A Literature Survey on Health Index Approach for Transformer's Condition Assessment

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I. Introduction

Power transformer has the most important role in electricity distribution and represents also one of the greatest expenditures for electrical utilities. Due to the high demand for reliable, safe and continuous supply of electricity, there is a need for reliable and uninterrupted performance of power transformers. Therefore, power utilities are challenged nowadays to properly assess costs and risks and according to that, to choose appropriate maintenance plan. Most of the utilities perform maintenance actions periodically, which is called Time-based Maintenance (TBM). This is not the most optimal and cost-effective type of maintenance, because some transformers, despite their average lifespan of 30-40 years, are still operational after 50 or even 60 years in service, and often with only minor deteriorations. This is why it is preferable to assess the condition of such assets and perform necessary actions when they are needed, which is called Condition-based Maintenance (CBM).

The Health Index (HI) is practical, simple and mostly used method to calculate the overall health of power transformers. It utilizes the results of on-line and off-line condition monitoring of transformers, as well as the results of different laboratory tests and routine inspections and then calculates one simple value that represent transformer's health condition.

The presented paper surveys a large number of practical examples found in scientific literature that have developed and applied HI algorithm on power transformers, presents their results and points out important findings and their contribution to HI methodology.

II. Diagnostic test and procedures for obtaining HI input parameters

Although there are numerous diagnostic procedures and tests that are done to obtain transformer's condition, they can be roughly classified into 4 main groups:

- ***dissolved gas analyses in oil and load tap changer,***
- ***oil quality tests,***
- ***operation, maintenance and failure records,***
- ***off-line and on-line condition inspections.***

For general transformer's diagnostics recommendations, standard IEEE Std C57.152 represents a document that has great significance when condition assessment is performed. According to this standard, all tests, inspections and measurements are classified in 3 categories – recommended, as-needed and optional. The standard also briefly explains procedures for basic tests and measurements. Examples of other important standards that focus on specific test procedures are presented in Table 1.

Dissolved Gas Analyses (DGA) in oil is commonly used procedure for transformer's insulation health assessment, and at the same time, dissolved gases are indicators of the overall health of transformer itself. The IEEE C57.104 and IEC 60599 are two standards that lead in the interpretation of DGA. These have been developed from empirical data and experience based on findings of case studies during long period of time. Example of ranges for common dissolved gases that these standards recommend as typical are presented in Table 2.

Table 1. Common standards for test procedures

Test	Standard
Dissolved gas analyses (insulating oil)	IEEE Std C57.104 IEC 60599 ASTM D3612
Dissolved gas analyses (load tap changer)	IEEE Std C57.139
Partial discharge measurement	IEEE Std C57.113
Frequency response analyses	IEEE Std C57.149
Dielectric breakdown voltage test	ASTM D877
Interfacial tension test	ASTM D971
Furan compounds test	ASTM D5837
Visual examination	ASTM D1524
Water content measurement	ASTM D1533
Power factor measurement	ASTM D924
Acidity measurement	ASTM D974

Table 2. Ranges of 90% typical gas concentration in power transformers in µL/L [6,7]

Gas	IEEE range	IEC range
H_2	40-100	50-150
CH_4	20-110	30-130
C_2H_6	15-150	20-90
C_2H_4	25-90	60-280
C_2H_2	1-2	2-20
CO	500-900	400-600
CO_2	3500-10000	3800-14000

HI is a practical method that uses parameters obtained during previously mentioned condition monitoring and diagnostic tests, and then calculates one quantitative index that represents overall health of transformer. There are different approaches for HI calculations, but mostly used is scoring and ranking method. Each parameter is assigned with appropriate score and weight. Scores are obtained from previously mentioned standards and guides. They represent typical or limit values for each parameter. Weight represents the degree of importance and it is usually assigned based on expert's experience and judgment. Empirical equations developed by utilities and international working groups in the domain of power engineering like CIRED, CIGRE and others are used for HI calculation. Regardless of the methods, the result of HI is a number from various ranges, like 0-100, 1-10 and 0-1 with each value having its meaning for health condition of power transformer. The algorithm for HI calculation has evolved as the condition monitoring has progressed. This is reviewed in the third chapter of presented paper.

III. Evolution of HI through literature survey

The concept of HI in engineering has been used commonly in previous two decades. Some early researches and works are presented in **[10-13]**. Mathematical equation or algorithm, which involves scoring and weighting technique, represents core of most researches about HI done until today. Some representative scientific papers **[14-23]** are briefly reviewed in this chapter of the paper. Conventional HI scoring method is mostly used because of its simplicity, but there are some uncertainties that restrain accurate implementation of this method. Even if excessive amount of data is obtained through diagnostic tests and condition monitoring, expert subjectivity in defining weights and scores is factor that reduces reliability and validity of method. In order to overcome this issue, some more sophisticated methods are used for calculation of HI and they are mostly based on machine learning and artificial intelligence. Papers that use these methods **[24-38]** are reviewed also in this chapter and listed in Reference part of the paper.

IV. Discussion

Scientific papers that are reviewed in the paper have important role for understanding and implementation of HI methodology nowadays. Some of them introduced formulations that are still in use among researchers, while some focused at procedures for determining parameters necessary for HI calculation. The majority indicates that not all parameters have the same importance for condition assessment, and that proper weighting is the key factor in HI formulation.

Table 3. presents an overview of certain references surveyed in the presented paper. First column of the table is reference number, while the second column shows variations in number of input parameters. Third column represents various ranges of HI output that are used in these references. Fourth column presents progress of method and contribution to HI methodology. Finally, fifth column is a summary with some highlights from the papers, which are either conclusions, actual problems or proposals for further researches. The reviewed papers from the table are listed in Reference part of the paper.

Table 3. Overview of different HI approaches

Ref.	No. of inputs	HI output (range of values)	Contribution to HI methodology	Summary
[14]	20	0-100 (0-very poor, 100-very good)	The paper introduced and listed an excessive number of parameters. It explained in detail the process of obtaining scores and assigning weights in tabular form.	HI calculation should be composed of two components, transformer and LTC. Weight for LTC is used from CIGRE survey that indicates 40% percent of all failures in transformer are due to LTC.
[15]	24	0-100 (0-very poor, 100-very good)	Four new parameters are added to the list, alongside with scores and weights. Probability of failure, effective age and remaining useful life are determined based on HI. Replacement capital plan is proposed.	It is proposed that weight for LTC's HI should be actual failure rate that utilities have in possession. If not, value of 40% can be used for this purpose.
[17]	27	0-1 (0-very poor, 1-very good)	Three new electrical parameters are added to the list: loss factor, polarization index and conductivity.	Experiments have shown that HI values were strongly influenced by variation of three new parameters. They were assigned maximum weight.
[22]	23	0-100 (0-very poor, 100-very good)	Degree of polymerization is presented as valuable parameter and used instead of load factor and age.	Age is not always a proper indicator of transformer's heath condition. It should be considered in relation to other available parameters.
[23]	15	0-100 (0-good, 100-risky)	Two formulations of HI are applied on power transformers. Different weights were assigned to ageing factors.	The main problem for HI calculation is the choice of parameters and determining their weights, because this is based on experts' knowledge and experience in the domain of power transformers. It must be done with caution.
[26]	6	0-1 (0-very good, 1-very bad)	Advanced probabilistic neural network is introduced for HI calculation. It is totally free of any assumptions or subjective impact.	The proposed method can be improved by adjustment of already available limitations of parameters from international standards and guidelines.
[29]	20	0-1 (0-normal/good, 1-poor/severe)	Complex and intelligent fuzzy inference model for condition assessment and transformer's criticalities is developed. It can indicate transformer's increased probability of failure.	There is an inevitable dependence of parameters on each other. In order to accurately assess condition of transformer, this dependence must be understood and considered.
[33]	15	0-100 (0-very bad, 100-very good)	Neural-fuzzy network where ambiguity of fuzzy logic has been overcome by neural learning from training datasets is developed. Monte Carlo simulation is introduced for obtaining training datasets.	Completely different approaches for calculation of HI can cause deviations of results. Better accuracy can be accomplished by using techniques like Monte Carlo simulation, because it doesn't depend on real in-service condition data.
[38]	9	0-10 (0-good, 10-bad)	Application of five different machine learning methods for feature classification, in order to determine the ones that contribute the most to HI calculation, and which ones are negligible.	Determination of important parameters for HI calculation can significantly reduce costs, optimize condition monitoring and improve accuracy of HI method. Random forest is proven to be the best classifier, while the most important parameter is determined to be furan content in oil.

V. Conclusion

Through presented literature survey, it can be concluded that HI approach for the purpose of condition assessment is very valuable and practical tool. It has significantly progressed in previous two decades, as it can be concluded from reviewed references. However, advanced on-line condition monitoring equipment is not available to all distribution systems, either because of its costs, or complexity of distribution system. When this equipment becomes widely used, more experts could gain experience in the domain of CBM, and thus HI approach could be further and more rapidly improved.

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