
# Transformer assessment using health index – Part I

## Sensitivity analysis and critical discussion


### ABSTRACT

Health Index (HI) is a very popular asset management tool. Several methods have been used to determine the transformer HI using the popular “scoring” and “weighting” method, which are now extended / improved using fuzzy logic, regression neural network, support vectors machine, etc. However,

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not much work has been documented on the sensitivity analysis of the “scoring” and “weighting” method. This paper presents a critical review of the “scoring” and “weighting” method by performing sensitivity analysis which shows the masking of issue(s) using this approach. The need for a risk of a failure-based approach based on non-linear scoring is discussed.

**KEYWORDS**

asset management, condition assessment, fault tree analysis, health index, risk of failure

**HI is calculated based on multiple data sources; based on the HI score, asset managers prioritise the next steps - be it asset replacement, repair, or refurbishment**

## 1. Introduction

Over the years, transformer health indexing (HI) has become a popular tool for performing transformer health assessments on a larger fleet of transformers. HI is a tool that allows asset engineers / managers to make informed decisions by processing available data of the transformer and convert those into an overall "condition" score. This condition is usually based on "scores" and "weighting", which are calculated from a set of algorithms designed to evaluate both field conditions, inspection results, on-site test results, etc. Sometimes there are additional sub-algorithms which assess different subsystems of the transformer, and the subsystem tiered values are finally combined to form the final HI, which corresponds to the overall condition of the transformer.

The first model was proposed in [1,2]. In this model, HI was developed as a practical tool, which combined results from the laboratory and field tests, field inspections, and general operating conditions. All the data was then combined and converted to a quantitative index which represents the overall health of the transformer. There are three basic requirements to develop this index: inputs, algorithms, and outputs. Inputs can range from quantities, measured regularly as part of routine maintenance by the power transformer owner, such as:

- Dielectric strength, dissipation factor, acidity, moisture, colour, and interfacial tension of the oil
- Dissolved gas content of the oil
- Furans content of the oil
- Transformer load and age.

Algorithms can range from simple weighted average [3], logarithmic scoring [4], tiered approach [5], group scoring [6], subset indexing [7], fuzzy logic [8], regression neural network [9], etc. Other widely used models include [10] and [11]. Outputs can be constructed in many ways. The classification designed in [1,2] with an expected lifetime is shown in Table 1.

In [7] the outputs have been constructed as listed in Table 2.

Based on the HI score, asset managers prioritise the next steps - be it asset replacement, repair, or refurbishment. However, neither do HI scores show the urgency of the next steps nor do they associate any consequence of the failure of a transformer with a good HI. HI scores additionally do not show the masking of one failure mode due to a poor choice of weights for another failure mode. Each "scoring" and "weighting" model requires the decision of experienced utility engineers to set up the score and weight number of considered items for the analysis. This is where the limitations of this approach are evident:

- **Weighting assessment of the model** - Is dielectric strength more important than moisture, or is oil colour more important than acidity, or which dissolved gas has the highest weight? Is it always acetylene?
- **Sensitivity analysis of the model** - Lack of sensitivity analysis of the health index model. Varying the scores / weights of the different parameters in order to identify the

Table 2. Health index scoring scale - Interpretation as in [7]

| HI | Status | Failure rate |
|---|---|---|
| 0 - 3.5 | Slightly aged | Low |
| 3.5 - 5.5 | Aged but in normal range | Relatively low |
| 5.5 - 7.5 | Ageing beyond normal | Significant increase |
| 7 - 10 | Poor state | Fault may happen any time |

Table 1. Health index scoring scale - Interpretation as in [1,2]

| HI | Condition | Description | Expected Lifetime |
|---|---|---|---|
| 85 - 100 | Very Good | Minor deterioration | ≥ 15 years |
| 70 - 85 | Good | Significant deterioration | ≥ 10 years |
| 50 - 70 | Fair | Widespread deterioration | Up to 10 years |
| 30 - 50 | Poor | Serious deterioration | ≤ 3 years |
| 0 - 30 | Very Poor | Extensive deterioration | At end-of-life |

importance of each parameter and to determine the most important parameter and dismiss those without significantly affecting the effectiveness of the model? Is this possible?

To answer some of the questions above, the paper is divided into the following sections:

- Section 2 presents a review of the existing literature for HI models with the focus on parameters selected for the HI model.
- Section 3 presents the sensitivity analysis of the "scoring" and "weighting" method.
- Section 4 presents the critical review and the discussion on the need for a more sensitive model.

## 2. Traditional health index: Parameter selection

The CIGRÉ working group A2.37 published the transformer failure survey [12] and a revised version [13]. Based on this, failure modes, failure causes (based on kV), and the position of failures were identified. Key findings in [13] include:

- **Failure mode:** Based on 964 transformers, the dielectric failure mode was the predominant one with 36.62 %, followed by mechanical failure at 20.02 %. Around 12.66 % of the cases were due to unknown causes!
- **Failure causes:** Failure causes include ageing (12.34 %), external short circuit (11.62 %), improper repair (6.02 %), etc. However, the majority (29.05 %) is unknown.
- **Failure position:** The three most common failure positions include: winding (47.4 %), bushing (14.4 %), and tap changer (23.2 %), while other positions did contribute to the failure, but in minor percentages.

Based on the above, different models have used a different number of inputs to identify failure modes. Some of the common parameters include dissolved gas analysis (DGA), oil quality parameters (dielectric strength, dissipation factor, acidity, moisture, colour, and interfacial tension of the oil), furans, etc. Others have included transformer age, loading history, tap-changer and bushing data, maintenance data, etc. In [2],

**Compared to traditional methods for identifying failure modes, HI model is considered a more reliable indicator of transformer overall health since it takes into account the time a transformer has been in service and its loading history**

Table 3. Health index scoring (parameter list)

| # | Parameter |
|---|---|
| 1 | DGA |
| 2 | Load history |
| 3 | Power factor |
| 4 | Infrared thermography |
| 5 | Conductivity factor |
| 6 | Polarisation index |
| 7 | Furan compound content |
| 8 | Oil quality |
| 9 | Overall transformer condition |
| 10 | Leakage reactance |
| 11 | Winding resistance |
| 12 | Bushing condition |
| 13 | Frequency response analysis |
| 14 | DGA of LTC |
| 15 | Turns ratio oil |
| 16 | LTC condition |
| 17 | LTC oil quality |
| 18 | Age |
| 19 | Paper Insulation factor |
| 20 | Inspection and maintenance |
| 21 | Internal faults history |
| 22 | Dielectric breakdown test |
| 23 | Water content |
| 24 | Surge arrestor |
| 25 | Cooling equipment |
| 26 | Location |
| 27 | Tank corrosion |
| 28 | Core-to-ground connection |
| 29 | Oil leaks |
| 30 | Oil level |
| 31 | Others – gaskets / seals, foundation, grounding, connectors conservator tank, PT / CT, cable box, manufacture, protection equipment, neutral grounding reactor |

> **The health index is calculated as a sum of weighted scoring parameters associated with the faults for different parts and systems; transformer with HI score of 100 has "excellent" health while less than 30 represents "poor" health**

24 parameters were used, and in [14], 27 parameters were used. In [15], a comparative study was carried out between the HI models proposed in [3] and [16], showing that the HI model [16] is a more reliable indicator of transformer overall health as this model takes into account the time a transformer has been in service and its loading history. In [17], an artificial neural network (ANN) approach used only 7 parameters, whereas in [18], 3 parameters have been used. As can be concluded, so far, there has been no fixed parameters for the calculation of HI. A generalised list compiled from different models is shown in Table 3.

Furans correlating DP, along with breakdown voltage and dissolved combustible gases, are listed as the most important parameters to estimate the HI, as in [8, 19]. The ranking used for DP is listed in Table 4, as in [20].

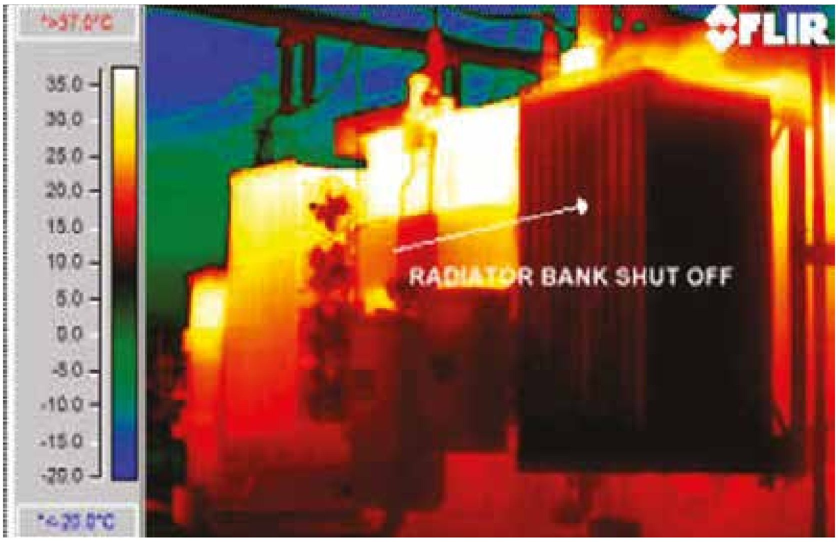


Figure 1. Thermal imaging of transformers

Table 4. Furans

| DP Value | Condition |
|---|---|
| DP ≥ 900 | Healthy |
| 900 < DP ≤ 350 | Moderate deterioration |
| 350 < DP ≤ 200 | Extensive deterioration |
| DP < 200 | End of life |

There is a wide range of variability among the furan and DP data with different equations proposed by various researchers, as in [21]. Any HI that is developed must rely on this fact before assigning scores and subsequent decisions. Similar to the choice of parameters, the choice of "weights" is also very important. The next section presents the sensitivity analysis carried out on the original HI model to show the limitations of the "scoring" and "weighting" method.

## 3. Traditional health index: Sensitivity analysis

As in [2], the overall HI is calculated as follows:

$$HI = 60\% \times \frac{\sum_{n=1}^{21} K_j HIF_j}{\sum_{n=1}^{21} 4K_j} + 40\% \times \frac{\sum_{n=22}^{24} K_j HIF_j}{\sum_{n=22}^{22} 4K_j} \quad (1)$$

where $K_j$ – weighting, and $HIF_j$ – scoring parameters, as listed in Table 5. A weighting factor of 40 % is assigned to the LTC, and 60 % to the other transformer parameters, as per CIGRÉ transformer failure survey [12]. Once the calculation of the overall HI is performed, 100 represents "excellent" transformer health while less than 30 represents "poor" health. Such a scoring system presents an "easy / understandable" tool for representing the overall health of a fleet of power transformers.

### 3.1 Sensitivity analysis

#### 3.1.1 The perfect transformer

The perfect transformer will have the highest scores in every condition criterion. The HI for the perfect transformer will be 100, as listed in Table 6.

#### 3.1.2 Infrared scan

In case of a malfunction that stops or restricts the flow of oil through a radiator, the malfunction can be easily detected by the infrared scan. The infrared scan image will reveal the areas where the oil flow is restricted and brighter areas where normal oil flow is taking place, as shown in Fig. 1.

Assuming all other parameters are "perfect", the HI scoring for no oil flow restriction to all the radiator blockage is shown in Table 7. Even under the condition of completely blocked radiators with a scoring parameter of $HIF_4$ (infrared) = 0, the HI score drops to 93.75, which indicates a very healthy HI score, as shown in Table 1.

#### 3.1.3 Load factor

The load factor (LF) is calculated as a linear interpolation of load score based on rated base load versus monthly peak load. The LF is classified as listed in Table 8.

Assuming a partially blocked radiator with $HIF_4$ (infrared) = 2, and variation of $HIF_2$ (load history) from 0 to 4, the calculated health indexes (assuming all other parameters have the best score of 4), are shown in Table 9.

Under these conditions, the worst health index calculated is 90.63, which again points towards a healthy transformer.

#### 3.1.4 Dissolved gas analysis

In this case, the DGA factor is calculated as:

$$DGAF = \frac{\sum_{n=1}^{7} S_i \times W_i}{\sum_{n=1}^{7} W_i} \qquad (2)$$

where $S_i$ = 1, 2, 3, 4, 5, or 6, and $W_i$ is the assigned weighting factor. The values for $W_i$ are: CO and $CO_2$ = 1; $CH_4$, $C_2H_6$, and $C_2H_4$ = 3, $C_2H_2$ = 5, and $H_2$ = 2. To calculate the DGAF factor, the following DGA results due to overheating [22] are used: $H_2$ = 29, $CH_4$ = 204, $C_2H_6$ = 264, $C_2H_4$ = 17, $C_2H_2$= 0, CO = 24, $CO_2$ = 2000. The calculated DGAF = 2.27, which translates to a rating of $HIF_1$ (DGA) = 1. The overall health index is shown in Table 10.

Even under these conditions, the calculated health index is 89.06, which indicates a healthy transformer.

### 3.2 Inference

Based on the sensitivity analysis, despite several known issues, the HI model gives a score indicating a healthy transformer. There have been many attempts to overcome this problem. One such approach proposed in [23] was to reduce the required condition monitoring tests in the

Table 5. Health index scoring - model [2]

| # | Condition criteria | K | 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 | Infrared | 10 | A, B, C, D, E | 4, 3, 2, 1, 0 |
| 5 | Oil quality | 6 | A, B, C, D, E | 4, 3, 2, 1, 0 |
| 6 | Overall condition | 8 | A, B, C, D, E | 4, 3, 2, 1, 0 |
| 7 | Furan or age | 5 | A, B, C, D, E | 4, 3, 2, 1, 0 |
| 8 | Turns ratio | 5 | A, B, C, D, E | 4, 3, 2, 1, 0 |
| 9 | Leakage reactance | 8 | A, B, C, D, E | 4, 3, 2, 1, 0 |
| 10 | Winding resistance | 6 | A, B, C, D, E | 4, 3, 2, 1, 0 |
| 11 | Core-to-ground | 2 | A, B, C, D, E | 4, 3, 2, 1, 0 |
| 12 | Bushing condition | 5 | A, B, C, D, E | 4, 3, 2, 1, 0 |
| 13 | Main tank corrosion | 2 | A, B, C, D, E | 4, 3, 2, 1, 0 |
| 14 | Cooling equipment | 2 | A, B, C, D, E | 4, 3, 2, 1, 0 |
| 15 | Oil tank corrosion | 1 | A, B, C, D, E | 4, 3, 2, 1, 0 |
| 16 | Foundation | 1 | A, B, C, D, E | 4, 3, 2, 1, 0 |
| 17 | Grounding | 1 | A, B, C, D, E | 4, 3, 2, 1, 0 |
| 18 | Gaskets / seals | 1 | A, B, C, D, E | 4, 3, 2, 1, 0 |
| 19 | Connectors | 1 | A, B, C, D, E | 4, 3, 2, 1, 0 |
| 20 | Oil leaks | 1 | A, B, C, D, E | 4, 3, 2, 1, 0 |
| 21 | Oil level | 1 | A, B, C, D, E | 4, 3, 2, 1, 0 |
| 22 | DGA of LTC | 6 | A, B, C, D, E | 4, 3, 2, 1, 0 |
| 23 | LTC oil quality | 3 | A, B, C, D, E | 4, 3, 2, 1, 0 |
| 24 | LTC condition | 5 | A, B, C, D, E | 4, 3, 2, 1, 0 |

**In the traditional HI approach, if few systems fail, that may not be detected if all other systems are healthy; in that case, HI score would have a high value**

Table 6. Perfect transformer health index

| Rating code | Overall HI |
|---|---|
| A (Score = 4) | 100 |

Table 7. Transformer health index with radiator blockage

| Rating code | Overall HI |
|---|---|
| A (Score = 4) | 100 |
| B (Score = 3) | 98.5 |
| C (Score = 2) | 96.88 |
| D (Score = 1) | 95.31 |

Table 8. Load factor rating codes

| Rating code | Description |
|---|---|
| A (Score = 4) | LF ≥ 3.5 |
| B (Score = 3) | 2.5 ≤ LF < 3.5 |
| C (Score = 2) | 1.5 ≤ LF < 2.5 |
| D (Score = 1) | 0.5 ≤ LF < 1.5 |
| E (Score = 0) | LF < 0.5 |

Table 9. Transformer health index with radiator blockage and high load

| Rating code | Overall HI |
|---|---|
| $HIF_4$ (infrared) = 2, $HIF_2$ (LF) = 4 | 96.88 |
| $HIF_4$ (infrared) = 2, $HIF_2$ (LF) = 3 | 95.31 |
| $HIF_4$ (infrared) = 2, $HIF_2$ (LF) = 2 | 93.75 |
| $HIF_4$ (infrared) = 2, $HIF_2$ (LF) = 1 | 92.19 |
| $HIF_4$ (infrared) = 2, $HIF_2$ (LF) = 0 | 90.63 |

computational method of [2] by restructuring the associated weights of each test to eventually eliminate some conditions. The number of condition parameters was reduced from 24 to 15, parameters such as main tank corrosion, cooling equipment, oil tank corrosion, foundation, grounding, gaskets and seals, connectors, oil leaks, and oil levels are designated as "ambiguous" and grouped under visual inspection. The furan measurement is not considered.

In part II of this paper, we will discuss sensitivity analysis of two new methods- modified scoring and weighting method, tiered scoring and weighting methods and discuss the need for a new approach.

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Table 10. Transformer health index with radiator blockage, high load, and poor DGA results

| Rating code | Overall HI |
|---|---|
| $HIF_4$ (infrared) = 2, $HIF_2$ (LF), $HIF_1$ (DGA) = 1 | 89.06 |


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