Condition Monitoring and Health Index Determination of Operating 20kV Distribution Transformers Using Analytical Hierarchy Process Method

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***Abstract*— The distribution system is one of the business processes in the utility system. The most crucial asset in distribution system is the transformer. The high failure rate of distribution transformers can lead to loss of revenue and decreased service quality. There are many factors that cause the failure of distribution transformers. thus, developing strategic planning to increase the reliability of transformers is a must. One of the strategic plans for the maintenance of the distribution transformer is Health Index. Health index consists of several stages, and one of the most influential factors in increasing the accuracy of the health index is weighting factors. Based on previous studies, there are several methods used in determining the weighting factor. In this study, the Analytical Hierarchy Process Method involves expert judgment applied to adjust the weighting factor. The experience of experts will serve as the basis for determination. The weighting factor will be applied to several parameters in the assessment of the transformer (i.e. Oil leakage, tank condition, Grounding, Unbalance, Load Profile, Hot spot). The findings oh the AHP show that Load profile has a highest with 32.17%, followed by Unbalance (18.93%), Hot Spot Temperature (18.72%), Oil Leakage (13.92%), Grounding (11.53%), and Tank Condition (4.73%). Furthermore, 538 samples of operating 20 kV distribution transformers will be assessed with Health Index.**

Keywords—Operating Distribution Transformers, Health Index, Analytic Hierarchy Process (AHP), Weighting Factor.

I. INTRODUCTION

The distribution system is a business process in which electricity is distributed to customers by distribution transformers. The distribution transformer is the last component for voltage transformation in the power grid. It is used to convert the medium voltage to the low voltage level that is used for households or for commercial use[1]. A good level reliability of distribution transformers can enhance service quality and prevent loss of sales revenue. It becomes difficult to do efficient maintenance when there are numerous number with different features of transformers. Consequently, in order to identify the essential maintenance actions for that asset, a strategic plan must be developed prior to a transformer breakdown.

A diagnostic transformer is the determination of the condition of a transformer by examining the results of condition inspections measured to detect anomalies. Various diagnostic tests and fault detection techniques have developed to effectively support utility operators in predicting failure [2]. This activity is carried out to determine the condition as a monitoring of anomalies present in the transformer asset. Online diagnostic is the activity of inspecting or collecting data on operating assets. So that the actual condition of the assets operation can be understood.

Fig. 1. Distribution Transformer.

One of the strategic plans that can be implemented is by applying the Health Index. Health index is a condition monitoring instrument to quantify the transformer condition based on technical diagnostics measurements[3]. By conducting periodic diagnostics, the condition of the transformer can be assessed, and appropriate follow-up actions can be determined based on the needs of the asset. The health index is compiled based on the scoring of conditions and the weight of the parameters being tested. Both have a significant influence on determining the final outcome of the Health Index value. The implementation of a good Health Index strategic plan is when the Health Index results align with the actual condition of the assets in the field.

The factor that plays an important role in determining the accuracy level in the implementation of the health index is weighting factor. The Weighting factor is identified which parameters have high levels of criticality, risk, and cost. The transformers that require high maintenance priority can then be identified.

In decision-making, there are several methods that can be applied, one of which is Analytical Hierarcy Process (AHP). AHP is a decision-making technique that identify the significance of one element compared to the other relying on the judgment using pairwise comparisons [4]. With AHP methode, The weighting factor can be determined by expert judgment, which raises the Health Index calculation's degree of accuracy.

In this paper, a study is conducted to determine the health index score based on the weighting factor obtained. The result of health index will then be compared with the conditions in the field.

II. Health Index

In the implementation of the Health Index, there are several steps that need to be taken.

A. Diagnose

In this study, there are 6 parameters that will be tested on each transformer that reflect the health condition of the asset. The operating 20kV distribution transformer is inspected using several measurement as follows.

- Oil Leakage, the condition when oil seeps out from the transformer body, potentially overflowing and contaminating the surrounding environment. Oil leakage leads to flashover and transformer breakdown[5].
- Tank Condition, The tank is the physical protection for the transformer core and windings as well as is an oil container for cooling the transformer[5]. In some cases, the bodies of transformers get fractures, dents, and corrosion.
- Grounding, Grounding provides an increase in the reliability of the electricity supply service as it enhances stability of voltage conditions, preventing excessive voltage peaks during disturbances, and a means of providing a measure of protection against lightning [6]. An electrical equipment must have a grounding threshold value to prevent failures due to lightning. Therefore, the insulation resistance of a distribution transformer needs to be measured periodically. The standard that discusses the threshold values for grounding resistance is IEC 60076-3 2000.
- Unbalance, the condition when the load between different phases is unequal and has a significant gap. The unequal distribution of loads between the three phases of the system causes a flow of unbalanced currents in the system and overloading one line that produces unbalanced voltage drops on the transformer windings[9].
- Load Profile, Load profile diagnosis on distribution transformers aims to avoid overload and underload condition. Overload describes a transformer is subjected to loaded above it's rating. It is a major and serious problem that causes frequent failure of transformers in the region. Most transformers that are used in the distribution network operate above the rating specified by manufacturers[9]. Meanwhile, underload is a condition where the load on distribution transformers approaches zero. This condition can cause distribution transformers to operate inefficiently and leading to losses.
- Hot Spot, the condition when the temperature was higher than standard operation. An overheated transformer leads to reduction in its life. Heat generation caused in the core and in the conductor due to losses, affect the performance [10]. The standard that discusses about temperature for distribution transformers is Standard IEEE C57.91-1995, IEC 60076-7

B. Scoring

At the scoring stage, the inspection results are categorized into 4 categories based on the observations made. The rating of each parameter describes the condition of distribution transformers condition based on guidelines in the reference [11].

C. Weighting

Weighting factor is an important part of health index calculation. This factor represents the significance of each parameter in order to derive a single health index value from various parameters[3]. It can be obtained by several methods, the result of this factor indicates which parameters have the highest priority in influencing the Health Index of distribution transformers. In this study, the method used to determine the weighting factor is AHP. First, through a hierarchical procedure, the goal, criteria and alternatives (measurement parameters) are determined.

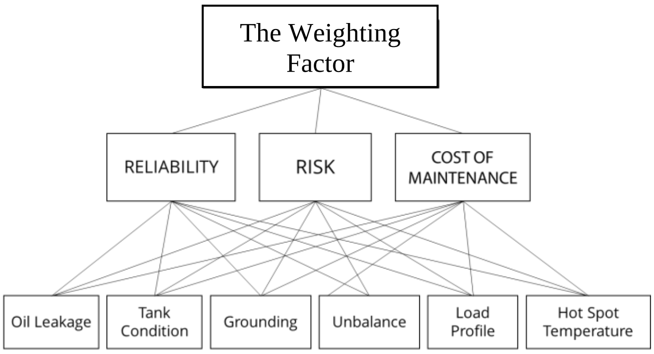

Fig. 2. AHP Hierarchy Design

Figure 2 shows the hierarchy of Goals, Criteria, and Parameter. To determine the weighting factor using the following three criteria: reliability, risk, and cost of maintenance. Then, all parameters are compared in pairs based on the established criteria. Thus, each parameter is interconnected and receives comparison results according to the criteria.

The next step is to establish the priorities of the elements by conducting pairwise comparisons involving experts, so that a comparison matrix can be obtained.

$$\begin{bmatrix} C_{11=1} & C_{12} & \cdots & C_{1n} \\ C_{21} = 1/C_{12} & C_{22} = 1 & \cdots & C_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ C_{n1} & C_{n2} & C_{n3} & C_{n4} \end{bmatrix}$$

In the pairwise comparison matrix, the diagonal values are always 1 because they compare the parameters with itself. In AHP, the assessment is reciprocal; if C12 has a value of a, then C21 has a value of 1/a.

Next, determine the synthesis calculation to obtain the Priority Vector value for each parameter. Then, conduct a Consistency Analysis using the following formula.

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (1)$$

$$CR = \frac{CI}{IR} \quad (2)$$

Equation (1) is the formula to get Concistency Index (CI) where λ_{max} is the largest eigenvalue and n is the number of element parameters. Then, Concictency Ratio (CR) can obtained by (2) where IR is constant depends on the number of element parameters. The results can be considered consistent if the CR value is no more than 0.1.

In the final step, the priority vector value for each parameter obtained is multiplied by the priority vector value for each criterion. This will yield the weight for each parameter.

D. Indexing HI

After the weighting factor values are obtained, the implementation of the Health Index can be carried out. In this study, 110 units of operating 20 kV distribution transformers samples were evaluated based on six preset parameters.

$$HI = \sum_{i=1}^{I} Si \times Wi \quad (3)$$

Indexing HI calculated by multiply Scoring (*Si*) and Weighting *(Wi)* of each parameters. The result of HI can categorized based on the following tables.

TABLE I. CONDITION CATEGORY

Index	***Condition***	***Descriptiom***
2.6 – 3	Good	Normal
2.01 - 2.6	Acceptable	1-2 parameters have anomaly
1 – 2	Poor	3-4 parameters have anomaly
< 1	Very Poor	5-6 parameters have anomaly

The worst condition of a distribution transformer is when it has a value of very poor, which means that the distribution transformer is in the lowest condition. The maintenance priority level will increase with a decreasing health index rating.

III. RESULTS AND DISCUSSION

In this study, the criteria divide by Reliability (cause of failure), Risk to the environment and the cost of maintenance. There are four comparison matrix created with the participation of three experts to determine which parameters are more important than others based on their experiences. In AHP method, all parameters will be compared with other parameters and quantified to obtain more objective results.. The results of calculation the weighting factor determination study using AHP with expert yielded the following values.

TABLE II. COMPARISON MATRIX OF CRITERIA

CRITERIA	RELIABILITY	RISK	COST
RELIABILITY	1	4.21	3.55
RISK	0.23	1	1
COST	0.28	1	1

Table II shows that the result of the comparison pairwise between three criteria with the most important criteria is Reliability. It is more important 4.21 times than risk criteria and 3.55 times than cost criteria.

TABLE III. COMPARISON MATRIX OF RELIABILITY

RELIABILITY	Oil Leakage	Tank Condition	Grounding	Unbalance	Load Profile	Hot Spot
Oil Leakage	1	4.38	1.81	0.65	0.21	0.48
Tank Condition	0.22	1	0.27	0.20	0.13	0.18
Grounding	0.55	3.63	1	0.58	0.22	0.45
Unbalance	1.53	4.93	1.71	1	0.32	0.79
Load Profile	4.71	7.61	4.48	3.10	1	2.41
Hot Spot	2.08	5.27	2.19	1.26	0.41	1

Table III shows the matrix comparison pairwise between parameters in Reliability Criteria. In this criteria, Load Profile is the most important parameter.

TABLE IV. COMPARISON MATRIX OF RISK

RISK	Oil Leakage	Tank Condition	Grounding	Unbalance	Load Profile	Hot Spot
Oil Leakage	1	6.25	1.55	3.91	3.00	0.87
Tank Condition	0.16	1	0.23	0.33	0.23	0.24
Grounding	0.64	4.32	1	2.52	0.87	1.21
Unbalance	0.25	3.00	0.39	1	0.63	0.46
Load Profile	0.33	4.21	1.14	1.58	1	0.58
Hot Spot	1.14	4.12	0.82	2.15	1.71	1

Table IV shows the matrix comparison pairwise between parameters in Risk Criteria. In this criteria, Oil Leakage Parameter is the most important parameter.

TABLE V. COMPARISON MATRIX OF COST

COST OF MAINTENANCE	Oil Leakage	Tank Condition	Grounding	Unbalance	Load Profile	Hot Spot
Oil Leakage	1	1.21	0.34	0.20	0.58	0.34
Tank Condition	0.82	1	0.60	0.43	0.84	0.69
Grounding	2.88	1.65	1	0.27	0.72	0.69
Unbalance	4.93	3.68	3.68	1	3.47	3.63
Load Profile	1.71	1.18	1.38	0.28	1	1.26
Hot Spot	2.88	1.44	1.44	0.27	0.79	1

Table V shows the matrix comparison pairwise between parameters in Risk Criteria. In this criteria, Unbalance Parameter is the highest number.

TABLE VI. CONSISTENCY ANALYSIS

	Consistency Analysis			
	λ_{max}	CI	IR	CR
Criteria	3.00	0.0023	0.58	0.0041
Reliability	6.15	0.03	1.24	0.0254
Risk	6.17	0.03	1.24	0.0285
Cost	6.30	0.06	1.24	0.0494

The results of the consistency analysis show that the CR value is no more than 0.1. This indicates that the results of the comparison determination are consistent.

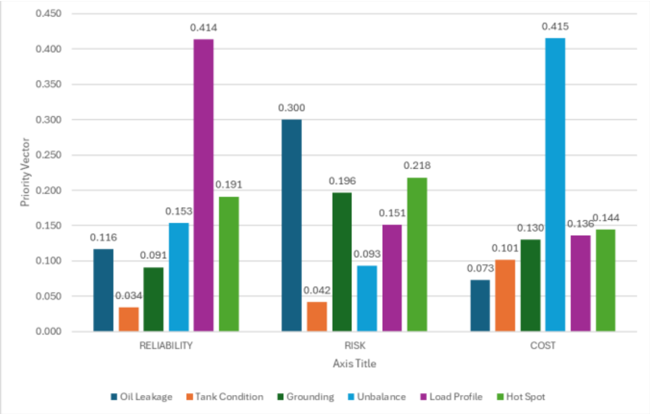

Fig. 3. The Result of Comparison

Figure 3 shows that in the Reliability criteria, the Load Profile parameter has the highest priority vector with 0.41, indicating that the influence of the load profile condition on reliability is quite significant. Then, in the Risk criteria, oil leakage has the highest priority vector value with 0.3. Meanwhile, in the cost category, the unbalance in maintenance costs is the lowest, resulting in a high priority vector with 0.41.

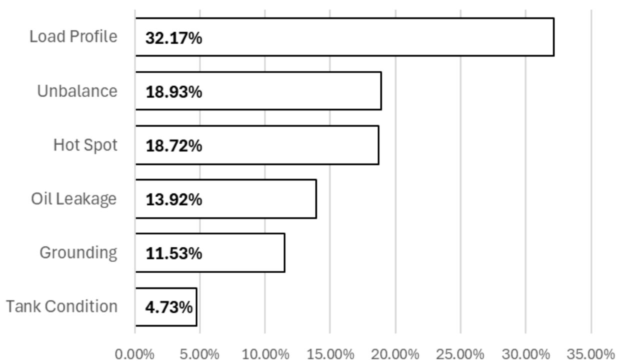

Fig. 4. The Weighting Factor with AHP

The result of weighting factor for the health index using the AHP method is shown in Figure 4. The involvement of these experts aims to achieve a higher level of accuracy for the health index. The determination of weighting using the AHP Method is adjustable, allowing for development through the addition of experts or other criteria according to utility needs.

The weighting results obtained are applied to the Health Index of 538 operating distribution transformer units with different year and different capacity. The purpose of this is to ascertain if the health index accurately represents the state of each different transformer sample. Here is a sample operating distribution transformers by year produced and by capacity.

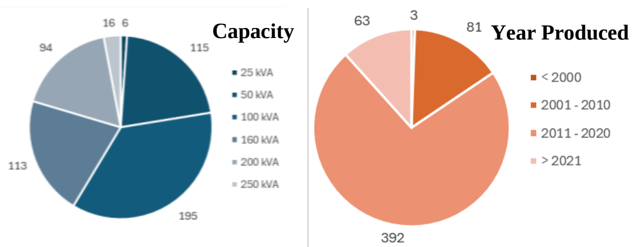

Fig. 5. Sample of Distribution Transformers

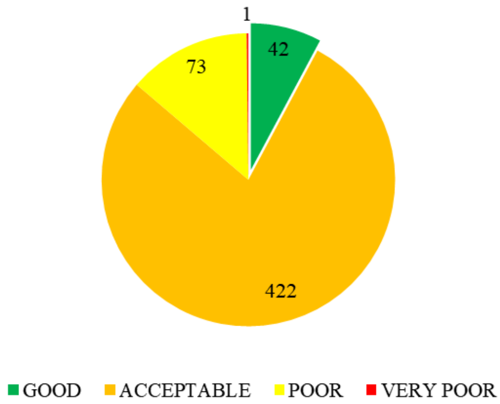

Fig. 6. The Result of Health Index

Using the health index method, it is possible to identify transformers that are in poor condition. In this study, 42 poor and 1 very poor condition has obtained and need maintenance follow-up. To measure how accurate the health index calculation results are, a comparison between the health index results and the disturbance history needs to be conducted.

TABLE VII. THE FAILURE OF DISTRIBUTION TRANSFORMERS

NO	Distribution Transformer (DT)	Time of Failure	Index	Health Index (HI)
1	DT-1	July	1.76	POOR
2	DT-2	July	1.89	POOR
3	DT-3	July	2.08	ACCEPTABLE
4	DT-4	Sept	2.03	ACCEPTABLE
5	DT-5	Sept	2.27	ACCEPTABLE

Table VII shows information about the historis of failure in last three months. There are two Distribution Transformers failure with poor condition and three with Acceptable condition.

Health Index can be applied as a strategic plan in monitoring. In previous study, there are a lot of method assessment of operating transformer (i.e. Health index calculation, Fuzzy Logic, Artificial Neural Network Effort, Random forest, and PSO)[1]. Although Health Index method has low accuracy, this method has a low level of complexity so it can serve as an early warning for the operating of distribution transformer.

IV. CONCLUSIONS

The weighting factors play a crucial role in determining the Health Index score of distribution transformers. The determination of the Weighting Factor using AHP can improve the accuracy level of the Health Index value.

The result of AHP shows that the parameter with the highest priority ranking is Load Profile (32.17%), followed by Unbalance (18.93%), Hot Spot Temperature (18.72%), Oil Leakage (13.92%), Grounding (11.53%), and Tank Condition (4.73%).

The health index is method with low level accuracy however it has a low level of complexity so it can assest condition of Distribution Transformers easily. The Health Index was applied to 538 distribution transformer units, resulting in 42 units classified as good, 422 units as acceptable, 73 units as poor, and 1 unit as very poor.

Furthermore, The method to determine Health Index can be combine with other method to increase the accuracy of Health Index.

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