-400	400-600	>600	3
C_2H_6	≤ 65	65-80	80-100	100-120	120-150	>150	3
C_2H_4	≤ 50	50-80	80-100	100-150	150-200	>200	3
C_2H_2	≤ 3	3-7	7-35	35-50	50-80	>80	5
CO	≤ 350	350-700	700-900	900-1100	1100-1400	>1400	1
CO_2	≤ 2500	≤ 3000	≤ 4000	≤ 5000	≤ 7000	>7000	1

In addition, daily or monthly rate of gas production is important. IEEE recommended more frequent oil sampling based on the growing rate of total dissolved combustible gas (TDCG)[6]. When sudden increases in the dissolved gas content of the oil occur, an internal fault is suspected. A reduction of the HI is recommended if the rate of gas increment is more than 30% for three consecutive gas samples or 20% for five consecutive oil samples.

B. Oil Quality

Table IV summarizes the recommended oil test standards. A combination of electrical, physical, and chemical tests is performed to establish preventive maintenance procedures, avoid premature failure and costly shutdown, and plan maintenance such as oil reclamation or replacement [5, 7, 8, 9].

TABLE IV
COMPARISON OF GAS LIMIT RECOMMENDATIONS

Parameter	ASTM recommended by IEEE[7]	IEC recommended by CIGRE[16]
Dielectric Breakdown	D877 D1816	IEC60156
Water content	D1533	IEC 60814
Power Factor	D924	IEC247
IFT	D971	ISO 6295
Acidity	D644 D974	IEC62021
Color	D1500	ISO 2049

Most of the limit recommendations for oil parameters are categorized based on the rated voltage in both IEEE and IEC standards [7, 8]. Table V is the developed rating method for oil quality evaluation considering all parameters. It is important to note that these values are recommended for continued use of service-aged insulating oil and not for new oil. Rating codes A, B, C, D, E are determined using (1) and Table 2.

TABLE V
GRADING METHOD FOR OIL TEST PARAMETERS

	U ≤ 69 kV	69 kV <U < 230 kV	230 kV ≤ U	*Score*	W_i
Dielectric Strength kV (2 mm gap)	≥ 45	≥ 52	≥ 60	1	3
	35-45	45-52	50-60	2	
	30-35	35-45	40-50	3	
	≤ 30	≤ 35	≤ 40	4	
IFT 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
	.05-0.1	0.04-1.0	0.03-.07	2	
	0.1-0.2	1.0-0.15	0.07-.10	3	
	≥ 0.2	≥ 0.15	≥ 0.10	4	
Moisture (ppm)	≤ 20			1	4
	20-30			2	
	30-40			3	
	>40			4	
Color	≤ 1.5			1	2
	1.5-2.0			2	
	2.0-2.5			3	
	≥ 2.5			4	

C. *Furfural*

Measurement of the furfural content of the oil can be used for a bulk measurement of the degree of polymerization of the paper insulation. If the data is available, the first 2 column of Table VI is employed to add those test results to the HI calculation. If the transformer oil has been reclaimed or changed, then this test cannot give real information on the paper degradation. In such cases, the age of transformer may be used in the HI calculation as per the third column of Table VI. This table does not imply a relation between the furan test and the transformer age.

TABLE VI
FURFURAL TEST RATING OR AGE RATING WHERE TEST NOT AVAILABLE

Rating Code	Furaldehyde [ppm]	Age Years
A	0-0.1	Less than 20
B	0.1-0.5	20-40
C	0.5-1	40-60
D	1-5	More than 60
E	>5	-

D. *Power Factor*

Power factor measurements are an important source of data to monitor transformer and bushing conditions. Measurement of a transformer insulation's capacitance and power factor at voltages up to 10 kV (at 50 or 60 Hz) has long been used as both a routine test and for diagnostic purposes [5]. Table VII recommends a ranking method for the power factor of the transformer. The tests can be done in the following configurations: high-voltage winding to ground, high- to low-voltage winding, low-voltage winding to ground, high- to tertiary-voltage winding, low- to tertiary-voltage winding, and the tertiary-voltage winding to ground insulation. PF_{max} is the greatest of all the measured power factors.

TABLE VII
GREATEST POWER FACTOR RATING

Rating Code	Maximum Power Factor [%]
A	$PF_{max}<0.5$
B	$0.5 \leq PF_{max} <1$
C	$1 \leq PF_{max} <1.5$
D	$1.5 \leq PF_{max} <2$
E	$PF_{max} \geq 2$

E. *Tap Changer*

General differences between tap changers used under IEEE and IEC standards are listed in Table VIII [3]. The focus of this paper will be on North American practice in the further steps.

TABLE VIII
TAP CHANGER STANDARDS DIFFERENCES

	IEC	IEEE
Designation	OLTC	LTC
Tap selection and Arcing control method	Diverter switch	Arcing switch
	Selector switch	Arcing tap switch
Current limiting method	Mainly resistor type	Resistor and reactor type

The insulation system of a LTC usually consists of oil, cardboard, fiberglass, or epoxy resin depending on the construction. The insulation quality of the oil is of primary concern [7,9]. The rate of degradation significantly increases at temperatures above 80 ^{0}C.

There are two main sources of gas in LTCs [12]:

- Arcing gasses (mainly acetylene) are affected by speed of operation, recovery voltage, and arcing tip wear.
- Heating gasses (methane, ethane, and ethylene) are created through coking, generated by I^2R losses from lead and contact impedances.

The concentration of DGA in a LTC depends on a number of variables, including breathing type, manufacturer, LTC model, oil brand, operating current, step-voltage of the LTC, and the number of operations. Therefore it is not easy to recommend gas limits for DGA of LTCs, nor is there a standard recommendation.

Table IX proposes a scoring method for the DGA analysis of three different types of LTCs. It is based on Kinectrics Inc. common practice and other references [3,11, 12, 13]. A similar DGA factor to (1) is employed to rank the LTC based on the DGA analysis. Table II is used to rate the LTC using the calculated DGAF.

TABLE IX
RATING OF THE LTC BASED ON DGA

	Score (S_i)					
	Gas	**1**	**2**	**3**	**4**	W_i
Vacuum LTC	CH_4	<30	30- 50	50-100	$\geq$ 100	3
	C_2H_6	<20	20- 30	40-50	$\geq$ 50	3
	C_2H_4	<50	50-100	100-200	$\geq$ 200	4
	C_2H_2	<3	3- 4	4-5	$\geq$ 5	5
Resistive LTC	CH_4	<100	100- 200	200-300	$\geq$ 300	3
	C_2H_6	<50	50-100	100-200	$\geq$ 200	3
	C_2H_4	<200	200- 400	400-600	$\geq$ 600	5
	C_2H_2	<500	500- 1000	1000-5000	$\geq$ 5000	3
Reactive LTC (Diverter comp.)	CH_4	<200	200- 300	300-700	$\geq$ 700	3
	C_2H_6	<100	100- 150	150-500	$\geq$ 500	3
	C_2H_4	<300	300-500	500-1400	$\geq$ 1400	5
	C_2H_2	<1000	1000- 3000	3000-7500	$\geq$ 7500	3
Reactive LTC (Selector comp.)	CH_4	<50	50- 150	150-250	$\geq$ 250	3
	C_2H_6	<30	30- 50	50-100	$\geq$ 100	3
	C_2H_4	<100	100- 200	200-500	$\geq$ 500	5
	C_2H_2	<10	10- 20	20-25	$\geq$ 25	3

F. *Load History*

Table X presents the recommendations of IEC 354 and IEEE C57.91-1995-cor. 1-2002 with respect to conductor and oil temperature inside the transformer [14]. The numbers are close, but IEC has a more conservative recommendation for conductor temperature.

Practically, recorded monthly load peaks can be employed to contribute load history to the HI calculation. The load history is categorized according to the five groups listed below:

N_0 : Number of S_i/S_B that are lower than 0.6, i=0
N_1 : Number of S_i/S_B that are between 0.6 and 1, i=1
N_2 : Number of S_i/S_B that are between 1 and 1.3, i=2
N_3 : Number of S_i/S_B that are between 1.3 and 1.5, i=3
N_4 : Number of S_i/S_B that are bigger than 1.5, i=4

Where S_i is the monthly peak load and S_B is the rated loading of the transformer.

Equation 2 proposes a linear method of load score calculation and Table XI describes a ranking method of transformer condition using the load history data. i is an integer 0 to 4.

$$LF = \frac{\sum_{i=0}^{4}(4-i)\times N_i}{\sum_{i=0}^{4} N_i} \tag{2}$$

TABLE X
TEMPERATURE AND LOAD FACTORS SUGGESTED BY IEEE/IEC

	Standard	Normal Life Expectancy	Long Time Emergency 1-3 months	Short Time Emergency ½-2 hours
Insulated conductor hottest temp ^{0}C	IEEE	120	140	180
	IEC	120	130	160
Top oil temp ^{0}C	IEEE	105	110	110
	IEC	105	115	115
Load factor per unit current	IEEE	NA	NA	1.5 pu
	IEC	1.3 pu	1.3 pu	1.5 pu

TABLE XI
LOAD FACTOR RATING CODES

Rating Code	Description
A	LF $\geq$ 3.5
B	2.5 $\leq$ LF<3.5
C	1.5 $\leq$ LF<2.5
D	0.5 $\leq$ LF<1.5
E	LF $\leq$ 0.5

G. Maintenance Data

A ranking system was developed to quantify the maintenance work orders issued in the last five years. Infra-red thermography and bushing condition are two important factors in this evaluation. Oil leak, oil level, cooling system, main tank condition, grounding, gaskets, overall condition of transformer and LTC are also taken into account. If there is no work order in the last five years for any of these factors, the condition rating will be "A," and if it is more than 6, it will be given an "E" rating.

III. HEALTH INDEX FORMULATION

Health indexing quantifies equipment condition based on numerous condition criteria that are related to the long-term degradation factors that cumulatively lead to an asset's end-of-life. Health indexing results differ from maintenance testing, which emphasizes finding defects and deficiencies that need correction or remediation to keep the asset operating during some time period. The critical objectives in the formulation of a composite Health Index are:

- The index should be indicative of the suitability of the asset for continued service and representative of the overall asset health.
- The index should contain objective and verifiable measures of asset condition, as opposed to subjective observations.
- The index should be understandable and readily interpreted.

Considering all the discussed parameters and factors, the total HI of a power transformer is proposed in Equation (3):

$$HI = 60\% \times \frac{\sum_{j=1}^{17} K_j HIF_j}{\sum_{j=1}^{17} 4K_j} + 40\% \frac{\sum_{j=18}^{20} K_j HIF_j}{\sum_{j=18}^{20} 4K_j} \tag{3}$$

K_j and HIF_j are introduced in Table XII. Parameters 8 to 17 in Table XII can be based on visual inspection or may be derived from corrective maintenance information. A weighting factor of 40% is assigned to the LTC and 60% to the transformer. This is based on an international survey done by a CIGRÉ working group on failures in large power transformers that found that about 40% of failures were due to LTC [5].

The power transformer is rated against a set of criteria for each condition parameter. The rating (A, B, C, D, E) is converted to a factor between 4 and 0, respectively, called HIF in Table XII.

TABLE XII
HEALTH INDEX SCORING

#	Transformer Condition Criteria	K	Condition Rating	HIF
1	DGA	10	A,B,C,D, E	4,3,2,1,0
2	Load History	10	A,B,C,D, E	4,3,2,1,0
3	Power Factor	10	A,B,C,D, E	4,3,2,1,0
4	Infra-red	10	A,B,C,D, E	4,3,2,1,0
5	Oil Quality	8	A,B,C,D, E	4,3,2,1,0
6	Overall Condition	6	A,B,C,D, E	4,3,2,1,0
7	Furan or Age	6	A,B,C,D, E	4,3,2,1,0
8	Bushing Condition	5	A,B,C,D, E	4,3,2,1,0
9	Main Tank Corrosion	2	A,B,C,D, E	4,3,2,1,0
10	Cooling Equipment	2	A,B,C,D, E	4,3,2,1,0
11	Oil Tank Corrosion	1	A,B,C,D, E	4,3,2,1,0
12	Foundation	1	A,B,C,D, E	4,3,2,1,0
13	Grounding	1	A,B,C,D, E	4,3,2,1,0
14	Gaskets, seals	1	A,B,C,D, E	4,3,2,1,0
15	Connectors	1	A,B,C,D, E	4,3,2,1,0
16	Oil Leaks	1	A,B,C,D, E	4,3,2,1,0
17	Oil Level	1	A,B,C,D, E	4,3,2,1,0
18	DGA of LTC	6	A,B,C,D, E	4,3,2,1,0
19	LTC Oil Quality	3	A,B,C,D, E	4,3,2,1,0
20	Overall LTC Condition	2	A,B,C,D, E	4,3,2,1,0

IV. HEALTH INDEX RATING

By using a multi-criteria analysis approach, the various factors can be combined into an idealized condition-based Health Index. This involves grouping together the various factors, crafting the mathematical and/or logical formulations, and establishing the importance weightings of all the factors to allow combining them into a single Health Index.

Finally, Table XIII provides categories of HI results and correlates these to an expected lifetime and required action. HI values are grouped into discrete categories from “very good” to “very poor.” This aggregation into discrete categories for a condition index requires fine-tuning of the health scoring system, because it is necessary that the relative degree of severity of the scores due to “dominant” factors and those due to generalized degradation align at the boundaries between each category. This may require iteration of the individual steps to ensure that the resulting index is rational and coherent, and reasonably reflects field conditions. Kinectrics Inc. has further developed methods to relate HI to expected life based on a condition-stress model yielding a probability of failure.

TABLE XIII
HEALTH INDEX AND TRANSFORMER EXPECTED LIFETIME

HI%	Condition	Expected Lifetime	Requirements
85 – 100	Very Good	More than 15 years	Normal maintenance
70 - 85	Good	More than 10 years	Normal maintenance
50 - 70	Fair	From 3 – 10 years	Increase diagnostic testing, possible remedial work or replacement needed depending on criticality
30 - 50	Poor	Less than 3 years	Start planning process to replace or rebuild considering risk and consequences of failure
0 - 30	Very Poor	Near to the end of life	Immediately assess risk; replace or rebuild based on assessment

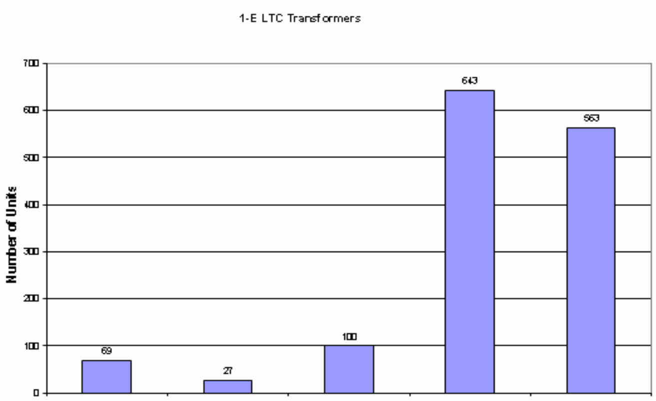

Fig. 1 Result of HI analysis for a group of power transformers

A sample of output results for power transformers of a large US utility is provided in Figure 1. In this case, 86% of transformers have a HI of more than 70% (good and very good). This classification gives a general idea to utilities about the overall health condition of the asset. Further studies to correlate the HI and probability of failure are to be presented in future.

V. CONCLUSION

Health indexing quantifies equipment condition based on numerous condition criteria that are related to the long-term degradation factors that cumulatively lead to an asset’s end-of-life. This paper described a realistic Health Index method for power transformers using available data and considering IEEE and IEC recommendations for condition parameters.

The calculation is based on weighting factors, condition ratings, and assigned scores for any specific parameter. By using a multi-criteria analysis approach, the various factors are combined into a condition-based Health Index. DGA, oil quality tests, furan, power factor, and load history are the parameters that have been used as quantitative data. The physical health condition of transformers was included using a count of corrective maintenance work orders. Some of the important factors include bushing condition, oil leak, tank corrosion, cooling system, infra-red thermography, grounding, and foundation.

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