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In-Service Distribution Transformer Health Index: Insights from Field Data

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Abstract

This study introduces the Transformer Health Index (THI), which is derived from the weighted scores of Dissolved Gas Analysis (DGA), Oil Quality Analysis (OQA), and Furan Fraction Analysis (FFA). The assessment methods include the Duval Triangle for DGA, the Chendong model for FFA, and the evaluation of breakdown voltage, acidity, and water content for OQA. The THI was applied to 120 in-service distribution transformers rated at 30 MVA, 33/11 kV. Results indicate that transformers classified as "Good" scored high in both DGA and FFA, while those rated "Fair" exhibited lower FFA scores relative to DGA. Conversely, transformers labeled "Poor" showed lower DGA scores compared to FFA, and those in the "Very Poor" category scored low in both DGA and FFA. The impact of service duration on THI indicates that transformer condition generally worsens with age. However, some newer transformers showed signs of rapid deterioration, while certain older units maintained a satisfactory health status.

Keywords

Dissolved Gas Analysis, Oil Quality Analysis, Furfural Analysis, Transformer Health Index, Distribution Transformers

1. Introduction

Transformers are among the critical and costly assets within electrical distribution networks, with failures capable of causing widespread outages and substantial economic impact. With increasing load and power consumption, utilities have been facing much difficulty in maintaining the ageing transformer fleets. As was brought up in a study [1], degradation patterns might lead maintenance costs to rise beyond RM 39 million by 2034. This factor alone stresses the urgency of monitoring the health condition of transformers in order to optimize maintenance schedules and increase the longevity of transformers. Traditionally, transformer monitoring involves determining the condition of the transformer parts such as cellulose materials, enameled copper windings, steel cores, and silver components of on-load tap changers that regulate the turns ratio of transformers [2]-[5]. For instance, dissolved gas analysis is utilize for determine internal faults, oil quality analysis is use to check the state of insulating oil, and furan fraction analysis is employ to determine insulating paper deterioration.

These well-established diagnostics are usually applied separately, resulting in perhaps uncoordinated evaluations that might miss important interplays between each other. For example, a transformer might be declared as in good condition from a DGA results but at the same time experience a severe degraded insulating paper. In other words, no single technique can comprehensively reflect the overall condition of transformer because each technique is applied independently. Hence, this study combines all three diagnostic approaches. Each diagnostic score works in order to complement each other to produce a Transformer Health Index (THI).

Keep in mind that the proposed THI incorporates only Tier 1 data, including dissolved gas analysis (DGA), oil quality analysis (OQA), and furan fraction analysis (FFA). Data from Tier 2 (Transformer Turns-Ratio, Winding Resistance, Dielectric Dissipation Factor, Excitation Current, Insulation Resistance, and Polarization Index) and Tier 3 (Frequency Response Analysis and Partial Discharge) are not included.

2. Methodology

The methodology involves in this study are: (1) Duval Triangle Method (DTM) for DGA, [6] [7], (2) breakdown voltage, acidity, and water content as OQA parameters, and (3) Chendong model for FFA, providing reliable estimates on the degree of polymerization of insulating papers [8].

DTM is user-friendly due to its graphical interpretation of gas data, allowing engineers and technicians to easily visualize fault zones. It can identify combined or mixed faults, a task that traditional ratio-based methods like the Rogers Ratio Method and IEC Ratio Method often find challenging. Additionally, DTM is recognized by IEC 60599 and widely adopted in the industry, ensuring diagnostic consistency and reliability.

The Chendong model utilizes a straightforward logarithmic equation, allowing for easy integration into condition monitoring systems without the need for complex calculations. As it is based on 2-FAL (one of the most reliable chemical indicators of paper degradation), the model closely reflects actual aging behavior. Developed from both laboratory and field data, it establishes a strong correlation between 2-FAL concentration in oil and paper aging. Its reliability has been confirmed through years of use in real-world transformer evaluations.

2.1. Dissolved Gas Analysis (DGA)

DGA via DTM [7] applies the percentages of three critical gases, namely methane (CH_4), ethylene (C_2H_4), and acetylene (C_2H_2), to determine the internal faults that occurred in a transformer. These gases are plotted on a triangular diagram, such that concentration ratios of the gases determine the location inside specified zones of the triangle, namely Partial Discharge (PD), low-energy thermal faults (T1, T2), high-energy thermal faults (T3), and electrical discharges (D1, D2), mixed thermal and electrical fault (DT) using **Figure 1**. The concentration ratios can be calculated using the following Equation (1), (2), and (3) [7].

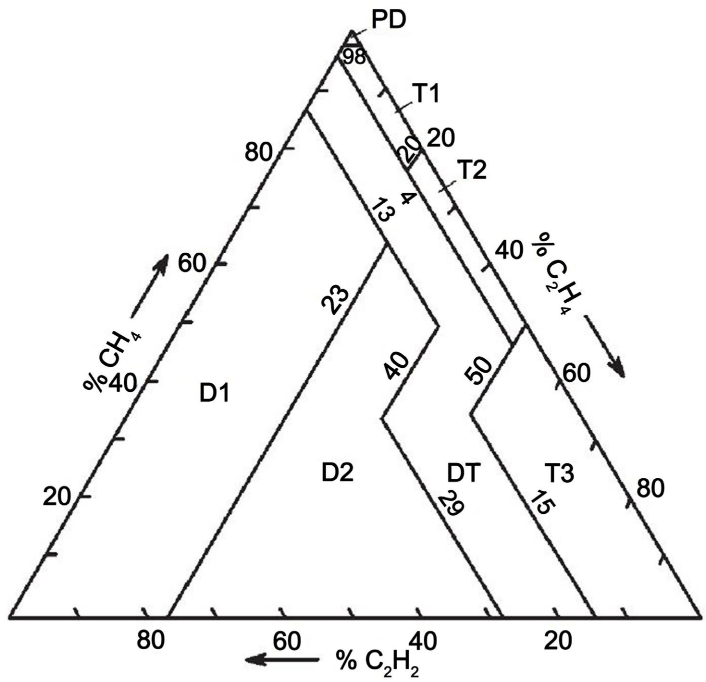

Figure 1. Coordinates and fault zones of the Duval Triangle Method [7].

$$\%CH_4 = \frac{CH_4}{CH_4 + C_2H_4 + C_2H_2} \times 100 \quad (1)$$

$$\%C_2H_4 = \frac{C_2H_4}{CH_4 + C_2H_4 + C_2H_2} \times 100 \quad (2)$$

$$\%C_2H_2 = \frac{C_2H_2}{CH_4 + C_2H_4 + C_2H_2} \times 100 \quad (3)$$

DGA severity, that assess the condition of transformers by classifying their internal fault types through DGA is shown in **Table 1**. Each fault type (PD, T1, T2, T3, D1, D2, DT) identified via the DTM is assigned a numerical severity between 0.1 and 1.0.

The severity represent the risk level associated with each fault, where higher severity corresponds to less critical faults, and lower severity indicate more critical internal fault conditions.

Table 1. DGA severity [9] [10].

Internal fault type	Risk level	DGA severity
None	Very low	1.0
PD	Low	0.8 - 0.9
T1	Medium-low	0.6 - 0.8
T2	Medium	0.5 - 0.6
T3	Medium	0.4 - 0.5
D1	High	0.3 - 0.4
D2	Critical	0.2 - 0.3
DT	Very critical	0.1 - 0.2

For example, a PD fault might receive a severity of 0.85 due to its relatively minor impact, while a D2 fault, linked to high-energy discharges causing major damage, could be scored at 0.25. By translating fault categories into severity-based rating, **Table 1** assists converting qualitative fault type data into a quantitative format suitable for integration into the overall THI model.

2.2. Oil Quality Analysis (OQA)

OQA is employed to evaluate the condition of transformer insulating oil, which is essential for both cooling and insulating of the transformer. Three parameters were utilized: breakdown voltage, acidity, and water content. Breakdown voltage indicates the oil's ability to withstand electrical stress; a low breakdown voltage suggests possible contamination or degradation. Acidity measures the chemical ageing of the oil, with higher acidity pointing to the presence of by-products that can accelerate insulation deterioration. Water content is also essential, as even small amounts of water can impair the insulating properties of the oil and hasten the deterioration of insulating paper. Collectively, these parameters offer insights into the overall condition of the transformer oil. **Table 2** shows the severity of OQA parameters (breakdown voltage, acidity and water content).

Table 2. Severity of OQA parameters [11].

Parameter	Risk level			
	Good	Fair	Poor	Critical
Breakdown voltage (kV)	>50	45 - 50	40 - 45	<40
Acidity (mg KOH/g)	<0.10	0.10 - 0.15	0.15 - 0.20	>0.20
Water content (ppm)	10 - 20	20 - 25	25 - 30	>30
Severity	0.70 - 1.0	0.50 - 0.70	0.30 - 0.5	0.10 - 0.30

The OQA severity is calculated via Equation (4)

$$\text{OQA severity} = \frac{(x \times 0.169) + (y \times 0.139) + (z \times 0.108)}{0.169 + 0.139 + 0.108} \quad (4)$$

where x = breakdown voltage's severity, y = Acidity's severity × 0.139, and z = water content's severity.

Each parameter applied a severity from 0.1 to 1.0, where a higher severity means better oil condition. For instance, a high breakdown voltage accompanied by low amounts of acidity or water content will almost have a severity of 0.9, suggesting that it is healthy insulating oil. Conversely, lower breakdown voltage or higher quantities of water content or acidity mean deterioration and lessen the severity. These severity account for the quality of the oil and are further aggregated with their respective weighted score [11] (*i.e.*, 0.169, 0.139, and 0.108 for breakdown voltage, acidity, and water content respectively) to find the OQA severity, which contributes to the overall THI model.

2.3. Furan Fraction Analysis (FFA)

FFA is used to evaluate the condition of insulating paper of transformer, which naturally deteriorates over time due to heat, chemical reactions, and electrical stress. As the paper ages, it produces chemical by-products called furans, which dissolve into the insulating oil. By measuring these furans, FFA provides an estimate of how damaged the insulating paper has become. A critical metric in this assessment is called Degree of Polymerization (DP), which reflects the strength of the cellulose fibres within the paper. A high DP indicates healthy, well-preserved insulation, while a low DP signals ageing insulation.

However, directly determining DP involves removing and testing the insulation, which is impractical for active transformers. Instead, FFA estimates DP indirectly through models such as the Chendong model, which translates furan concentrations into approximate DP values as in Equation (5).

$$\mathrm{DP} = \frac{1.51 - \log 2\mathrm{FAL}}{0.0035} \tag{5}$$

The Chendong model's ability for providing non-invasive, precise estimations of insulating paper's condition makes it a valuable instrument in transformer diagnostics. FFA severity is listed in **Table 3**.

Table 3. FFA score [8] [12].

DP value	>800	600 - 800	450 - 600	<450
FFA severity	0.7 - 1.0	0.5 - 0.7	0.3 - 0.5	0.1 - 0.3

The FFA severity is from 0.1 to 1.0, where better DP values receiving higher rating, indicating healthier insulation. This scoring permits furan statistics to be translated into a measurable health indicator, contributing substantially to the overall THI model.

2.4. Transformer Health Index (THI)

The combination of DGA, OQA, and FFA weighted scores gives a complete THI. Each analysis offers independent information about the transformer's insulation system. Yet, while combined, yields an assessment of the transformer's health. THI is calculated by combining the weighted scores of DGA, OQA, and FFA (see Table 4) using Equation (6).

$$\text{THI},\% = (a+b+c)\times 100 \quad (6)$$

Table 4. Weight factor of the transformer health index parameters [11].

Factor	*a*	*b*	*c*
Weighted score	DGA severity × 0.348	OQA severity × 0.216	FFA severity × 0.436

Table 4 shows how DGA, OQA, and FFA contributes to the health index of a transformer: DGA (34.8%), OQA (21.6%), and FFA (43.6%). FFA having the very highest weight because insulating paper degradation is irreversible.

The THI (Equation (6)) is then compared with Table 5, which classify the transformer's condition as Good, Fair, Poor, or Very Poor.

Table 5. Transdormer health index (THI).

THI	70 - 100	50 - 70	30 - 50	0 - 30
Grade	Good	Fair	Poor	Very poor

Based on the THI classification, the suggested actions are as follows: for a "Good" rating, continue data collection at a 1-year interval; for "Fair," adjust the data collection frequency to every 6 months; for "Poor," decrease the transformer loading; and for "Very Poor," plan for significant repair, upgrade, or replacement.

3. Results and Discussion

Table 6 shows sample data: 10 out of the 120 units of in-service transformers. Data of dissolved gases, namely methane (CH_4), ethylene (C_2H_4), and acetylene (C_2H_2), breakdown voltage (BDV), acidity, water content, and 2-Furaldehyde (2FAL) were collected from 120 units of 30MVA, 33/11 kV in-service distribution transformers in Peninsular Malaysia.

Table 6. Data of 10 units of in-service transformers.

ID	Age (years)	CH_4 (ppm)	C_2H_4 (ppm)	C_2H_2 (ppm)	BDV (kV)	Acidity (mg KOH/g)	Water content (ppm)	2FAL (ppb)
1	50	0	12	6	58	0.08	137	15641
2	36	4	1	0	56	0.01	13	115
3	27	0	7	7	42	0.02	17	145
4	30	15	10	11	31	0.19	41	115
5	29	5	7	0	66	0.09	14	396
6	41	4	2	8	28	0.22	60	2756
7	40	3	0	0	38	0.03	32	757

Continued

8	61	11	19	0	47	0.02	34	1112
9	30	35	141	343	60	0.03	23	293
10	30	199	50	0	22	0.04	35	7

The dissolved gases were determined via Gas Chromatography. Breakdown voltage, acidity, and water content were measured according to ASTM D1816, ASTM D664, and ASTM D1533 respectively. Data of 2FAL were collected through High Performance Liquid Chromatography (HPLC) technique, executed according to ASTM D5857.

Table 7 shows results of DGA, OQA, and FFA severity, as well as THI of the 10 transformer sample under consideration.

Table 7. Severity (DGA, OQA, FFA), THI and Grade of 10 units of in-service transformers.

ID	Age (years)	DGA severity	OQA severity	FFA severity	THI (%)	Grade
1	50	1.00	0.72	0.20	58.20	Fair
2	36	0.70	0.90	0.60	69.96	Fair
3	27	1.00	0.70	0.60	75.37	Good
4	30	0.25	0.27	0.60	40.62	Poor
5	29	0.45	0.90	0.40	52.24	Fair
6	41	0.35	0.20	0.20	25.22	Very poor
7	40	0.90	0.43	0.40	58.13	Fair
8	61	0.35	0.60	0.20	33.78	Poor
9	30	0.25	0.82	0.40	43.90	Poor
10	30	0.70	0.43	0.90	72.97	Good

Figure 2 shows weighted scores of DGA, OQA, and FFA throughout the 10 transformers, alongside their corresponding THI grades. By combining these 3 weighted scores into a THI (expressed in percentage), a complete assessment of the transformer overall condition is classified into four grades (*i.e.*, good, fair, poor, and very poor).

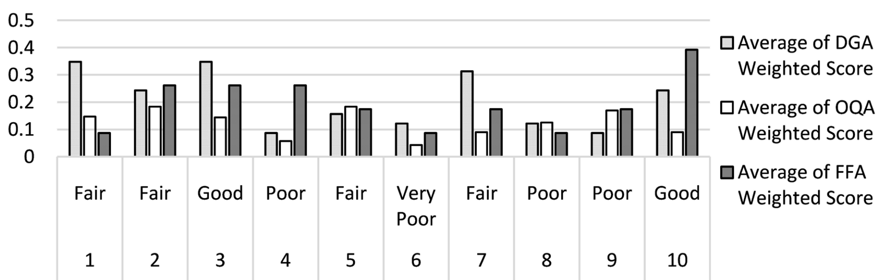

Figure 2. Weighted scores (DGA, OQA, FFA) of 10 units of in-service transformers.

Figure 2 reveals several key patterns: transformers labelled as "Good" (Transformer 3 and 10) show high DGA and FFA score. In comparison, Transformer 6, rated "Very Poor", shows a critically low score in all categories, with its FFA score being poor, indicating extreme paper insulation degradation. The "Fair" and "Poor" rated transformers showcase blended styles, some hold slight OQA and DGA scores despite lower FFA score (e.g., Transformer 7), at the same time as others display balanced but suboptimal performance throughout all metrics (e.g., Transformer 5). Notably, the FFA score appears to be the large differentiator among THI, underscoring its dominant role inside the THI assessment. **Figure 3** shows the grade of 120 units of in-service transformers by their age group.

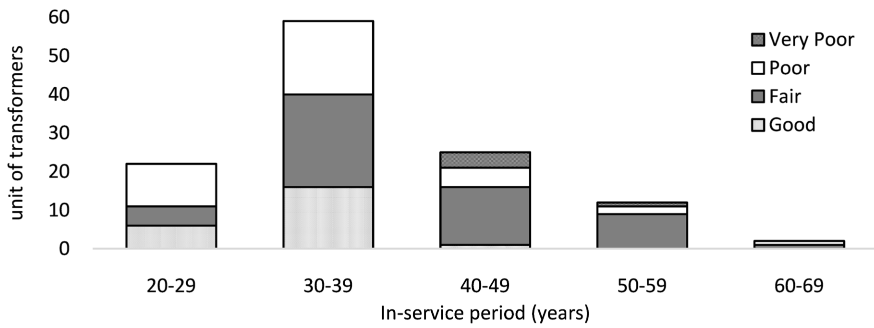

Figure 3. Grade of in-service transformers by their in-service period (years) group.

The 30 - 39 age group includes the most transformers, where most of them fall into "Good" and "Fair" health categories. The units in this age group show signs of ageing yet most remain operational, indicating the health condition of transformers deteriorates as their age increases. The 40 - 49 age group demonstrates a shift toward "Fair", "Poor", and "Very Poor" conditions which indicates the progressive breakdown of insulation and internal components. Most units in the 50 - 59 and 60 - 69 age groups receive "Fair" or "Poor" ratings while "Good" condition units remain scarce. The observed trend shows the natural degradation which occurs in ageing transformers. Some units in older age groups show acceptable health status, may result from proper maintenance practices and reduced operational stress. The 20 - 29 age group contains transformers with "Good" and "Fair" grades but only a few units have "Poor" condition. The data shows that most recent transformers function properly yet some units from this group may already display early signs of ageing.

Regarding limitations, the proposed THI models may not consider variations in transformer designs (such as power transformers), loading conditions, or environmental factors. Rather than representing the actual operational risk, the THI serves as a predictive tool to support asset management strategies.

4. Conclusion

The proposed Transformer Health Index (THI), formulated through weighted integration of Dissolved Gas Analysis (DGA), Oil Quality Analysis (OQA), and Furan Fraction Analysis (FFA), offers a framework for assessing transformer condition. Diagnostic methods utilized include the Duval Triangle for internal fault classification, the Chendong model for Degree of Polymerization (DP), and key OQA parameters (breakdown voltage, acidity, and moisture content). Application of the THI to a dataset of 120 in-services 30 MVA, 33/11 kV distribution transformers demonstrated clear differentiation across health categories. "Good" units presented consistently high DGA and FFA scores, while deviations between these parameters in "Fair" and "Poor" categories indicated varied degradation modes. "Very Poor" units exhibited uniformly low DGA and FFA scores. Furthermore, the analysis established a general correlation between operational age and declining THI values. Nonetheless, exceptions such as accelerated deterioration in relatively newer units and sustained performance in some older transformers, highlight the need for condition-based maintenance strategies over age-based assessments alone.

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Conflicts of Interest

Authors state no conflict of interest.

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