High voltage power transformer condition assessment considering the health index value and its decreasing rate

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Abstract
A health index method is a useful tool for the transformer assessment condition. This method has been used in several previous studies. However, most of them have not observed the health index decreasing rate as an aspect to improve the transformer condition assessment. A health index method with different approaches is proposed, considering the values and decreasing rate to assess the transformer condition. Inspection data from in-service and out-of-service 150 kV power transformers provided by the Indonesian electric company are included. The correlation between operation age and Health Index value and Health Index decreasing rate was also observed. With increasing operation age, the Health Index value tends to decrease with a correlation coefficient $R^2$ of 0.631. Further analysis was conducted to power transformers with historical data of 3 years or more, which showed that the tendency of the Health Index value decreasing rate is higher with older transformers. This paper also illustrates the Health Index analysis of 35 out-of-service transformers, resulting in a more suitable Health Index value compared to the previous approach. This study proposes the transformer risk assessment based on its health index value and the decreasing rate.

1 INTRODUCTION

Power transformers are essential and expensive utilities in electrical systems. This equipment is expected to be operated for years with maintaining its reliability and performance to provide a reliable electrical system [1–4]. Generally, the transformer has a life expectancy of 40 years or more. However, sometimes the power transformer failure may occur faster than it should because of degradation under the combination of thermal, electrical, chemical, mechanical and environmental stresses. While the transformer is operating, it is experiencing things that accelerate ageing, such as water content, temperature and oxidation [5, 6]. Therefore, transformer assessment has to be done to anticipate the sudden failure of the transformer.

The health of its insulation system can be used to determine the transformer's condition due to the importance of the insulation system in the performance of the power transformer [7]. Transformer insulation failure can be caused by several factors, some of them are fault factor, oil quality factor, and paper condition factor. Those three factors have a major effect on the transformer insulation system. The health index method is a comprehensive method that can aggregate those factors into a single value that indicates the overall transformer condition.

Studies about the health index method have been conducted by several researchers before [8–11]. However, the rate of gas level is rarely used in the analysis of the health index. A study about health index in Ref. [8] is still the most cited research by other researchers to propose the new health index method. Then it is developed and modified by other researchers to give more proper and suitable calculations within other transformer populations. A study in Ref. [9] developed and modified health index from previous research [8] for the Indonesia transformers population. It observes Dissolved Gas Analysis (DGA), oil condition and Furan value as health index factor. The gas rate of dissolved gases and Duval Pentagon Method (DPM) analysis were not included in the calculation parameters. Therefore, the rate of dissolved gas levels are included into the health index calculation analysis. Those dissolved gases are also analysed using Duval Pentagon Method to find out the fault type due to dissolved gases. Its results will be considered in determining the health index score of
transformers. In addition, CO and CO\textsubscript{2} parameters commonly placed in faults factor determination were moved into paper condition analysis. This action is taken because CO and CO\textsubscript{2} are known to result due to the thermal ageing of oil-immersed paper insulation [12]. The proposed approach also employed an updated standard of IEEE C57.104-2019 for DGA analysis and IEC 60,422 - 2013 for oil analysis [13, 14].

The in-service and out-of-service transformer inspection data are analysed. As much as 143 in-service transformer inspection data were analysed, then the correlation between operating age and health index value was conducted. This correlation has been done in several previous studies [15–18]. However, the correlation between the health index decreasing rate and the transformer age is rarely observed. Therefore, the transformer historical data of 3 years or more were explored, and the trend of health index decreasing rate corresponding to the operating age was also observed. The health index decreasing rate is obtained by calculating the slope of those recent health index values. This analysis is carried out to obtain the normal health index decreasing rate based on its operating age. In addition, based on the out-of-service transformers inspection data, the proposed method’s results were compared to the previous approach to justify the suitability of the proposed method. An updated method is provided to help the asset manager rank the power transformer within the population based on the multi-parameter condition monitoring data in health index value and its decreasing rate to assess transformer risk conditions. Based on the transformer risk assessment, it is expected that the proposed method can judge the transformer condition better due to the incorporation of health index decreasing rate. The proposed transformers risk is aimed to be a useful tool for the asset manager to decide better maintenance strategy to prevent sudden failure.

2 | METHODOLOGY

2.1 | Transformer population

Power transformers are periodically inspected by testing their insulation properties. Generally, there are two groups of frequently measured insulation properties. Those are dissolved gases and dielectric characteristics. Inspection data consists of the concentration of H\textsubscript{2} (hydrogen), CH\textsubscript{4} (methane), C\textsubscript{2}H\textsubscript{2} (acetylene), C\textsubscript{2}H\textsubscript{4} (ethylene), C\textsubscript{2}H\textsubscript{6} (ethane), CO (carbon monoxide) and CO\textsubscript{2} (carbon dioxide). While dielectric characteristic parameter consists of breakdown voltage, water content, interfacial tension, acidity, and colour scale data. Some of the transformer inspection data provide Furan measurement value. Herein, the transformer population is 143 operating power transformers from Indonesia electric company PT PLN (Persero) UIIT East of Java and Bali. The specific primary voltage for the transformer population is 150 kV and the voltage ratio of 150/20 and 150 kV/70 kV. Most of the observed transformers are using kraft paper insulation. The age of transformers is vary, and the detail is shown in Figure 1. From those transformer inspection data, data selection is conducted before it is used for calculation [19]. The inspection data are inspection data which meet the minimum requirement herein. Furthermore, inspection data from 35 out-of-service transformers will be used here.

2.2 | Health index

Health Index is a comprehensive method for the transformer assessment. This method is a scientific approach to objectively and quantitatively assess power transformer because it combines the results of operating data observations, field inspections and laboratory testing [20–23]. This method calculates all those parameters to produce a health index value from equipment. The health index method aims to rank power transformers based on the condition of the equipment based on various parameters related to equipment condition factors that cause degradation of the equipment. In the end, the health index method can decide which transformer is more critical than others. Then sudden failure can be denied by giving the appropriate action to the equipment. Usually, the health index method is referring to industry standards and expert judgement. Herein, the health index parameters are divided into three categories, which are Faults Factor, Oil Quality Factors and Paper Condition Factor. Figure 2 is an explanation of the health index calculation schemes.

The Faults Factor consists of the gas rate, gas level, and DPM interpretation of dissolved gases in transformer mineral oils. Oil Quality Factor contains parameters that correlate with oil quality, such as breakdown voltage (BDV), colour scale, water content, and interfacial tension (IFT). Then, Paper Condition Factor consists of operating age, CO & CO\textsubscript{2} calculation, and Furan (2FAL). In every parameter within the Health Index calculation is determined by international standards limits. Assessment of those parameters refers to the IEEE standard C57.104-2019 and IEC 60,422 - 2013. To provide a single value of overall transformer condition, scoring and aggregation will be conducted based on those three factors. Aggregation for each factor can be calculated using the following formula

$$HI_{each\ factor} = \frac{\sum_{i=1}^{n} S_i W_i}{\sum_{i} W_i} \quad (1)$$

![FIGURE 1](https://example.com/figure1.png) 

**FIGURE 1** Transformer population grouping by age
From the formula above, the number of parameters used in every factor is denoted by \( n \). Parameter scores (Si) are the value of scoring for each parameter based on the scoring tables in Sections 2.2.2 and 2.2.3. Besides the parameter score, there is a weighting parameter (Wi), representing their importance in every factor and is shown in Section 2.2.4. Those three values of the Health Index for each factor will be interpreted into a rating code shown in Section 2.2.4. Then, finding the Final Health Index value will be using the following formula.

\[
HI_{\text{final}} = \frac{\sum_{j=1}^{n} SF_j W_j}{\sum_{j=1}^{n} W_j} \times 100\% \quad (2)
\]

Final Health Index value calculation is the multiplication between health index each parameter’s score factors (SF\( j \)) and their weighting factors (WF\( j \)), then divided by summaries of their weighting factor, then multiplied by the maximum score of the health index value. Due to the maximum score factor is 4, it is used on the numerator of the formula to obtain 100 point of the health index value if all SF\( j \) is 4. The scoring factor is obtained by converting the rating code into a score, and the weighting factor is defined in Section 2.2.4.

2.2.1 | Faults factor

The faults factor obtained in the result is the product of scoring and aggregation from five DGA gases, which are Hydrogen (\( \text{H}_2 \)), Methane (\( \text{CH}_4 \)), acetylene (\( \text{C}_2\text{H}_2 \)), ethane (\( \text{C}_2\text{H}_6 \)), and ethylene (\( \text{C}_2\text{H}_4 \)). Gas levels of DGA data are commonly provided [24]. However, the rate of a gas level has to be determined by observing past transformer DGA data tests. The gas rate is obtained by calculating the difference between present data with the previous data taken, and then it is normalized into per year value. If the rate value is negative, it means that there is a decrease in those gases concentration. On the other hand, if the value is positive, then there is an increase in those gases and scored as follows in Table 1. Any negative rate value it will be scored as R1, which is the best score of gas rate score. DGA gases level and rate scoring limitation, as shown in Table 1, are based on the local population, and comply with the guideline in the IEEE C57.104-2019 [13].

Table 1 shows the scoring limitation for gas level and rate based on the standard. There is a different situation for determining the \( \text{C}_2\text{H}_2 \) rate score. Based on [13], if there is an increasing level of \( \text{C}_2\text{H}_2 \) gas, then it indicates some serious conditions. Therefore, any increase of \( \text{C}_2\text{H}_2 \) gas will be scored as ‘4’. Instead of using formula (1) to find Fault Factor value, the value will be obtained by considering maximum gas level, gas rate, and also DPM interpretation for dissolved gases. The maximum gas level and rate are obtained by the highest value of its level and rate in a single data test. Then those values will be assigned to a condition based on Table 2.

In addition, dissolved gas data value will be interpreted into DPM analysis and will then provide a category shown in Figure 3. Those categories indicate the transformer’s faults type. Then to determine the DPM score, the calculation between gas level, gas rate, and DPM category is conducted as shown in Figure 4 [25].

| TABLE 1 | Dissolved gases scoring table |
|---|---|---|---|---|
| Gas (ppm) | Score |
| Level \( \text{H}_2 \) | 1 | 2 | 3 | 4 |
| \( \text{CH}_4 \) | 1 | 2 | 3 | 4 |
| \( \text{C}_2\text{H}_2 \) | 1–3 | 2–3 | 3–4 | 4–5 |
| \( \text{C}_2\text{H}_6 \) | 1 | 2 | 3 | 4 |
| Rate \( \text{H}_2 \) | 1 | 2 | 3 | 4 |
| \( \text{CH}_4 \) | 1 | 2 | 3 | 4 |
| \( \text{C}_2\text{H}_2 \) | 0 | 1 | 2 | 3 |
| \( \text{C}_2\text{H}_6 \) | 7 | 15 | 23 | 31 |

| TABLE 2 | Gas level and gas rate condition |
|---|---|---|
| Gas level (Max) | Gas rate (Max) | Assigned condition |
| 1 | Any | Cond.1 |
| 2 | 1 | Cond.1 |
| 2 | 2–3 | Cond.2 |
| 2 | 4 | Cond.3 |
| 3 | 1 | Cond.2 |
| 3 | 2–3 | Cond.3 |
| 3 | 4 | Cond.4 |
| 4 | 1 | Cond.3 |
| 4 | 3–4 | Cond.4 |
After all of the required parameters are complete, a calculation can be done. Using a gas level and rate conditions and Duval pentagon scores, the fault factor value can be determined using schemes in Figure 5 [25]. Then, gas level and rate condition are combined with DPM scoring to provide Faults Factor categories whose values are A, B, C, D or E, as shown in Table 3. Category A, B, C, D and E, respectively, represent Normal, Acceptable, Need Caution, Poor and Very Poor interpretation of Fault Factor. If there is an incompatibility between those concerning values, the Faults Factor category will be mentioned as FALSE. This condition can occur when there is incorrect data retrieval from the equipment.

This Fault Factor category also will be known as a Fault Factor rating code. This rating code represents a score that will be used in calculating the final Health Index value at the end.

### 2.2.2 Oil quality factor

Oil quality factor consider the values of breakdown voltage, water content, acidity, colour scale, and interfacial tension of transformer insulation oil, which represent the insulation degradation in the transformer [26, 27]. The given values in those power transformer data tests are scored and aggregated by scoring in Table 4 and formula mentioned earlier herein. At
2.2.3 | Paper condition factor

Paper insulation is considered to be the most important factor that indicates the condition of the transformer. In this proposed method, the paper condition factor is determined by aggregating CO\&CO₂ score, age score and furan score. Table 5 shows the scoring and weighting of the Paper Condition Factor’s parameter. The scoring of CO \& CO₂ is using the assessment diagram in Figure 6.

The concentration and ratio of CO and CO₂ in transformer oil can give some vital information about its paper condition. So, the assessment of CO and CO₂ will be conducted differently with other paper condition factor parameters. Beside observing CO and CO₂ value, the ratio between both of them is also included in consideration to determine CO and CO₂ scoring [28]. CO and CO₂ analysis are moved from commonly DGA analysis into paper insulation analysis because CO and CO₂ are more likely to represent the condition of oil-immersed paper insulation condition [12]. After obtained the CO \& CO₂ score, aggregation can be done using formula (1).

2.2.4 | Final health index calculation

The final health index calculation aggregates three main factors. Those three factors have each weight that represents how important the factor is to the transformer health condition. Since paper insulation is considered to be the most significant factor in transformer health condition, its weight is the biggest among the others. Overall, the weighting value can be seen in Table 6. The factor score is obtained by determining the factor categories into a score based on Table 7. Equation (2) is used to get the final score of the Health Index.
TABLE 8 Health Index category description

| Health index | Health index code | Description |
|--------------|-------------------|-------------|
| 85–100       | VG                | Very good   |
| 70–85        | G                 | Good        |
| 50–70        | C                 | Caution     |
| 30–50        | P                 | Poor        |
| 0–30         | VP                | Very poor   |

The maximum value of the health index is 100, represents that the transformer condition is in good shape or as a brand new one. In contrast, the minimum value of the health index score indicates that the transformer condition is completely degraded. Herein, the range of health index value is divided into five categories, which are Very Good, Good, Caution, Poor and Very Poor. Those categories represent health index value, which is shown in Table 8.

Weighting parameters and factors in Table 6 are obtained by using Analytical Hierarchy Process (AHP) technique. This technique uses judgements from five experts with in-depth experience in transformer condition and monitoring [29]. The developed health index structure accommodates other measurements such as Dielectric Dissipation Factor (DDF), Sediment, and Degree of Polymerisation (DP). Due to the unavailability of the data, this study does not include those parameters in the health index calculation. For that reason, the sum of weighting parameters in the Oil Quality Factor and Paper Condition Factor in Table 6 are not equal to 1.

Overall, this study started with data collection from operating and non-operating transformers from PT PLN TJBTB. The transformers' voltage ratings are 150/70 kV and 150/20 kV. Then, those inspection data will be selected in preprocessing data before it is used for further calculation. For operating transformers inspection data, Health Index values and Health Index rate calculation will be conducted. Those values correlation with age will be analysed to find out whether the transformer is in accelerated ageing or not. For non-operating transformers inspection data, since they do not have any historical data, this study only calculates the Health Index value from those inspection data. Then those values will be compared with the previous research health index method. Figure 7 shows the methodology of this study.

3 RESULTS AND DISCUSSION

3.1 Study case

In this section, a study case of several operating transformer data test acquired from Indonesia electrical company PT PLN is presented. Due to the limited space, only 14 transformers data testing is presented. The data of power transformer includes dissolved gas data, oil dielectric characteristic data, age, and furan data will be shown in Appendix 1.

Testing data of 14 power transformers were evaluated. Health index values and categories from those 14 transformers will be compared with the real transformer's condition in the field. Each factor had been analysed using scoring and aggregation mentioned earlier herein. The results of the calculation and analysis are shown in Table 9. As transformer sample data are given in Appendix 1, furfural data is not available for health index calculation because furfural data testing is not a routine test. Therefore, some transformer inspection data do not consist of furan value. Nevertheless, Paper Condition Factor still can be determined. Paper insulation condition can be evaluated by an approach using other transformer parameters [27, 30–32]. In this calculation, paper condition factor determination only uses the available parameter. There is a risk of using a combination scheme to provide a single health index value. Every health index category is presented for every factor to avoid missing information about each of factor condition. For instance, when the paper and oil show good condition but the fault factor shows the bad condition, the fault factor should be dealt separately to maintain or fix the problem that causes that condition. The root cause of the problem should be tracked down by observing other transformer inspection data.
Table 9 shows the health index results of 14 transformers sample which has been validated by the asset manager. It also shows health index category from three factors, Fault Factors (FF), Oil Quality Factor (OQF), and Paper Condition Factor (PCF). The result indicates a high similarity of proposed method with the real transformer condition in the field. This also verified by the asset manager. With less parameter than assessment from the company, the proposed Health Index method shows the suitability to be implemented for power transformer condition assessment.

| Transformer | Age | FF | OQF | PCF | HI value | HI category | Real transformer condition |
|-------------|-----|----|-----|-----|---------|-------------|---------------------------|
| 1           | 5   | A  | A   | A   | 100     | VG          | Very good                 |
| 2           | 10  | B  | A   | A   | 91.3    | VG          | Good                     |
| 3           | 7   | C  | A   | A   | 82.6    | G           | Good                     |
| 4           | 13  | D  | A   | A   | 73.9    | G           | Good                     |
| 5           | 21  | B  | D   | B   | 64.2    | C           | Caution                   |
| 6           | 23  | D  | C   | B   | 52.2    | C           | Bad                      |
| 7           | 39  | C  | C   | C   | 50      | C           | Bad                      |
| 8           | 6   | B  | A   | A   | 91.3    | VG          | Very good                 |
| 9           | 23  | D  | C   | C   | 41.3    | P           | Poor                     |
| 10          | 27  | A  | A   | B   | 89.1    | VG          | Very good                 |
| 11          | 24  | B  | A   | B   | 80.4    | G           | Good                     |
| 12          | 28  | A  | A   | B   | 89.1    | VG          | Very good                 |
| 13          | 32  | D  | B   | D   | 35.8    | P           | Very poor                 |
| 14          | 21  | D  | C   | C   | 41.3    | P           | Very poor                 |

3.2 | Out-of-service study case

The proposed method is then also applied to 35 non-operating/out-of-service power transformers for comparison. The proposed Health Index method will be compared with the health index proposed by previous study [9]. Reference [9] was chosen because the method used is similar to the proposed method. However, the standards used in Ref. [9] are the old version of the standard use in this proposed method [33]. It analyses transformers’ health index by considering DGA of gas level (H₂, CH₄, C₂H₂, C₃H₄, C₄H₁₀, CO and CO₂), oil insulation condition (breakdown voltage, acidity, water content and interfacial tension), and furan value. The purpose of this comparison is to find out whether the proposed method can produce better judgement in assessing the transformer condition.

The comparison is made by comparing the health index values from not operating or out of service transformers. The last inspection data from those transformers are provided. Those inspection had been conducted before the transformer taken out of service, and considered as suitable to be used as comparison with the previous Health Index method. However, there is no such detail about the time difference between the inspection and the failure, and no available historical data from those transformers. As much as six sample of inspection data from out of service or not operating transformers will be shown in Appendix 2. The comparison of health index value between two methods is shown in Figure 8.

Figure 8 shows the 35 transformers health index values comparison between the proposed method and the previous method. The health index value resulted from the proposed method is mostly lower than the results of the earlier method. The value differences are mostly caused by the difference between scoring and weighting for each method. Moreover, this study uses different DGA analysis approaches and moved CO and CO₂ analysis into the paper condition factor.

The discrepancy in results between two approaches can be explained due to the difference in scoring table and health index.
structure. For example, the previous approach has Hydrogen gas minimum value of 100 ppm. Herein, 80 ppm is used as normal limit of Hydrogen gas. In addition, the worst score of $H_2$ for the previous method is above 700 ppm, which in this study is 320 ppm. The same condition applied to $C_2H_2$. In the contrary, for $CH_4$ and $C_2H_6$, the minimum value for this study is higher than the previous one. However, for $CH_4$, this study's high limit value is still significantly less than the previous study. The updated scoring used in this study is more sensitive than the previous one.

Another significant difference is in paper condition analysis, which this study considers the operating age of transformers and shifted CO and CO$_2$ from DGA analysis to the paper condition factor, in addition to furan parameter. The previous study uses only furan value to determine paper condition.

Figure 9 shows the cumulative plot of health index value and percentage of the population from 35 out-of-service transformers. Based on the results, the overall health index values of the proposed method for out-of-service transformers are below the previous method.

The transformers used in this analysis are the out-of-service transformer or non-operating transformer. Those transformers are considered to be in bad conditions, therefore taken out of service. The health index calculation results using the proposed method have a mean value of 43.63, lower than the previous method, which has 59.68 mean value. The standard deviation for the proposed method and previous method, respectively, are 10.4 and 16.73. So, it can be concluded that this proposed method resulting in more suitable value in determining the transformer condition than the previous method based on the presented data. The results comparison indicates that the updated scoring table and Health Index structure used in this study is more representative for the transformer assessment condition.

After getting the validation from the asset manager, this method then was applied to bigger transformer population data and historical data in the next subsection.

3.3 | Correlation between age and health index value

The transformer age may indicates the performance of the transformer insulation system. The older the age of the transformer, the higher the chance that its condition is decreasing. This phenomenon is caused by the ageing of the equipment, especially in its insulation. The insulation of power transformers might decrease faster than it should be. However, there are also possibilities of old transformers that still show excellent performance when it is properly maintained. A wrong decision in determining the loading factor is one of the causes of the decrease in performance. In addition, a maintenance strategy is also an important matter. Transformers that are maintained in a good and proper way will have higher chance to be in a better condition than the one which is not.

In this section, the health index method will be applied to a single periodic transformers' inspection data. As much as 143 transformers inspection data in 2018 provided by PT. PLN (Persero) UIT East Java and Bali were observed. Health index values from those transformers data are shown in Figure 10, where each condition differs by colour based on their category. The summary of the health index condition category is shown in Figure 11. It shows that almost half of transformers are in a very good condition.

Figure 12 shows the cumulative method of health index value to the percentage of the population. It shows that 88% of the transformers are still in C condition or above, while as
much as 12% are in Poor and Very Poor condition, hence require more attention.

From the health index value results, the correlation to the age of the transformer is analysed. This correlation is carried out to comprehend the effect of operating age on the transformer's health condition. Linear regression correlation has been conducted to discover the relation between two parameters. The correlation coefficient between them is shown in Figure 13.

Figure 13, shows the correlation between age and health index values. Note that the health condition of the transformer is defined by the health index value, ranging from 100 which represents excellent condition, to 0 which represents terrible transformer condition. Linear regression is conducted to find a correlation formula between the operating age of the transformer and its health index value. The dotted regression line may be considered to represent the normal ageing condition of a population of transformer. It shows a trend of health index values, which decreases with age. Figure 13 shows that the transformer's age has a negative correlation with health index value as the value tends to decrease with transformer ageing with correlation coefficient 0.63. Since this study analyses the paper condition by using age value as a parameter, the health index has been recalculated excluding the age factor to show its influence on the outcome. It is found that the $R^2$ value is decreased to 0.403. This value shows that those parameters are still correlated. A correlation coefficient 0.35 or higher is usually considered to be significant [34]. It shows that there is still a tendency of a decrease in the value of the health index along with transformer age, although it is less significant.

The regression line in Figure 13 indicates the normal age of each health index values and vice versa. Thus, the ageing condition can be determined based on it. The apparent age concept could be implemented, which is the product from a combination of a transformer's service age and its health index condition. If the point is drawn into the regression line, that intersection between the regression line and the point then correspond with age abscissa, will indicate the apparent age of power transformer [35]. The apparent age can be older than the actual operating age based on its health index value, and vice versa. Then it can be concluded that the points which are below a trendline can be concluded as transformers with accelerated ageing, which is worse than average. Meanwhile, the points above the regression line means the state of the transformer is better than average [34]. On the other hand, the transformer ageing condition can be determined by comparing the health index value from the calculation with health index value from the following formula.

$$y = -1.8074x + 104.51$$  \hspace{1cm} (3)

Where $y$ stands for normal health index and $x$ is operating service age for the transformer. If the health index value from the proposed method in this study is below the normal health index, transformer ageing condition can be concluded as accelerated ageing.

However, transformer service age should not be a sole indication of transformer condition. With proper maintenance, good asset management, and keeping the transformer in low failure rate, an old transformer might still maintain a high performance. The aim of correlation analysis of Health Index with age, and deriving equation (3) is to obtain a better judgement of transformer Health Index results in comparison to the average of transformer population.

3.4 | Correlation between age and health index decreasing rate

The performance and condition of equipment might decrease along with the ageing subjected, consequently the health index value of the equipment. Therefore, it is also important to evaluate the decreasing rate of the health index value.

In this section, observation is conducted to obtain the relationship between the transformer age on the health index decreasing rate. The health index decreasing rate can be considered to be an assistive tool for better judgement on a condition of transformers based on its health index value progression. The health index decreasing rate is obtained by observing transformer historical inspection data for the past few years with minimum 3 years or more, then calculate the health index of each year. The decreasing rate that is used in this study is defined as the slope of regression line from multi-years Health
Index value of a power transformer. The reason of using regression line to calculate the decreasing rate is to handle the noise in the input data and in the Health Index calculation. In the multi-years data, outlier should be removed or re-test before being evaluated. This process has already been done by the data provider as a result of good condition monitoring and asset management process.

However, not all transformer has a good historical data, in which some only have single period data. To get a decreasing rate that can represent the rate of equipment based on its age, that transformer must have at least a historical data for three years or more. Herein, data selection had been done to select transformers which meet all requirements which were used in the analysis. Of all the transformer data collected, as much as 101 transformers that were used for this section analysis. After calculating its health index value for every period, the difference between those values will be calculated by its slope into a decreasing rate per year values.

The relationship between age and decreasing rate of health index was analysed. Figure 14 shows the boxplot of the correlation between those two parameters. Boxplot diagram is chosen because it is a standardized way of displaying the distribution of data based on a five numbers summary (minimum, first quartile (Q1), median (Q2), third quartile (Q3) and maximum). It is useful in comparing the distribution between many groups or datasets.

Figure 14 shows a relationship between the age group of transformers and their health index decreasing rates based on groups of age for entire transformers. The older the equipment, greater decreasing rate is observed. Since the ageing of the transformer causes some deterioration in its performance, especially its insulation quality, the older transformers have higher probability of failure. This is due to an increasing in the number of dissolved gases, decreasing transformer oil quality and an increasing furan value as an indicator of transformer paper deterioration. It indicates that there is a dependency between age and health index decreasing rate.

As seen in Figure 14, the correlation is shown by dividing the service age of transformers into four groups. The median value of the health index decreasing rate for each group is presented. The box in the boxplot shown in Figure 14 is the 25th percentile to 75th percentile (known as an interquartile range) of yearly health index decreasing rate by the group of age. It shows the most probable decreasing rate value based on probability density function. Then the total range of the value for every group of age is shown by a line (whiskers) in every box. For example, for the group age of 1-5 years old transformer, it has a minimum of 0 value until almost five for a decreasing rate. It means that for the particular group age, it has the possibility of having a decreasing rate of 0-5 HI value per year. The value of 0.66 is the median of the decreasing Health Index value per year in that age group. There is a tendency of the increase in value of the health index decreasing rate as indicated by its median in every boxplot chart for the older age group. With the older group (more than 20 years), the median shows the most in Health Index decreasing rate, as much as 10.15 per year. However, each whisker of each group is different within each other. The widest whisker is on over 20 years group of age. It shows the variety of health index decreasing rates is more noticeable.

Their difference in operation may cause variations in health index decreasing rate for a transformer. In addition, the maintenance decision of each transformer will affect the decreasing rate value. Considering its maintenance, the transformer, which is properly maintained, will have a high possibility of maintaining its health index value in good condition. When it happens, the health index decreasing rate will be low even if it is an old transformer. It explains why those three groups of age (1–5 years, 6–10 years, and 11–20 years) have a quietly same minimum value of decreasing health index rate. However, they have different interquartile range value that implies the difference of most value within that range.

Another factor of the transformer health index decrease rate is transformer loading factor. Generally, transformers whose age is relatively young will be loaded greater than the one which is already old, because old transformers are considered to be more vulnerable than the younger ones. Unfortunately, transformer loading factor data is not provided.

3.5 Transformer risk assessment

Relationships of Health Index values and its decreasing rate with age have been presented. Based on those analysis, this study proposes the transformer risk assessment considering Health Index value and its decreasing rate. Table 10 shows the details of the assessment.

Table 11 shows the transformer risk assessment by considering its health index value and the decreasing rate. The decreasing rate limitation is obtained by using all the health index decreasing rate in the previous section analysis, which is divided based on the value of Q1 and Q3 in the boxplot method. Herein, the assumption had been made. Based on the transformer population, IQR (Interquartile Range) illustrates the distribution of the normal health index decreasing rate. Since there is no standard or earlier research to determine the condition of the health index rate, this study proposes the value below IQR to be a good health index decreasing rate and
TABLE 10 Transformer risk assessment condition

| Risk Assessment | Health Index Decreasing Rate (point/year) |
|-----------------|------------------------------------------|
|                 | 0-5 | 5-10 | >10 |
| Health Index Value |     |      |     |
| 85-100          | Low | Low  | Low |
| 70-85           | Low | Low  | Medium |
| 50-70           | Medium | Medium | High |
| 30-50           | High | High | Very High |
| 0-30            | Very High | Very High | Very High |

TABLE 11 Risk assessment condition study case

| Transformer Sample | Age | HI Value | HI Decreasing Rate | Risk Condition |
|--------------------|-----|----------|-------------------|----------------|
| T1                 | 6   | 91.3     | 3.23              | Low            |
| T2                 | 10  | 71.8     | 6.16              | Low            |
| T3                 | 10  | 73.9     | 12.19             | Medium         |
| T4                 | 23  | 50       | 13.2              | High           |
| T5                 | 22  | 52.2     | 15.9              | High           |
| T6                 | 15  | 49       | 11.74             | Very High      |

FIGURE 15 Health index value and decreasing rate correlation

The health index value and the health index decreasing rates is shown in Figure 15.

Table 10 shows how important to assess the transformer condition by considering the transformer health index value and its decreasing rate. This assessment gives more information to produce better judgement. For example, T2 and T3 in Table 10 have similar health index values of 71.8 and 73.9, which indicates that those transformers conditions are both ‘Good’, based on health index description. However, T3 has a higher health index decreasing rate than T2. Due to that difference, it results in different risk conditions. T3, which has a higher health index decreasing rate than T2, has a ‘Medium’ risk condition. Meanwhile, T2 is considered to have a ‘Low’ risk condition.

For this transformer population, Figure 14 shows that the health index decreasing rate have a tendency to be increasing while the health index value is decreasing. The correlation between them has $R^2$ value of 0.5285. Based on this analysis, we can determine the normal decreasing rate for every health index value by using the regression formula. Therefore, this study can conclude that by determining the transformer condition by observing its present condition (the health index value) and the historical data (the health index decreasing rate), a more accurate decision can be made in power transformer assessment. Furthermore, it could help the asset manager to plan a better maintenance strategy and prevent sudden failure.

4 | SUMMARY

The health index method examines equipment conditions based on various factors and criteria that are related to equipment degradation that cumulatively leads to equipment end-of-life. A health index method is proposed based on three major factors of the transformer condition using available inspection data and considering updated IEEE and IEC standards.

Health Index calculation in this study is based on the change in oil characteristics and dissolved gases in the transformers. It is divided into three factors, which are Faults Factor, Oil Quality Factor, and Paper Condition Factor. The Fault Factor is
calculated with an advanced analysis by observing the gas rate, gas level, and Duval Pentagon Method interpretation result. CO and CO$_2$ parameters, which are commonly used in DGA analysis, are shifted into Paper Condition Analysis because of its high correlation with the condition of the paper. The calculation of health index is done by using scoring and weighting that are different for each parameter, depending on the measurement reliability, criticality, and the correlation with equipment condition. This proposed health index method has already been validated by the asset manager, and have a high agreement with the real condition of the transformers. Another analysis has also done to compare the result with previous approach, which this method resulting in more suitable Health Index value for out-of-service power transformer.

From the correlation analysis between the transformer age and its health index, the relationship is presented. With increasing transformer service age, the health index value tends to be decreased. This condition generally due to the transformer insulation condition, which has deteriorated due to the ageing of the equipment. That condition does not rule out the possibility that with good and proper maintenance and monitoring, the health index value or transformer condition can be maintained in a reasonably good condition.

Besides the correlation between transformer age and its health index value, this study also observes the relationship of the transformer service age on its health index decreasing rate. The result indicates that age will influence power transformer health index decreasing rate. The group of older transformer shows the tendency of higher decrease of Health Index than the new transformers.

Then, by considering transformer health index value and its decreasing rate, the transformer risk assessment can be done. This means that not only observing the present condition, but also observing the historical condition by looking at health index and its decreasing rate. This risk assessment might be useful for the asset manager to plan the transformers' maintenance strategy better.

## 5 CONCLUSION

Power transformers are an essential equipment in electrical power delivery. Their insulation system is the most critical factor that may cause transformer failure. Hence, it has to be assessed to prevent sudden failure. This study proposed a transformer assessment condition using the health index method with updated standard, gas rate and gas level observation, and DPM analysis. It shifted CO and CO$_2$ into paper condition factors. The proposed method is applied to 143 in-service transformers and 35 out-of-service transformers. From in-service transformer data, the correlation between the operating age and the health index value and the correlation between the operating age and the health index decreasing rate are presented. With the increasing operation age, the health index value tends to decrease with a correlation coefficient $R^2$ of 0.631. Based on the analysis on 101 transformers with historical data of 3 years or more, the tendency of the health index value decreasing rate is higher with older transformers. Then, the transformer risk assessment can be performed based on the transformer health index value and its decreasing rate. By combining the present and historical assessment in the form of risk assessment, a better judgement and maintenance planning on power transformer condition can be performed.

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APPENDICES

APPENDIX 1 Sample of transformers inspection data

| Transformer | Data Test | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|-------------|-----------|-----|-----|-----|-----|-----|-----|-----|
| H₂          | 0.00      | 2.00| 5.00| 39.00| 11.26| 0.00| 3.00|
| CH₄         | 11.60     | 510.00| 217.00| 580.00| 61.98| 114.16| 2.00|
| C₂H₄        | 0.00      | 0.00| 1.00| 0.00| 0.00| 2.00|
| C₂H₆        | 0.00      | 563.00| 15.00| 660.00| 39.14| 23.23| 8.00|
| Rate H₂     | 39.51     | 317.00| 593.00| 349.00| 217.96| 288.93| 7.00|
| Rate CH₄    | 0.00      | Neg| 7.16| Neg| 10.84| 0.00| 4.24|
| Rate C₂H₂   | Neg       | Neg| Neg| 304.49| Neg| 44.71| Neg|
| Rate C₂H₆   | 0.00      | 0.00| 0.00| 0.00| Neg| 9.42|
| Rate C₂H₆   | Neg       | Neg| Neg| Neg| Neg| 6.97|
| Rate C₂H₆   | Neg       | Neg| Neg| Neg| Neg| 6.75|
| Rate CO     | 24.44     | 73.00| 190.00| 50.24| 202.03| 342.76| 261.00|
| Rate CO₂    | 347.4     | 949.00| 2256.00| 1074.8| 1904.5| 1962.5| 2483.0|
| CO + CO₂    | 249.86    | 1022.00| 2456.00| 1125.0| 2106.5| 2305.3| 2744.0|
| CO₂/C0     | 19.13     | 13.00| 11.93| 21.40| 9.43| 5.73| 9.51|
| WATER       | 5.85      | 15.33| 7.28| 4.02| 20.73| 17.42| 15.68|
| VBD         | 80.20     | 51.50| 73.50| 85.40| 68.30| 76.50| 57.70|

APPENDIX 1 (Continued)

| Transformer | Data Test | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|-------------|-----------|---|---|----|----|----|----|----|
| H₂          | 19.74     | 4.83| 4.28| 15.00| 0.00| 2.50| 11.00|
| CH₄         | 43.86     | 5.57| 10.17| 83.48| 10.51| 100.00| 148.00|
| C₂H₂        | 0.00      | 0.00| 0.00| 0.00| 0.00| 0.00| 0.00|
| C₂H₄        | 4.37      | 108.42| 0.00| 8.52| 0.00| 23.00| 66.00|
| C₂H₆        | 161.80    | 6.25| 38.39| 268.05| 37.47| 175.00| 308.00|
| Rate H₂     | 12.75     | 5.26| 6.75| 6.75| Neg| Neg| Neg|
| Rate CH₄    | 28.33     | Neg| Neg| Neg| Neg| Neg| 98.65|
| Rate C₂H₂   | 0.00      | 0.00| 0.00| 0.00| 0.00| 0.00| 1.19|
| Rate C₂H₆   | 2.82      | Neg| Neg| Neg| Neg| Neg| Neg|
| Rate C₂H₆   | 104.53    | Neg| 12.17| 34.71| Neg| Neg| Neg|

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### Appendix 1 (Continued)

| Data Test | Transformer | 8   | 9     | 10   | 11   | 12   | 13   | 14   |
|-----------|-------------|-----|-------|------|------|------|------|------|
| CO        |             | 53.30 | 1100.89 | 13.01 | 242.59 | 18.43 | 358.47 | 706.00 |
| CO₂       |             | 779.65 | 4738.34 | 796.23 | 2336.44 | 353.07 | 1578.97 | 2837.00 |
| CO + CO₂  |             | 852.95 | 5839.23 | 809.25 | 2579.02 | 371.30 | 1937.44 | 3543.00 |
| CO₂/CO    |             | 14.63 | 4.30 | 61.18 | 9.63 | 19.16 | 4.40 | 4.02 |
| WATER     |             | 6.25 | 23.54 | 6.47 | 6.64 | 5.64 | 10.16 | 19.475 |
| VBD       |             | 99.5 | 74.1 | 86.4 | 71.3 | 95.3 | 78.1 | 72.0 |
| ACIDITY   |             | 0.02 | 0.0165 | 0.0149 | 0.0066 | 0.0056 | 0.0082 | 0.0315 |
| IFT       |             | 32.9 | 27.1 | 32.6 | 27.7 | 36.3 | 30.2 | 31.0 |
| COLOUR    |             | 0.5 | 3.5 | 1.3 | 0.8 | 0.5 | 1.7 | 4.0 |
| AGE       |             | 6 | 23 | 27 | 24 | 28 | 32 | 21 |

### Appendix 2

Sample data of non-operating transformers

| Data Test | Transformer Id | 5   | 6     | 7     | 13   | 14   | 29   |
|-----------|----------------|-----|-------|-------|------|------|------|
| H₂        |                | 132.36 | 20.00 | 216.50 | 313.37 | 355.84 | 1353.96 |
| CH₄       |                | 3.54 | 50.24 | 8.53 | 10.03 | 86.37 | 17.32 |
| C₂H₂      |                | 26.34 | 14.86 | 10.39 | 109.63 | 12.69 | 8.13 |
| C₂H₄      |                | 0.00 | 372.81 | 6.80 | 0.00 | 25.93 | 5.15 |
| C₂H₆      |                | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 19.30 |
| CO        |                | 152.44 | 55.90 | 1103.35 | 255.75 | 711.18 | 885.87 |
| CO₂       |                | 452.12 | 41.42 | 1086.15 | 1458.83 | 711.18 | 611.92 |
| CO₂/CO    |                | 604.56 | 97.32 | 2189.50 | 1714.58 | 1482.85 | 1497.79 |
| CO₂/CO₂   |                | 2.97 | 0.74 | 0.98 | 5.70 | 0.92 | 0.69 |
| WATER     |                | 7.55 | 1.03 | 8.87 | 14.89 | 8.29 | 18.05 |
| VBD       |                | 67.90 | 89.00 | 66.30 | 21.60 | 41.30 | 20.70 |
| ACIDITY   |                | 0.09 | 0.03 | 0.06 | 0.03 | 0.09 | 0.04 |
| IFT       |                | 29.20 | 33.20 | 29.80 | 31.40 | 28.00 | - |
| COLOUR    |                | 3.70 | 0.90 | 3.40 | 2.40 | 7.00 | 2.70 |
| 2FAL      |                | 648.24 | 19.50 | 264.35 | 29.00 | 1172.97 | 152.19 |
| AGE       |                | 23 | 15 | 25 | 21 | 27 | 24 |
| HI value  |                | 41.30 | 65.20 | 41.30 | 57.70 | 33.70 | 44.60 |
| HI other  |                | 75.00 | 78.26 | 69.57 | 60.87 | 39.13 | 35.87 |