Prediction of Distribution Transformer Age Loss using the Linear Regression Method

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ABSTRACT

Distribution transformer is one of the important equipment in the distribution of electricity to consumers. The electricity demand increases every year, so that the transformer works optimally, it must also be considered regarding the loading. According to IEC 354 if the transformer is loaded stable 80% with conditions around 20℃ and the winding temperature is 98℃, but if the ambient temperature is more than 20℃ then the age of the transformer will decrease. With an average loading of 71.75%, based on the calculation that the predicted useful age of the 160 KVA distribution transformer in 2027 will have an age loss index of 1.1 p.u, so it is estimated that the remaining age of the distribution transformer is 12 years and 7 months. Analysis using a statistical approach assisted by SPSS software was also carried out to see how much influence the loading has on the age loss of the transformer.

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1. INTRODUCTION

A component of the electric power system is the electric power distribution system. Electricity from huge power sources (also known as bulk power sources) may be delivered to customers via this distribution system [1]. PT. PLN (Persero) ULP Kenjeran, Surabaya has had extremely quick growth every year. The stability and dependability of the electric power system are crucial for its functioning since they enable the provision of comfortable services to customers. This may be done by keeping an eye on and examining the condition of the current electrically powered machinery. A transformer is one of the most crucial pieces of electrical equipment for an electric power supply to function.

Equipment for electrical power systems, such as distribution transformers, have a design life set by the manufacturer so that they can run for a specific amount of time. However, the transformer's life may differ from its intended life depending on usage and environmental factors. Several factors can shorten a transformer's life. Loading is one of the factors that contribute to a transformer's shorter service life. The temperature of the transformer may rise as a result of loading. The heat generated leads to the degradation of transformer materials, which might quicken aging. The structural characteristics of the transformer parts can be altered by the presence of excessive heat. Reduced age will occur from deviations from the permitted limit of roughly 6°C [2].

The aging of this insulation will be so fast if the insulation operates in temperatures that exceed the permissible limits. A transformer will operate normally for its entire lifespan at a Hot Spot temperature of 98°C while continuously loaded, according to the IEC 354 standard. The aging process can be sped up and the loss of age will occur so quickly that it may shorten the transformer's age, which is not what is planned, if the hotspot temperature surpasses 98°C [3].

Alternating current is utilized for the generation and distribution of electric power in a very large scale for a number of fundamental reasons, one of which is that it is highly simple and dependable [4]. Three-phase and single-phase step-down transformers rated at 20 kV/400 volts are the most used distribution transformers; some systems even employ three single-phase transformers. The low voltage network system has 380 V of phase-to-phase voltage. In order to ensure that the voltage at the receiving end is more than 380V, the low voltage is raised above that value due to a voltage loss [5].

Load unbalance is a condition where one or all of the phases in the transformer experience differences. The amount of the current or voltage and the angle of each transformer phase may be used to determine this difference. If a transformer phase satisfies the following requirements, it is said to be in a balanced state: (a) the three current vectors of each phase (R, S, and T) have the same magnitude; and (b) the angle difference between the three phase vectors is, respectively, 120° [6]. If the load imbalance is more than 20%, the system is not compliant [7]. The decrease in the ability of an insulating material due to heat is called aging. This is the primary reason preventing distribution transformers from lasting as long as they should. In other words, overloading will result in heat in the transformer coil's winding, which will eventually result in a shorter lifespan (age depreciation) for the transformer. Water temperatures for transformers using water cooling medium shall not exceed 25°C, whereas air temperatures for transformers using air cooling media should not exceed 40°C and may not be lower than -25°C for exterior installations and -5°C for installation within [8].

Insulation deterioration will accelerate if the insulation works at temperatures that exceed the permissible limits (in this case the hot spot temperature). The IEC 354 standard, which is now the current PLN standard, states that a transformer will operate normally when the "hot spot temperature is 98°C at continuous loading" and the ambient temperature is 20°C. The predicted age of the transformer will be shortened if the hot spot temperature exceeds 98°C since the loss of age would be higher and faster [9]. It is possible to determine the continuous loading capability based on ambient temperature thanks to the continuous loading factor provided by the IEC 354 standard, which will generate a hot spot temperature of 98°C from different temperatures or environmental conditions in the area where the transformer is installed and for each type of cooling in the transformer. According to SPLN, transformers in Indonesia are made to function at temperatures below 40 °C, with daily averages of 30°C and annual averages of 30°C.

The IEC stipulates that the age of a transformer is around 20 years or the equivalent of 7300 days when it is loaded at 100% of the rating value of the transformer power at an ambient temperature of 20°C, so that the normal age loss is 0.0137% per day. Various researchers do not fully agree on the loss of age of a transformer at a certain temperature. But they agree that over a range of 80 ÷ 140°C the aging rate of the transformer doubles for every 6°C increase in temperature and this value is used as the basis of the study [10].

When the transformer is on voltage and not loaded, losses will arise which can cause the transformer to be hot, but the heat generated is small. If the transformer is loaded, the coils and oil in the transformer will heat up according to the increase in load. Based on the background above, to determine load imbalance and age losses in distribution transformers due to loading, it is necessary to carry out an analytical study with a statistical approach using the simple linear regression method to determine the age losses of 160 KVA transformers at PT. PLN ULP Kenjeran Surabaya. In the research methods section, we will explain the use of the linear regression method to calculate loading predictions from 2023 to 2027. In the results and discussion section, the predicted loading results will be used to calculate the age loss value of the transformer using a statistical approach assisted by SPSS software. Furthermore, the overall research results are written in the conclusion.

2. METHODS

Research at PT. PLN (Persero) ULP Kenjeran was conducted using a quantitative research design, in which the outcomes of field measurements were processed using a statistical approach and formula conversion without giving the variables under study any special consideration. Distribution transformer-specific data as well as information on the loading of distribution transformers during the day and night are needed for the calculations in this study. Direct measurements are taken on a 160 KVA three-phase transformer in the Kenjeran ULP region to collect loading information. Determine the transformer load on the R, S, and T phases by measuring the load using an ampere meter.

Figure 1. Transformator 160 kVA PT. PLN ULP Kenjeran

2.1. Regression Linear Methods

The trend method is a method that is made based on the tendency of past relationships without regard to the causes or things that influence it (economic influences, climate, technology, etc.). Time series analysis whose results are trend equations that can be used for forecasting [11]. The following is the linear regression equation used for forecasting transformer loads in this study as follows [12]:

$$Y_t = aX_t + b \tag{1}$$

Where,

Y_t = Loading at time t

X_t = Time period t (day, week, month, year)

a = slope (slope) or changes in the value of Y over time

b = fixed value (constant) or the value of Y_t at X_t equals zero

To determine the constant values a and b as follows [12]:

$$a = \frac{n\sum XY - \sum XY}{n\sum X^2 - (\sum X)^2} \tag{2}$$

$$b = \frac{\sum Y}{n} - a\left(\frac{\sum X}{n}\right) \tag{3}$$

Where,

n = Amount of data

$\sum X$ = Number of time periods t

$\sum Y$ = The amount of loading at time t

$\sum XY$ = the number of time periods t multiplied by the amount of loading at time t

2.2. Thermal Effect on Transformer

The hotspot temperature is one factor that influences the distribution transformer's temperature. The transformer winding experiences the transformer section's hot spot temperature, which is the highest possible situation. The change in hotspot temperature is dependent on the surrounding temperature. The hotspot temperature rises with increasing ambient temperature and vice versa [13]. The transformer's temperature rise is also influenced by the quantity of loads applied to it. The temperature rise can be assumed as shown in Figure 3. This figure is understandable because it is a simplified diagram of a more complicated distribution.

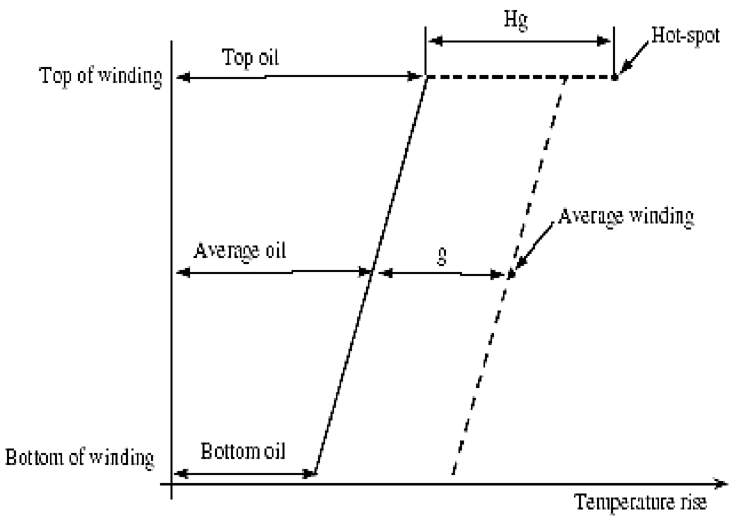

Figure 2. Thermal transformer diagram

In calculating the prediction of the age of a transformer, there are several equations that must be used in order to determine how much the remaining age of the transformer. First calculate the loading ratio with the following equation:

$$K = \frac{S}{S_r} \quad (4)$$

Where,

K = Load ratio

S = Load percentage

Sr = Full load (100%)

Furthermore, after determining the predicted results of transformer load in the following year with linear regression, then proceed to determine transformer losses using equation as follows:

$$d = \frac{P_{cu}}{P_{core}} \quad (5)$$

Where,

d = Loss ratio

Pcu = Copper losses (Watt)

Pcore = Core losses (Watt)

After knowing the ratio of losses, then determine the top oil temperature rise using the following equation [14]:

$$\Delta\theta b = \Delta\theta br \left(\frac{1+dK^2}{1+d}\right)^x \quad (6)$$

Where,

Δθb = Increase in top oil temperature

Δθbr = 40℃ (Off), 55℃ (On)

d = Loss ratio

K = Load ratio

x = 0,9 (ONAN/ONAF), 1,0 (OFAF/OFWF)

After knowing the results of the calculation of the top oil temperature increase, then determine the hotspot temperature increase with the following equation [14]:

$$\Delta\theta H = \Delta\theta b + (\Delta\theta cr - \Delta\theta br)\, K^{2(y)} \quad (7)$$

Where,

ΔθH = Increase in hostspot temperature

Δθb = Increase in top oil temperature

Δθcr = *78*℃

Δθbr = *55*℃

K = Load ratio

y = 0,8 (ONAN dan ONAF), 0,9 (OFAF dan OFWF)

After knowing the results of calculating the hotspot temperature rise, then determine the difference in temperature between the hotspot and the top oil with the following equation [14]:

$$\Delta\theta ou = (\Delta\theta cr - \Delta\theta br)k^{2y} \quad (8)$$

Where,

$\Delta\theta ou$ = Temperature difference between hotspot and top oil

$\Delta\theta cr$ = 78℃

$\Delta\theta br$ = 55℃

K = Load ratio

Y = 0,8 (ONAN dan ONAF), 0,9(OFAF dan OFWF)

Then determine the hotspot temperature linearly which is calculated based on the following equation (9) [14]:

$$\theta H = \theta a + \Delta\theta H + \Delta\theta ou \quad (9)$$

Where,

θH = Hotspot temperature

θa = Ambient temperature

$\Delta\theta H$ = Increase in hostspot temperature

$\Delta\theta ou$ = Temperature difference between hotspot and top oil

2.3. Relative Aging of The Winding Insulation

The decrease in the ability of an insulating material due to heat is called aging. The main factor that limits the ability to maintain the age of a transformer is due to overload [15]. The overload that is carried by the transformer will result in an increase in the temperature of the transformer. The heat that arises causes the decomposition of transformer materials which can accelerate the aging process of a transformer. The IEC standard 60076-7 of 2005 stipulates that the normal life of a transformer is 30 years [16] when loaded at 100% of the rating value of the transformer power at an ambient temperature of 20℃ with a hot spot temperature reaching 98℃. The aging factor for the age of the transformer at each hot spot temperature increase above normal temperature (98 ℃) can be calculated using the Monstinger formula as in equation (10) [17]:

$$V = 2^{\frac{\theta H - 98℃}{6}} \quad (10)$$

Where,

θH = Hotspot temperature

V = Relative thermal aging factor (p.u.)

After determining the relative value of the lifespan of the transformer, the last step is to calculate the predicted lifespan of the transformer with the following equation (11) [17]:

$$Estimated\ age = \frac{based\ age - n}{V} \quad (11)$$

Where,

n = Transformer operating time (tahun)

V = Relative thermal aging factor (p.u.)

3. RESULT AND DISCUSSION

In this study, the transformer used was a transformer with a capacity of 160 KVA, the transformer loading data was taken from peak load historical data. Calculation of the estimated remaining age of the transformer is calculated using a calculation method based on daily loading and a calculation method based on forecasting transformer load using the linear regression method. The research procedure shows the process of calculating the estimated remaining age of a transformer starting from a literature study and then continuing with a location survey, after which it collects data, namely transformer specification data, transformer peak load history data from 2021 - 2022, and environmental temperature data for Surabaya. After the data is complete, start calculating the load forecast using the regression linear method based on equations (1) – (3). After obtaining the results of the next period's load forecasting, we will then calculate the estimated age of the transformer based on forecasts (4) - (11).

3.1. Transformer Load Prediction Data

Based on the results of observations on distribution transformers with a rating of 160 kVA at PT. PLN ULP Kenjeran with 5 observation periods is explained in figure 2 and figure 3. In figure 2 and figure 3 there is an increase when observing the load at night, this is because at night there is a peak load so that the performance of the transformer increases to with 75% both in 2021 and 2022. Peak load (maximum demand) is defined as the largest demand load that occurs during a certain period [18].

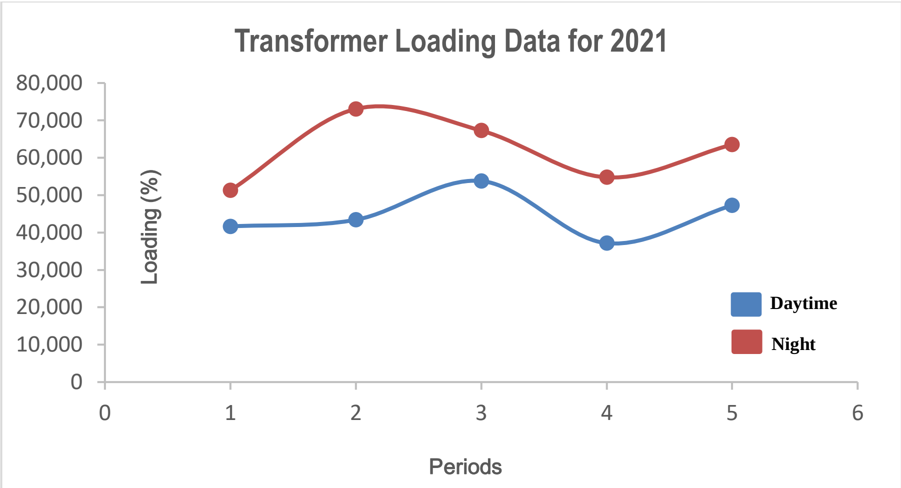

Figure 3. Loading chart during the day and night in 2021

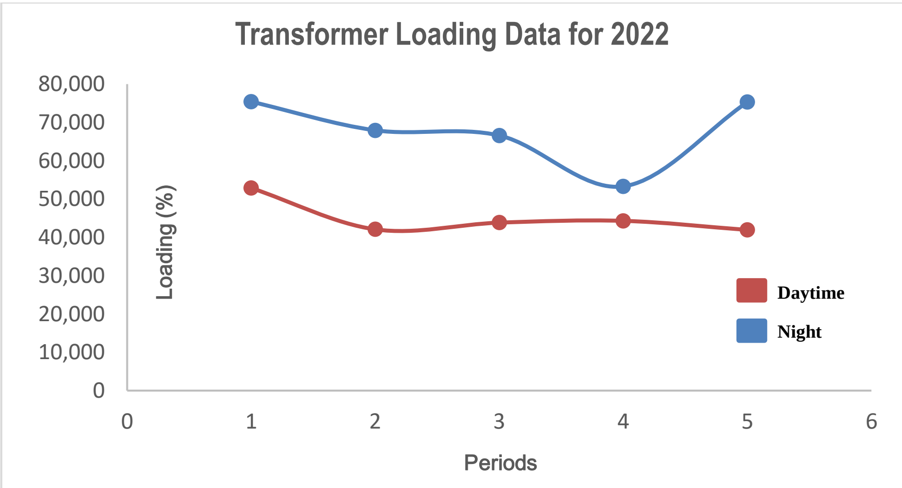

Figure 4. Loading chart during the day and night in 2022

This research was conducted to determine the prediction of transformer service life which is influenced by hotspot temperature and the effect of loading. Table 1 is the loading data and hotspot temperature from the distribution transformer which is the subject of research.

Table 1. Load Percentage and Hotspot Temperature

Year of The Operation	Data Collection Period	Load Percentage & Hotspot Temperature			
		Daytime		Night	
		Loading (%)	Hotspot Temperature (℃)	Loading (%)	Hotspot Temperature (℃)
2021	1	41,636	40	51,273	30
	2	43,416	39	73.060	32
	3	53,786	40	67,270	33
	4	37,162	42	54,766	31
	5	47,291	41	63,537	29
2022	1	52,872	35	75,410	32
	2	42,083	38	67,941	30
	3	43, 838	40	66,587	31
	4	44,305	33	53,310	29
	5	41,941	41	75,305	33

Table 2. Result of Forecasting the Load

Year	Load Percentage (%)	
	Daytime	Night
2023	55,37	63,18
2024	57,14	65,38
2025	59,32	67,62
2026	61,86	69,86
2027	63,95	71,75

To find out the results of forecasting the load, first look for the constants and coefficients using equations (2) – (4). After the constants and coefficients are obtained to predict the load in the coming year. The results of the load forecasting can be seen in table 2. According to the results of the predicting, it is certain that over the course of the next five years, the proportion of transformer load will rise by 2% annually at peak load. Additionally, after applying linear regression to forecast the consequences of transformer loads over the following few years, use equation (5) to calculate transformer losses. Equation (6) can be used to calculate the top oil temperature rise after knowing the transformer losses. The next step is to use equation (7) to calculate the hotspot temperature increase after knowing the outcomes of the calculation of the top oil temperature rise. The temperature difference between the hotspot and the top oil temperature may then be calculated using equation (8) after the results of the hotspot temperature rise calculation are known. After that, use equation (9) to calculate the hotspot temperature linearly. After then, use equation (10) to determine the relative value of the transformer's age in units per unit (p.u.). The final step is to use equation (11), after establishing the relative value of the transformer lifespan, to get the predicted transformer lifetime. The results predictions for 2023 – 2027 age loss of the 160 kVA transformer can be seen in table 3 and you can also see the graph of the loading will reduce the age of the transformer in Figure 5.

Table 3. Prediction of age loss in transformer 160 kVA

Year	Loading Prediction (%)		θH (℃)		$V_{(p.u)}$		Total $V_{(p.u)}$	Age Loss (year)
	Daytime	Night	Daytime	Night	Daytime	Night		
2023	55,37	63,18	86,09	90,24	0,26	0,43	0,7	25,7
2024	57,14	65,38	87,018	91,62	0,28	0,48	0,76	22,4
2025	59,32	67,62	88,40	92,54	0,33	0,53	0,86	18,6
2026	61,86	69,86	89,46	93,92	0,38	0,61	0,99	15,1
2027	63,95	71,75	90,24	95,29	0,41	0,73	1,1	12,7

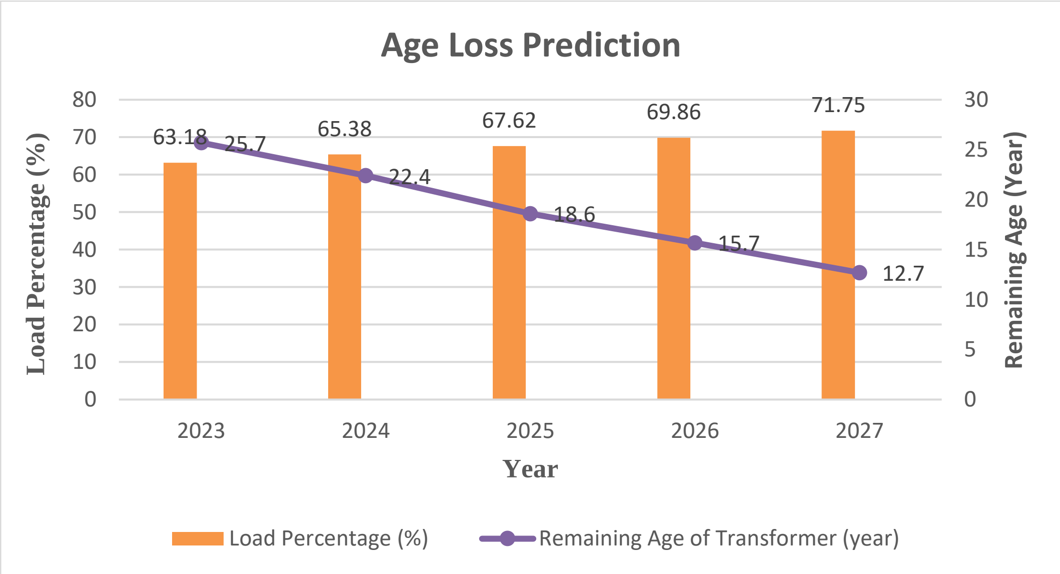

Figure 5. Age Loss Prediction Graph of a Transformer.

Because it hasn't achieved its maximum loading capacity of 80%, the percentage of 160 KVA transformer loading in 2027 is anticipated to utilize the load to reach 71.75%, which is a long life of the transformer and indicates that its lifespan is still quite long. Apart from the level of loading on the transformer and the environmental temperature around the transformer, there are several other factors that influence the life of the transformer. The quality of the insulation also greatly influences the service life of the transformer. Insulation in a transformer, such as insulating assembly, insulating oil, and dielectric materials, is very important. Poor insulation quality or one that degrades over time can accelerate the aging process of the transformer [19].

3.2. Analysis the Regression Linear Methods using SPSS

The use of SPSS software helps process various types of formats such as transformer loading data by calculating raw data faster than manual calculations. So, can make reports in the form of tabulations, charts (graphs), plots (diagrams). The Summary model explains the correlation/relationship (R) value of 0.987. From the output, a determination coefficient (R Square) of 0.975 is obtained which means that the effect of the independent variable (total loading (p.u)) on the dependent variable (transformer age loss) is of 97.5% can be seen in Figure 6. The calculated F value = 114.816 with a significance level of 0.002 <0.05, so the regression model can be used to predict the age loss variable of the transformer or in other words there is an effect of variable (X) on variable (Y) can be seen in Figure 7.

Model Summary				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	,987[a]	,975	,966	,9727

Figure 6. Result of Model Summary

ANOVA[a]						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	108,622	1	108,622	114,816	,002[b]
	Residual	2,838	3	,946		
	Total	111,460	4			

Figure 7. Result of Analysis of Variance

3.3. Discussion

Predicting loss over the life of a distribution transformer using the linear regression method can be done by collecting historical data about the age of the transformer and factors that influence the life of the transformer. Linear regression is a prediction method, and the results will be better if you have good data and understand well the factors that influence the life of a distribution transformer [20]. In addition, other factors that may not be documented in the data can also influence the life of the transformer. Therefore, the use of linear regression for predictions must be accompanied by a deep understanding of the system that will be studied further later. The hope is that the relevant parties can carry out load stability and maintain the operational temperature of the transformer in accordance with its working temperature. The linear regression method is a statistical approach that is often used to predict damage or loss of distribution transformer life. Linear regression can provide consistent and reliable transformer life predictions if used correctly. This is useful in planning maintenance and replacement of distribution transformers.

4. CONCLUSION

In this research, the loading data used is a 160 kVA distribution transformer from 2021-2022 at PT. PLN ULP Kenjeran, Surabaya using the linear regression method, the linear regression method aims to predict the loading in the following year. From this analysis, the loading increases by 2% every year, it is obtained that the lifetime prediction of the 160 kVA distribution transformer in 2027 is 12 years and 7 months, which has experienced an increase in load percentage of 71.75%. The effect of temperature on the prediction of the age of a 160 kVA transformer is very influential because the greater the loading, the temperature of the transformer will increase which will cause the age of the transformer to decrease from its standard.

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