HEALTH INDEX AS CONDITION ESTIMATOR FOR POWER SYSTEM EQUIPMENT: A CRITICAL DISCUSSION AND CASE STUDY

Jan Henning JÜRGENSEN
KTH - Sweden
jhjur@kth.se

Axel SCHEUTZ GODIN
KTH - Sweden
scheutz.axel@gmail.com

Patrik HILBER
KTH - Sweden
hilber@kth.se

ABSTRACT

Over the past decade, the health index has become an increasingly popular asset management tool in utilities. The health index as a condition indicator can improve the decision making process. However, it also has challenges which need to be considered during development and implementation. This paper addresses the advantages and disadvantages of the health index as a condition indicator in a critical discussion. Moreover, a case study is presented where a health index is calculated for three transmission power transformers. The case study illustrates that age and the load factor included in the health index calculation lead to an immoderately high health index for the transformers T2 and T3. Thus, the paper ageing of the transformer windings are used instead which results in a plausible condition representation of all three transformers. The case study also demonstrates that the observation of condition trends over time is lost if the health index is transformed into a linguistic expression.

INTRODUCTION

The implementation of Smart Grid technology enables the gathering of equipment monitoring information in an economic manner. Therefore, condition-based maintenance which replaces or maintains equipment based on the actual condition becomes more popular. This maintenance strategy could improve the secure operation of the equipment and decrease the operation costs. The achievement of these two targets has led to the development and implementation of equipment condition estimators in more and more utilities. The desirable improvement in energy supply and cost savings requires that the condition of the equipment is estimated as accurately as possible. If the condition is incorrectly estimated, cost savings might vanish and additional costs emerge.

One tool that merges all condition monitoring information into a single value is the health index [1]. The health index represents the overall condition of the power system equipment by incorporating operating observations, field inspections, and site and laboratory testing [2]. The health index can be used as an asset management decision support, end of life estimation, risk indicator, and to plan maintenance strategies [3]. Different health indices have been developed in the literature [4-6], and as practical applications [7-9]. The computation of the health index is based on different techniques depending on the developer. The most common approach is the weighting of the condition monitoring information by a weight factor, but other methods such as fuzzy logic [6], Bayesian networks [8], and artificial neural networks [10] are also used. The resulting health index score is commonly between 0-1, 0-10, or 0-100 and simplified linguistic expressions are assigned to predefined score intervals. However, different condition monitoring input parameter and calculation methods result in dissimilar health index scores. Thus, a case study in [11] compared the recently developed health indices [12] and [13]. The authors in [11] concluded that [13] is a more reliable indicator for the overall health and state that the age and the loading of a transformer are essential. This study showed that the utility which applies a health index concept should be well aware of the method and input parameters it will use to gain reasonable and reliable condition estimation.

This paper discusses the advantages and challenges of using the health index as a condition estimation tool and points out what is necessary to consider during the implementation. Moreover, the discussion addresses the subjectivity in setting the weights to different measurements and the problem of incomplete measurement information. The second part of the paper illustrates the identified challenges in a case study of three transmission transformers. The case study shows the impact of maintenance on the health index and suggests a load factor adjustment as well as the need of a higher weighting of the degree of polymerization (DP) which reflects the natural ageing. The overall aim is to create awareness about the health index challenges and this paper is thus a helpful guide to a successful implementation.

A CRITICAL DISCUSSION

The aim of the health index is the condition representation of an individual asset. This enables a more effective comparison between individuals in a population to gain a better overview of a utility's assets. Consequently, maintenance and replacement decisions can be based on a common indicator. The health index processes the gathered condition monitoring data into an easily understandable value, especially if the health score is transformed into linguistic expressions such as: very good, good, moderate, bad, and very bad. This also allows the automatic monitoring of assets and alarms to be created if certain predefined thresholds are crossed. The health index can also illustrate long-term degradation, or short-term changes can become visible if it is recorded over time.

Using the health index as an effective decision making tool does come with a number of challenges that every user has to be aware of when developing or using health indices. These challenges can be divided into data acquisition, definition and calculation, interpretation, and implementation.

Data acquisition

In general, to express the overall condition and degradation as a health index, as much data as possible should be available for a realistic assessment [2]. However, condition monitoring can be costly and the actual condition information of measurements might be low. Thus, already available condition information should be evaluated first and additional measurements should be assessed with a cost benefit analysis. For example, [14] discusses the data availability challenge and states that input data should be easily accessible. The amount of input data can therefore differ heavily as shown in [15]. [15] compared 5 different health indices where the input data varies from 4 to 24 input parameter which include condition and operational data sources. It is important that the condition measurements cover the most important parts and not just certain subcomponents. Moreover, the condition monitoring data must be reliable over time and measured in regular intervals. One advantage of the health index to compare assets among each other or over time disappears if the same condition monitoring information is not available for all assets or time trends are less meaningful when data is measured unregularly.

Definition and Calculation

When all possible condition information is available and collected, the health index calculation can combine the data into one single score. Here, it is necessary to define the health index particularly when a condition estimator is the aim. The condition or health is the physical state of the asset and should not be mistaken with the operating conditions which are external impact factors. Moreover, importance, risk, and consequences of faults are also essential information but do not reflect the asset's condition. Thus, it has to be clarified what is meant by a health index when other input data are used in addition to condition information. For example, the loading or maintenance history of a power transformer has an impact on the condition over time but this should be measured by condition measurements of subcomponents. The actual loading at time *t*, however, is an external stress factor that has a direct impact on actual condition and the risk of failure but does not describe the physical state. Similarly, the age is not a condition measurement in general. It will be shown in the case study that the age does not reflect the actual condition, which is also argued in [2, 14, 16].

The calculation method of the health index also influences the outcome of the results. Different approaches can cause different results with the same input data. Despite overall similar results in [6], the health indices of one transformer differ notably. To state which method gives the better results is difficult and depends on each individual case. However, the method should be understood by the user, so that unexpected results can be explained, understood, and questioned. Here, the weighting approach for the health index calculation is the most transparent whereas artificial neural networks are less transparent due to the hidden layers between the input data and the health index. On the other hand, the weighting approach relies on the right setting of the weights by experts. The advantage of this approach is that weights can be adjusted depending on the asset population under investigation but how the weights are set needs to be clearly communicated to the decision maker.

Interpretation

The development of different health indices lead to different definitions of the health index score. Outcomes can be in the intervals 0-0.5 [16], 0-1 [6, 12, 17], 0-10 [9], 0-100 [2, 14]. The interpretation if a low or high value is good or bad depends on the health index. Certain health index scores are then further transformed into a linguistic expression. This makes the interpretation easier for the decision maker but the health index will become inaccurate. Consequently, condition trends over time cannot be observed anymore.

Implementation

The awareness of the health index challenges during development or implementation are necessary to gain the expected results which lead to better asset management. However, developing or adjusting a health index will lose the benefit of comparison between utility assets on a national or international level. A comparison on this level could be interesting to identify problems in particular areas which can be considered during policy making. Examples of such national projects to standardise the health index are the 'Network Asset Indices Methodology Working Group' on a national level in the United Kingdom or the Cigré Study Committee A2.49 on an international level.

CASE STUDY

In [15] a case study was conducted to investigate diagnostic measurement techniques and the use of health indices for 3 transmission transformers. The study used a modification of the health index developed in [2] to estimate the transformer condition. The health index in [2] was modified due to the different input data and later improvements suggested and implemented. We use this case study to demonstrate certain challenges discussed in the previous section.

Transformer Data

The transmission system operator Svenska Kraftnät provided the data for three transmission power transformer. These transformers are:

1. **T1**: A 500 MVA transformer from EBG installed in Ångermanland in 1995.
2. **T2**: A 750 MVA transformer from ASEA delivered to Uppsala in 1985.
3. **T3**: A 550 MVA transformer from ASEA installed in Södra Jämtland in 1975.

The main difference between the three transformers is the age with 20, 30, and 40 years in 2015. All transformers have no tap changer.

Independent of if a health index is newly developed or an existing health index is taken, historical failure data should be assessed to gain an in-depth understanding of possible failure causes, modes, and locations. This is particularly important when choosing which diagnostic measurements should be taken and what subcomponents should be monitored. For example, the failure statistics in [18] show that mechanical (53.1 %), dielectric (30.8 %), thermal (9.2 %), and chemical (1.1 %) failure modes make up 94.2 % of the total. Thus, a health index should monitor these failure modes with diagnostic methods to have a good coverage of the overall condition. For example, [19] sorts and divides diagnostic methods regarding the failure modes.

Available condition monitoring information for the three transformers is:

- **Oil analysis**: oil temperature, water content, acidity, colour, dissipation factor, and inhibitor
- **Gas analysis**: Hydrogen, Oxygen, Carbon Monoxide, Carbon-dioxide, Ethylene, Ethan, Acetylene, Propene, Propane, Nitrogen, and the total combustible gases
- **Electrical parameter**: active and reactive power, voltage, and the current is calculated
- **Other**: thermography, and maintenance records

This diagnostic information covers most of the input data requirements in [2] except the non-necessary tap changer information. As aforementioned, including the age as diagnostic information could be deceptive. An alternative approach could therefore be to describe the age by the paper insulation condition of the windings which is optional in [2] with a furan test. The paper condition is measured by the DP value and is an indicator of the mechanical stability. A furan test or the measurement of the hotspot temperature can lead to the estimation of the DP value. Estimating the DP value with the hotspot temperature is illustrated in Figure 1. [15] compared the suitability of both methods and recommended that measuring the hotspot temperature has an advantage due to cost savings and more reliable results. This paper ageing information as input data will be discussed subsequently.

The input data used for the case study is listed in Table 1

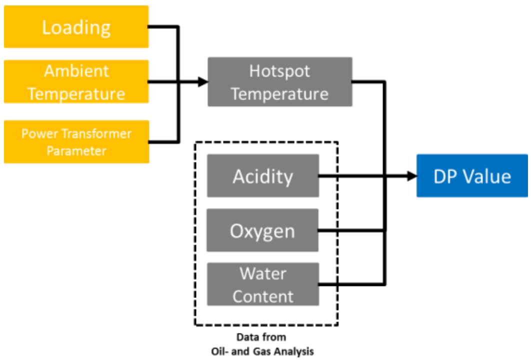

Figure 1: Calculation of the DP-value with the Hotspot temperature [15]

Table 1: Diagnostic measurements, weights, and condition ratings which are used as input data for the health index.

Number	*Measurement*	*Weights w_i*	*Condition Rating CR_i*
1	Gas analysis	10	4,3,2,1,0
2	Oil analysis	6	4,3,2,1,0
3	Loading	10	4,3,2,1,0
4	Ageing	5	4,3,2,1,0

and shows the weights w_i and the condition rating CR_i. The condition ratings 4 to 0 describe very good to very bad, respectively.

Based on the condition ratings and condition criteria descriptions from [2], the calculated health index condition ratings for each transformer are shown in Figure 2. Figure 2 shows the ratings for gas and oil analysis, load factor, and ageing. Particularly, the ageing is very constant due to the age range definitions in [2].

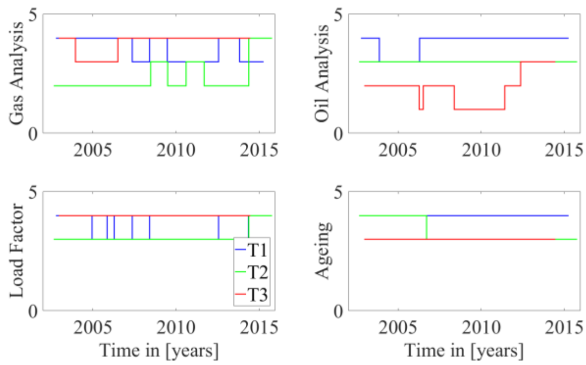

Figure 2: Input Data for the health index calculation.

Calculation

After fitting the input data to the case study requirements, the health index is calculated with

$$Health\ Index = \frac{\sum_{i=1}^{4} w_i * CR_i}{4 * \sum_{i=1}^{4} w_i}$$

In accordance with [2], the health index can be transformed into a linguistic terms with the intervals: Very Good (85-100), Good (70-85), Fair (50-70), Poor

(30-50), and Very Poor (0-30). For example, the state 'Fair' suggests that the expected transformer lifetime is up to 10 years.

Results

The health index results from 2003 to 2015 for all three transformers are illustrated in Figure 3. A linear function was estimated for each health index over time to better illustrate trends. The steps in the functions reflect changes when maintenance was conducted.

Transformer 1, the newest of all three, shows a decrease in the health index over time with only one exception in 2013. The values are reasonably decreasing from 100 to 86. Likewise, this is the case for transformer 2 and 3 until maintenance actions are conducted and a health index increase can be observed. Transformer 3 experienced a reinhibiting of the oil, the installation of a degasser, and the renewing of oil. Thus, these two transformers have a higher health index in the end of the case study compared to the beginning. Considering that transformer 3 is the oldest and has a higher health index than transformer 1, the results seem misleading. It can be explained by the high gas ratings, load factor ratings, and the constant age factor over time. All three transformers did not experience any load rating of 1 or above.

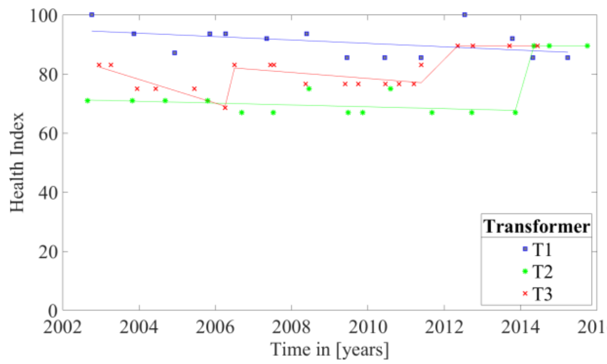

Figure 3: Calculated health indices based input data shown in Figure 2

Health Index Adjustments

The assessment of the calculated health index and the previously discussed challenges suggest an adjustment of the input data and health index parameter to gain better results. Especially, the load factor and the age as input parameter do not seem suitable since the load is low and actually not a condition indicator and the age itself hardly reflects the condition. Moreover, the results for T2 and T3 are unreasonably high. Therefore, two changes are made to the health index input data: Firstly, the load factor input data will be excluded and secondly the age as condition is included by monitoring the DP value of the paper insulation. The paper insulation reflects the age of the transformer as well as includes the load, see Figure 1. Moreover, the paper ageing gets a higher weight. The paper ageing input data is depicted in Figure 4 and a continuous decrease can be observed. The condition rating scores 4 and 0 are equal to a DP-value of 1300 and 200, respectively. The health index results with the adjusted input data are shown in Figure 5. Generally, the health index values are lower for all three transformers and there are fewer values which do not follow the trend.

Discussion

One remaining challenge of the adjusted health index is the impact of maintenance actions such as the installation of a degasser or the oil change. The impact is clearly visible but it is questionable if this positive effect should be observable. A degasser and the change of oil are activities which slow the ageing process of the transformer but not put the transformer in a better condition. However, this challenge can be overcome by the definition of the condition and the health index.

The results also reflect the importance of recording the health index over time. In both cases, a decrease of the health index can be observed. This shows that the condition is changing. Here, the importance of using numerical values becomes clear. If the health indices would be assessed based on the transformed linguistic expressions, the results for transformer T1 would stay in the category 'very good' over the whole study period. Only health index of transformer T2 would change between 'fair' and 'good'.

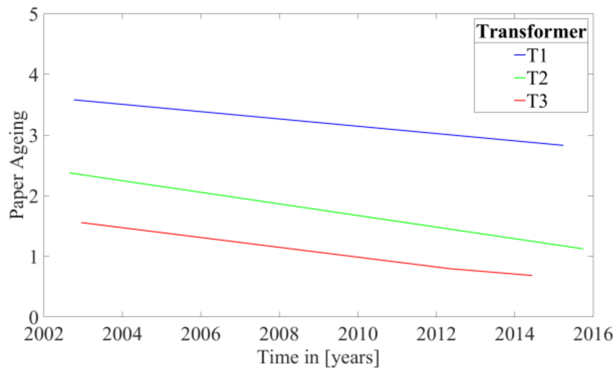

Figure 4: Paper Ageing converted from DP value

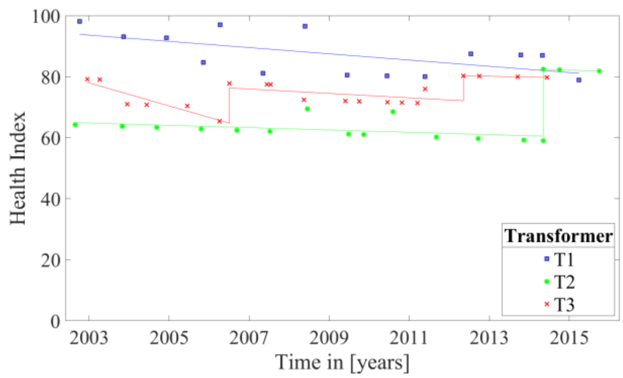

Figure 5: Health Indices for the three transmission transformers based on paper ageing and neglecting the load factor

CONCLUSION

This paper discusses the challenges of the health index which occur during design and implementation. The discussion underlines the importance of a clear health index definition and that the calculation should be transparent to gain a better understanding of the results. Moreover, both should be clearly communicated to the decision maker. To illustrate certain challenges, a case study of three transmission power transformers is presented. It shows how an existing health index is modified to fit the available input data. The results show that age and the load factor are input data which lead to high health indices for transformer T2 and T3. Thus, the paper ageing of the transformer windings in form of the DP value is utilized to represent the age condition of the transformers. The recalculated health indices are plausible and better reflect the overall condition. The case study showed that using linguistic expressions for the health index values will hide trends.

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