Transformer assessment using health index – Part II

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, not much

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Tiered "scoring" and "weighting" method is introduced as an attempt to fix the issue of misdetection of the malfunctioning transformer as healthy using the HI method

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

It is difficult to get the scoring and weighting correct; there is no standard to adhere to, and all the weighting factors differ depending on the expert assessment

3.3 Pitfalls of modified "scoring" and "weighting" approach

The pitfalls of this modified "scoring" and "weighting" approach is very evident. The new scoring model is listed in Table 11, and the rating codes are listed in Table 12.

Assuming the transformer has a perfect DGA, excellent oil quality, good thermal scan profile, good load profile, etc., but there is an issue with the foundation and / or anchorage of the transformer, from the visual inspection, a rating of E with score = 0 is decided.

Table 11. Health index scoring model [23]

#	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	Visual inspection	10	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	DGA of LTC	6	A, B, C, D, E	4, 3, 2, 1, 0
14	LTC oil quality	3	A, B, C, D, E	4, 3, 2, 1, 0
15	LTC condition	5	A, B, C, D, E	4, 3, 2, 1, 0

Table 12. Visual inspection rating codes

Rating code	Description
A (Score = 4)	Good, normal operation
B (Score = 3)	Acceptable, 1 - 2 items have a problem
C (Score = 2)	Caution, 3 items have a problem
D (Score = 1)	Poor, 4 items have problem
E (Score = 0)	Very poor, more than 4 items have a problem

The overall health index is calculated as 93.3, which represents a very healthy score. However, foundation issues may result in the failure of both Class 1 and Class 2 components, as follows:

1) Class 1:

- Failure of transformer internal parts
- Relative movement of the transformer and the radiator leading to oil leaks
- Failure of the structural support system for the conservator
- Failure of the pipe connection between the conservator and transformer tank, which may result in an oil spill, etc.

2) Class 2:

- Inertial loads on bushings due to tilting and subsequent bushing failure
- Failure of the lightning arrester and tertiary bushing, which require full replacement due to limited flexibility of bus support structures.

3.4 Tiered "scoring" and "weighting" approach

In [24], a tiered "scoring" and "weighting" was introduced. Tier 1 served as the base to determine the presence of faults (DGA), the quality of the insulating oil (OQF), degradation insulation paper (furan), as well as physical and operating performance of the transformers. Tier 2 is applied if Tier 1 tests classify a transformer having HI < 55 (poor / very poor). Tier 2 involves the diagnostics of transformer turns ratio, winding resistance, tan delta, excitation current and insulation resistance, and polarisation index measurements. Tier 3 will then be performed if Tier 2 tests again classify the condition of a transformer as poor / very poor. Tier 3 involves advanced diagnostic tests such as FRA and partial discharge (PD) measurement. Each parameter has been assigned to a certain weighting factor and scores as listed in Table 14.

With the worst ranking for thermography and physical condition, TH1 = 60. This classifies as "fair" with the recommendation to either maintain or revise the frequency of tests to a six-month interval. Whether this is adequate or not, is for experts to decide. There is a correlation between DGA, load, bad thermography, etc., and this may cause the parameters to violate the limits before the six-month interval. Until such correlations are adequately addressed in any model, the conventional time frame for retesting in six-months' time needs to be questioned.

There is no risk of failure associated with this transformer with bad "thermography" and "physical condition". Similarly, in [25,26] a HI model was developed that combined transformer test data: dielectric and thermal conditions (DGA, furan), mechanical conditions (sweep frequency response analysis), oil condition, and non-transformer dependent data, such as lightning frequency, substation layout, and external events.

Any of the above will result in transformer failure, and it is difficult to get the weighting correct. Several permutations and combinations that need to be carried out make this "scoring" and "weighting" method difficult. Additionally, there is no standard to adhere to, and all the weighting factors differ depending on the expert assessment. This shows that HI based models are not modelled on reliability centred maintenance (RCM) approach. RCM always ensures the following:

- Transformer functionality is always maintained.
- Every individual component of a transformer maintains its functionalities to maintain the overall transformer functionality.

Drawback of HI method is the false estimation of the healthy transformer in the case when most of the failure mode scores are good, and only one or two failure mode scores are bad; the overall score will mask the issue associated with the faulty system

Table 13. Transformer health index with a very poor visual inspection

Rating code	Overall HI
HIF_7 (visual inspection) = 0	93.3

- Identification of different failure modes and prioritisation of failures.
- Identification and prioritisation of maintenance / refurbishment or replacement to control failure modes.

3.5 Limitations of using health index

3.5.1 Masking of failure modes

The sensitivity analysis study clearly demonstrated that the overall assessment score masks a bad failure mode. As shown, when most of the failure mode scores are good, and only one or two failure mode scores are worse, the overall assessment will mask the issue associated with the worse failure mode. An option is to decouple failure modes or use the worst-case scoring in the overall assessment.

3.5.2 Data quality

The quality of health assessment ultimately depends on incoming data quality - be it the accuracy of data or completeness of data. Sometimes the DGA data for the main tank is available whereas from the OLTC compartment it is not available. It is paramount to understand what it means not to have data or below-par data. It is essential to understand the questions below:

- Is the new incoming data "normal"? What is "normal"?
- Is the new data a statistical outlier?
- Why is it important to know if it is an outlier?
- Does the sensor output make sense at all?
- Is there a trend? Is there a sudden trend? How critical or significant is the trend?
- What is the reliability of the incoming data?

3.5.3 "What next" scenario

Health index does not provide any indication on the urgency of follow up action

Table 14. Tiered "scoring" and "weighting" approach

Condition indicator	Weighting factor	Ranking	Amplified ranking	Total
DGA	1.2	3	20	24
OQA	1.2	3	20	24
FFA	1.2	3	20	24
Thermography	0.6	0	-20	-12
Physical/op condition	0.4	0	-20	-8
Age	0.4	3	20	8
			Tier 1 total (TH1)	60

Health index does not provide any indication on the urgency of follow-up action for transformers with poor scores, nor does it provide any indication of what should be done next

for transformers with poor scores, nor does it provide any indication of what should be done next. Whether the transformer needs to be replaced, repaired or refurbished is not answered.

3.5.4 No associated risk

There is no risk associated with the failure of the transformer with a HI score = 100. There is a need to address this concern. The question on "what if a transformer with good HI score fails" is not answered by "scoring" and "weighting" method.

4. The requirement of a new approach

The new approach / alternative to HI based asset management strategy should be based on the following:

- Decoupled failure mode analysis - probabilistic fault tree-based analysis [29]
- Inclusion of the probability of failure and risk associated with failure
- Inclusion of replacement or repair / refurbishment scoring based on economics [30].

The CIGRÉ Working Group A2.49 [28] published the laid down general guidelines for transformer assessment index development, including the use of on-line monitors. A detailed summary and advantages / disadvantages of aggregation methods used to calculate HI has been listed. These methods include:

- Weighted sum
- Sum of non-linear scores
- Worst case
- Statistical regression
- Artificial intelligence

Detailed tables are provided for condition assessment of different factors, such as:

- Dielectric condition assessment - core assessment, winding insulation
- Thermal condition assessment
- Mechanical condition assessment
- Bushing condition assessment
- Cable box assessment
- OLTC assessment
- Cooler / radiator condition assessment
- Oil (mineral / natural ester / synthetic ester) assessment.

The scoring matrix developed by the working group has six levels - Level A (minimal signs of deterioration) to Level E (very poor condition), with Level F (denoting de-energise as soon as possible) not used for scoring but for immediate action. Each level is colour coded for easy visualisation. The basic steps to develop the transformer assessment index (TAI) are listed below [28]:

1. Determine the purpose of the TAI
2. Identify the failure modes to be included in the TAI
3. Determine how each failure mode will be assessed
4. Design a calibrated system for categorising failure modes (scoring matrix)
5. Calculate a TAI score for each transformer.

Fig. 2 shows the scoring assessment sheet for this new method. In [28], the scoring for replacement or repair / refur-

	Replacement Index				
		Refurbishment Index			
	Replacement of TX	Maintenance Index			
Analysis Summary	Active Part	OLTC	Bushing	Dielectric Fluid	Cooling system
Main Tank DGA (1-4)	D				
Main Tank Oil (1-3)	A			A	
Furan -DP (1-4)	D				
Corrosive Sulfur (0,50)	A				
LTC DGA (1-4)		A			
LTC Oil (1-3)		A			
Doble Test (1-3)	A				
Bushings (1-3)			A		
Arresters (1-3)			A		
Cooling System History (1-3)					A
IR Scan History (1-3)					A
Main History (1-4)					C
Loading (1-3)					C
Fault Duration Multiplier (1, 10, 25)					A
Substation 3 - T1	A2.49 Summation + Colour Score			**12 Pink**	

Figure 2. TAI scoring method [31]

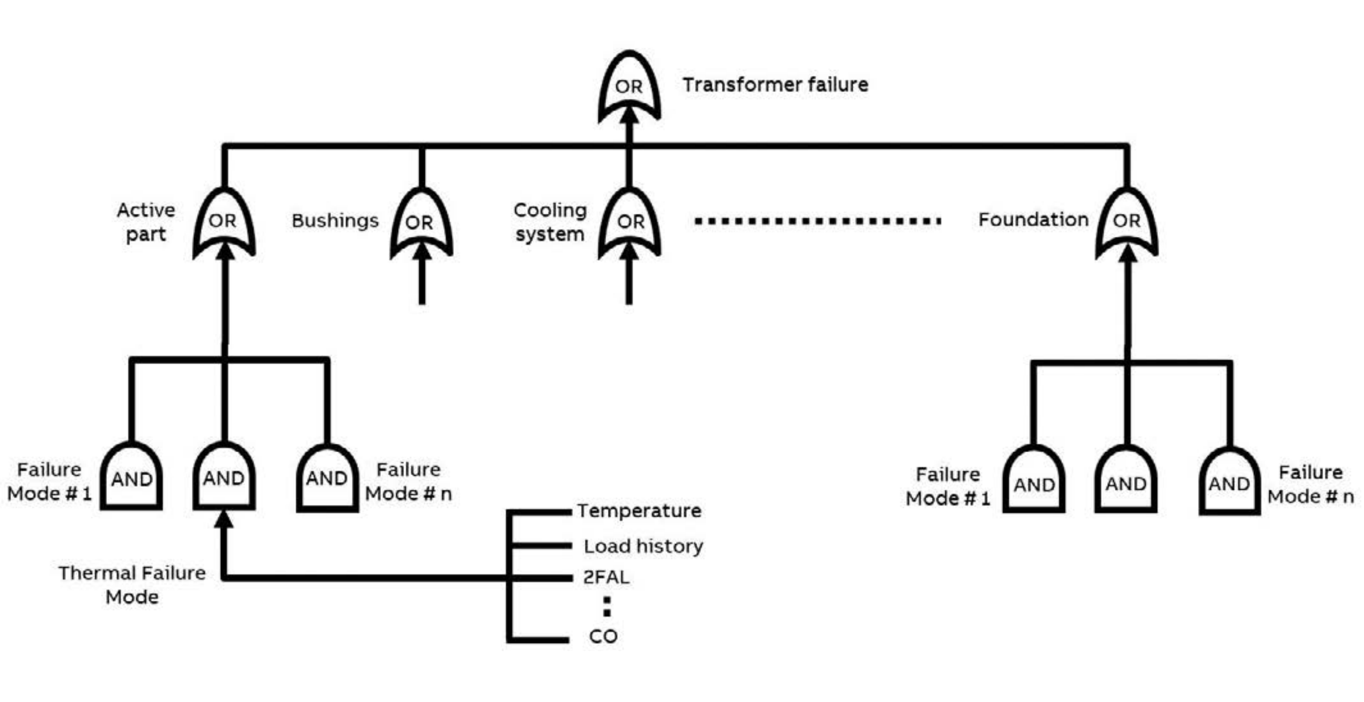

Figure 3. Illustration of fault tree-based assessment method

bishment has been introduced. The idea behind introducing this is as mentioned by CIGRÉ Working Group A2.49:

1. "High moisture content is not a driver for replacement, as the moisture can generally be removed as part of a refurbishment. However, a transformer will not be considered for refurbishment if the paper is already significantly degraded (high furans). Similarly, transformers with high levels of partial discharge or arcing will not be considered for refurbishment as it is unlikely that these problems can be easily corrected during the refurbishment process".

2. "Bushings can be replaced as part of either the repair or refurbishment process. However, as replacing bushings can be expensive if identical bushings are not available, defective bushings are also one of the drivers for replacement."

However, both the above can be achieved with the associated cost – be in repair / refurbishment in workshop or possibility to replace bushings by having the right match & engineering support from the factory. Thus, the cost of replacement or repair / refurbishment must be part of any new approach.

In [27-29], a decoupled failure mode approach based on the RCM philosophy was presented (Fig. 3). The procedure developed selects those failure modes for each of the components and brings to the "analysis matrix" those operational parameters that play a role in that specific failure mode. It is very important to note that parameters that are not correlated or those that do not contribute to a given failure mode are not analysed together with those directly associated with a failure mode.

As an example, a bushing may fail due to several reasons such as design and manufacturing issues, storage, maintenance and operations, external causes, etc. In order to be properly assessed, each of these possible failures may require different data inputs, such as:

- Bushing installation date
- Bushing power factor and capacitance
- Bushing reference power factor and capacitance as per manufacturer
- Bushing voltage class
- Bushing construction type
- Bushing inspection results - hot spots, cracked, oil, oil leak?
- Bushing maintenance date.

After all major components and their failure modes are duly evaluated, a global associated probability of failure (POF) score is produced out of the individual scores of each component. This score is mapped in a criticality index matrix, designed to map the POF score against the importance of the unit. This model also incorporates the "expert system" within the fault tree-based assessment method. One such example is the data

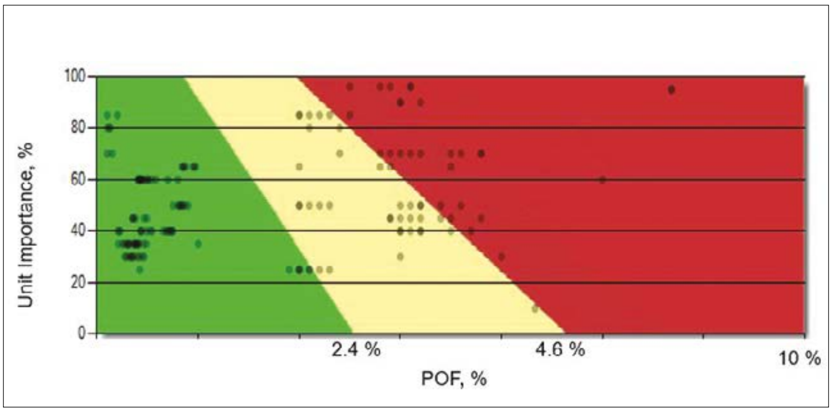

Figure 4. Criticality index matrix - Risk-based POF mapping

As an alternative to traditional HI score method, there are several different modelling techniques proposed such as TAI scoring method and fault tree-based assessment method

quality check and management by employing statistical packages within the model. As data is generated every few minutes / hours from technology deployed within a smart grid, such as online DGA equipment or other online devices, assessment of data quality by manual methods becomes tedious. Statistical packages, such as outlier identification, box plots, piecewise linear approximation, normal data distribution, etc., are inbuilt in this model to automatically process data and perform data quality checks. The "expert system" raises flags for either causes or components responsible for the causes. Based on the causes or components, replacement or refurbishment scores are calculated.

Conclusion

The paper has presented a critical review of the limitations of weighting and scoring concept of the transformer health indexing. This approach fails to maintain the functionality of the transformer as a whole system and fails to identify individual components which are required for maintaining the overall transformer functionality. Limitations of the traditional health index system are clearly demonstrated. The need for a new index which is based on the philosophy of reliability centred maintenance is clearly identified. A discussion on future assessment model is presented, which addresses problems of the traditional health index system.

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