[1] Syah Afrizka Mareta Arum

[2] Moses Laksono Singgih

Effective Power Transformer Maintenance Strategy Decision-Making: Health Index, Statistical Analysis, and Life Cycle Cost

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Abstract: - As a State-Owned Enterprise, PLN must provide sufficient quantity and quality electricity for the public interest. Still, on the other hand, according to the articles of association, PLN is required to make a profit. Power transformer failures significantly impact electrical system reliability, as they can disrupt electricity delivery. Many studies have been conducted on the health index of power transformers. However, previous studies only considered health indexes from one or several aspects of testing results. Life Cycle Cost is a method that helps select the best cost approach for establishing an effective maintenance strategy over the transformer's lifetime. A transformer lifetime uses a Weibull Analysis of a failure transformer in PLN TJBT from 2017-2022. This study uses a comprehensive health index by considering failure modes in transformers that integrate results from various aspects, such as observations while in operation, field inspections, and on-site and laboratory testing. After conducting a comprehensive health index, a risk evaluation was performed to simulate the impact of different maintenance decisions. Considering the health index and life cycle cost of the transformer, a new maintenance decision-making model was developed to choose the best maintenance strategy based on the current condition of the transformer.

Keywords: power transformer, health index, comprehensive, risk, Life Cycle Cost

I. INTRODUCTION

As the grid size and customer demand in Indonesia escalate, ensuring the safe and cost-effective operation of power transmission equipment becomes crucial for electric enterprises, including PLN. Therefore, more than any other components, the performance of transformers is the main factor that influences the reliability and economy of the power system[1]. An effective maintenance and asset management strategy is needed to ensure and optimise electricity assets in Indonesia to maintain good utilisation. Maintenance is a combination of technical, administrative, and managerial efforts to ensure that industrial assets are cost-effective and can carry out their operations following the design plan[2].

Issues related to transformer condition assessment have long been a concern in industry and academia. In practice, various online and offline monitoring techniques have been developed and used to perform condition assessment and management of transformer assets. However, each of the above methods generally only focuses on evaluating the transformer condition from one aspect. A practical and reliable health index should be based on combining data and information, integrating all available evidence from online and offline measurements of operation and maintenance, failure statistics, on-site inspections, and experts' experience so that combining them will become a performance indicator that produces a comprehensive health index[3].

Life Cycle Cost is the total cost of ownership, including the cost of the project or asset acquisition, operation and maintenance, and disposal. The objective of the Life cycle cost is to choose some alternatives of the most cost-effective approach to determine the lowest long-term cost of ownership[4].

This study proposes effective maintenance decision-making to solve the problem based on the combined consideration of a comprehensive health index, statistical analysis, and the associated cost impact using Life cycle cost. The comprehensive health index used considers the failure modes in the transformer by integrating the results from various aspects, such as observation during operation, field inspection, and on-site and laboratory testing. In total, 41 power transformers with a rating of 150 KV and a rated capacity of 60 MVA in PLN were used for the case study.

II. LITERATURE REVIEW

A. Health Index

A health index is an index or score that shows the "current" health status or condition of an individual asset based on the results of processing indicators that represent the asset's condition. Condition indicators are obtained through inspection, monitoring, diagnostics, measurement, and testing activities on the asset. The

[1,2] Department of Industrial and System Engineering, Institut Teknologi Sepuluh Nopember

1syah.afrizka@gmail.com, 2mosesIsinggih@ie.its.ac.id

health index score represents the "health" condition of the asset. The calculation must show a clear relationship between "condition indicators," failure modes, and the scoring system[5].

The calculation procedure is as follows in Figure 2. Convert the condition indicators into logarithmic scale scores of 1, 3, 10, 30, and 100 ("logarithmic base 3") with the definitions in Table 1. The score will represent the probability of a failure mode occurring within each transformer subsystem.

Table 1 Logarithmic Condition Indicator Scoring Scale and Definition

Score	Statement	Definition
1	Very good	“as new” condition, very low likelihood of failure over many years
3	Good	low likelihood of failure over a long period
10	Fair	Deterioration that could affect the asset's lifetime begins to be detected, which can affect the long-term performance of the asset unless intervention measures are taken.
30	Poor	Progressive deterioration has been detected
100	Critical	High likelihood of failure. Required immediate action, possibly followed by asset shutdowns

The scores obtained on a logarithmic scale are then converted to a linear scale using the conditions stated in Table 2. Scoring on a linear scale is used to group assets based on the possibility of disturbance and can later be used in calculating asset risk.

Table 2 Scoring Conversion to Linear Scale

Score	Statement	Conversion
1	Very good	If all condition indicators have a value = 1
2	Good	If there is at least 1 condition indicator with a value = 3 and no condition indicator with value > 3
3	Fair	If there is at least 1 condition indicator with value = 10 and no condition indicator with value > 10
4	Poor	If there is at least 1 condition indicator with a value = 30 and no condition indicator with value > 30
5	Critical	If there is at least 1 condition indicator with value = 100

B.

C. Statistical Analysis

The failure trend of a power transformer is described by the “bathtub curve”[6]. However, utility companies may encounter varying failure rates, making it essential for each company to maintain precise records of failures. The projection of the life expectancy curve is determined using a Weibull distribution[7].

The equation to determine Mean Time to Failure is expressed as:

$$\mu = \theta = \int_0^\infty t.f(t)dt \qquad (1)$$

D. Life Cycle Cost Analysis

The LCC process discussed in this paper is shown in Figure 1[8].

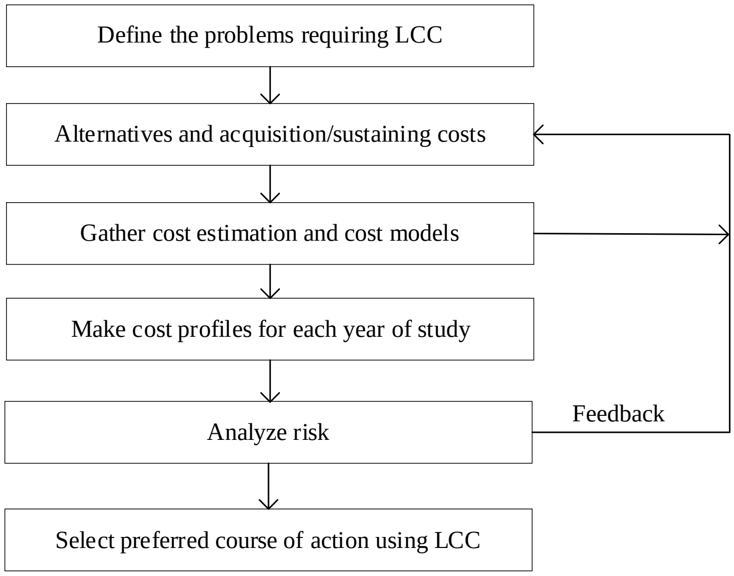

Figure 1 LCC Process Diagram

The alternatives for maintenance decisions to be made are as follows:

a. Continuous running
   Transformers run as usual without repair
b. Transformer Repair
   Repair of the transformer depends on the part that is damaged
c. Transformer Replacement

The cost of a transformer in its life includes the cost of investment (T_{CI}), cost of operation (T_{CO}), cost of maintenance (T_{CM}), cost of failure (T_{CF}), and salvage value of the transformer (T_S) [9].

$LCC = T_{CI} + T_{CO} + T_{CM} + T_{CF} + T_s$……………………………..(2)

$T_{CO} = (P_O + \beta^2 x\ P_k) x\ h\ x\ a$…………………………………..(3)

$T_{CM} = (periodic\ maintenance, repair) cost$ ………………(4)

$T_{CF} = energy\ not\ served\ cost$ (3.5)………………………...(5)

$T_{CF} = a\ x\ S_n x\ I\ x \cos\theta\ x\ t_f$…………………………………..(6)

P_O = transformer no-load loss (kW)

β = average load rate

P_k = transformer load loss (kW)

h = annual service hour (h) = 8760 jam

a = electricity price (Rp/kWh)

S_n = rated capacity (kVA)

t_f = annual interruption

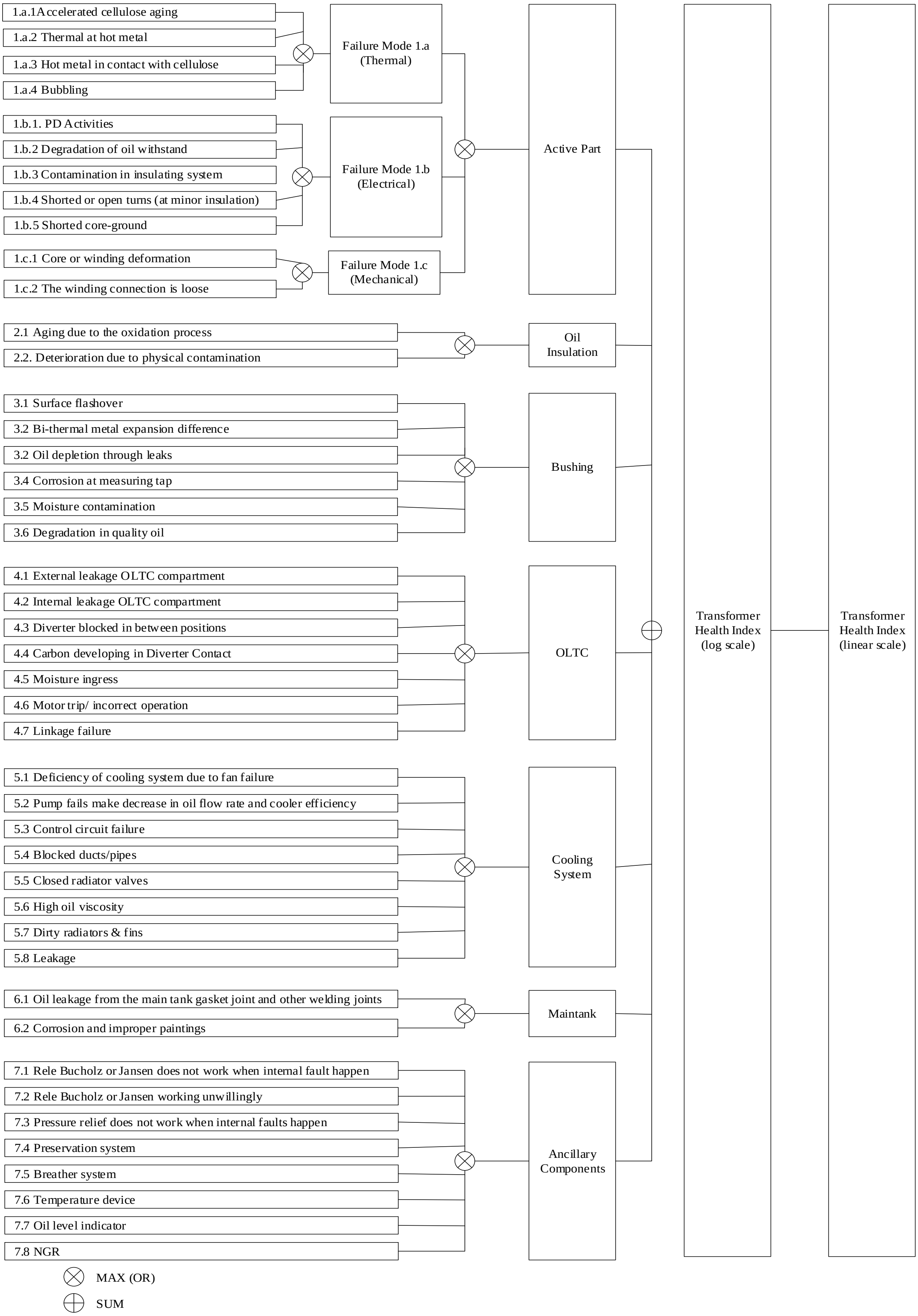

Figure 2 Health Index Score Calculation Process Flow

III. MAINTENANCE DECISION MAKING

The maintenance results carried out at PLN UPT Bogor for the 150/20KV 60 MVA transformer are inputted and processed according to the explanation in Table 2.

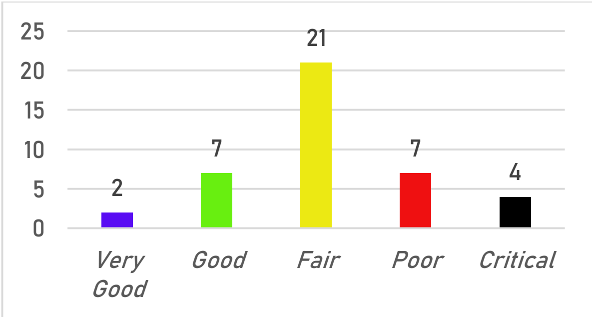

Figure 3 Health Index of Transformer at PLN UPT Bogor

The results of the health index calculation showed that four transformers have a critical assessment that requires the correct maintenance decision-making using life cycle cost. The current age of each transformer is listed in Table 3. The present age is used as a reference for the age at which maintenance decisions will be made on transformers in life cycle cost analysis.

Table 3 Critical Transformer Age

ID	Age (year)
TRF#A	28
TRF#B	19
TRF#C	19
TRF#D	13

The data available at electricity utilities are generally limited to a specific range of observations, also known as "right censored data." Transformer failure data for the past seven years was used as input.

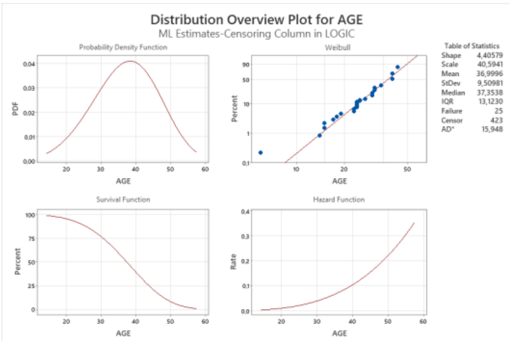

Figure 4 Statistical Function of Transformer Population

Statistical analysis showed the results of mean time to failure (MTTF) 37 years. This indicates that transformers in the TJBT region have an average age before failure (lifetime) of 37 years, above the IEC 60076-7 standard, where the age of a power transformer is 30 years.

Life cycle analysis for critical transformer has an outdoor type, 150 KV, 60 MVA, and the cooling mode is ONAN/ONAF. The average load rate is 80%, no load loss is 30 kW, and load loss is 115 kW. The annual service hours are 8760, and the electricity price is Rp. 1447/kWh. The cost of periodic maintenance is Rp. 11.562.224.

According to the references [10], major transformer repairs will reduce the age by ten years. Repair in this paper includes major repairs. Transformer repairs conducted are adjusted based on the results of the health index; for example, if there is bushing damage, a bushing replacement will be carried out, etc.

Risk analysis is the final process before choosing an alternative. Risk is the probability of failure multiplied by the consequences if the transformer breaks down. The consequence of the breakdown of the transformer is Rp. 13.259.792.000. Based on references [5], the probability of failure for a critical transformer is 0,90-1,00, repair 0,31-0,70, and new transformer after replacement is 0,01-0,10.

The result of the calculation for different maintenance decision-making of life cycle cost and risk is shown in Table 4.

Table 4 Life Cycle Cost Three Kinds oF Maintenance

ID	Continuous running	Repair	Replacement
TRF#A	17.512.607.949	17.528.635.374	17.816.964.840
TRF#B	17.512.607.949	17.508.269.619	18.588.185.710
TRF#C	17.512.607.949	17.445.156.327	18.588.185.710
TRF#D	17.512.607.949	17.491.014.993	19.840.949.890
Risk	11.933.812.800 - 13.259.792.000	4.110.535.520 - 9.281.854.400	132.597.920 - 1.325.979.200

Based on Table 4, LCC analysis TRF#A shows the decision to do continuous running until the transformer lifetime of 37 years has the smallest LCC of 17.512.607.949 but the greatest risk between Rp. 11.933.812.800 - Rp. 13.259.792.000. LCC analysis TRF#B shows that the decision to repair the transformer has the smallest LCC, 17.508.269.619, with a risk between Rp. 4.110.535.520 - Rp. 9.281.854.400. LCC analysis TRF#C shows that the decision to repair the transformer has the smallest LCC, 17.445.156.327, with a risk between Rp. 4.110.535.520 - Rp. 9.281.854.400. Last, LCC analysis TRF#D shows that the decision to repair the transformer has the smallest LCC, 17.491.014.993, with a risk between Rp. 4.110.535.520 - Rp. 9.281.854.400.

CONCLUSION

In conclusion, according to some relevant standards and expert experience, a maintenance decision-making optimisation model of power transformers considering both technical and economic factors was proposed in the paper. The creation of this maintenance decision-making can be a consideration for selecting alternative maintenance to be carried out on power transformers.

The analysis results include four transformers with a critical health index with a mean time to failure of 37 years. Life cycle cost analysis for four transformers with critical health index shows the results that doing continuous running alternatives is taken as a decision on TRF#A. Meanwhile, repairs will be carried out for TRF#B, TRF#C, and TRF#D according to the type of damage in each of these transformers.

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AUTHORS PROFILE

Syah Afrizka Mareta Arum is a postgraduate student in the Department of Industrial and System Engineering at Institut Teknologi Sepuluh Nopember (ITS) Surabaya and an engineer at Perusahaan Listrik Negara, an electricity company in Indonesia. My research interests include transformer assessment analysis, technic-economic analysis, and risk analysis, with a current focus on power transformers.

Moses Laksono Singgih is a Professor in the Department of Industrial and System Engineering at Institut Teknologi Sepuluh Nopember (ITS) Surabaya. He graduated with bachelor's and master's degrees in Industrial Engineering at Institut Teknologi Bandung. He received his MRegSc and PhD at the University of Queensland, Australia. Moses's research interests in Productivity and Quality in Smart Manufacturing Systems, including TRIZ, Lean Six Sigma, Cost and Quality Management, Internet of Things, Value Chain Analysis, and Risk Management.