Prediction of Transformer Age Based on Temperature Due to Loading Using Linear Trend Method: Case Study of 60 MVA Transformer

Reza Sarwo Widagdo[1*], Puji Slamet[1], and Muhammad Ubaidillah[1]

[1]Department of Electrical Engineering, Universitas 17 Agustus 1945 Surabaya, Surabaya, Indonesia

[*]Email: rezaswidagdo@untag-sby.ac.id

***Abstract*— Power transformers are a key piece of equipment in substations. Every year, the demand for power rises, and in order for the transformer to function properly, the loading must also be addressed. According to IEC 354, a transformer operating at full load is considered stable when the ambient temperature is around 24℃ and the copper temperature reaches 98℃. However, if the natural temperature exceeds 24℃, the transformer's lifespan will reduce. The study in question analyzed loading data from a 60 MVA power transformer spanning the years 2020 to 2022. The objective was to predict the transformer's remaining lifespan based on load increases using a linear trend approach for future years. The linear trend technique predicts the load for the following year, and the burden grows with each passing year. A 2% rise. To determine the outcomes of load forecasting, the prognosis for 2030 has a life loss value of 1.2 p.u, or the power transformer's anticipated remaining life is 1 year 6 months with a load of 88.64%.**

Keywords: Age loss transformer, linear trend methods, power transformer

I. INTRODUCTION

TRANSFORMER are the core equipment of transmission and distribution systems. Therefore, it is hoped that the transformer can work well, because with the hard work of the transformer it is also necessary to maintain it as well as possible. Therefore, correct systems and equipment must be used for transformer maintenance [1]–[3]. According to this principle, the condition of the power transformer must be monitored and maintained if unstable load conditions can affect the life of the power transformer [4]–[6]. Power transformer life can be reduced for several reasons. One of the causes of decreasing power transformer life is over voltage, over voltage causes an increase in winding temperature [7]–[10]. The generated heat leads to overheating of the power transformer, thereby accelerating its aging process.

Excessive heat can alter the structural characteristics of transformer components. An increase in temperature by about 6°C above the permissible limit can shorten the service life [11]–[13]. This temperature rise must be controlled. The insulation of transformer winding conductors will deteriorate when exposed to high temperatures. The higher the load percentage, the faster the remaining service life will decrease. As the transformer load increases, the hot spot temperature will approach the maximum allowable value [14],[15].

In the previous research [16], Transformer life estimation is based on the influence of load and environmental temperature using a linear trend based on overload conditions and exposure to environmental temperatures that exceed standards. This will cause overheat of the transformer insulation, which can reduce its lifespan. To predict the life loss of the power transformer, it can be evaluated using the hotspot temperature.

According to research [17], the first life loss estimate is based on distribution transformer load data with a power capacity of 160 kVA from 2021-2022. In forecasting the useful life of a power transformer, the author considers the factor of increasing loading in the coming year using the linear regression. The results are that in 2027, it is predicted that the remaining life of the transformer will only last for 12.7 years. Another article [18] also explained that the influence of the transformer hotspot temperature is if it is still below the maximum limit set, namely for the ONAN cooling type, namely 92.74ºC. Meanwhile, the ONAF cooling type is 66.63ºC. The loss in life of the ONAN/ONAF transformer is 0.10 hours/day or 35.53 hours/year. In other words, the predicted remaining life of a transformer with the ONAN/ONAF cooling type is 13.92 years. Another research in 2022, Suganda [19] predicted the service age of transformers from the load increase factor in the coming year using the trend linear. Based on the calculations, the predicted remaining lifespan of a 60 MVA power transformer, based on loading data from 2019 to 2020, indicates that by

2030, the transformer is expected to have 1 year and 6 months of remaining service life.

From the results of previous research, this research will take an approach to predict the lifetime of a 60 MVA Power transformer which is forecasting using the linear trend analysis method. Several variables including the influence of temperature due to loading and an increase in load of 2% each year will also be observed. Then the transformer that will be studied is a type of power transformer with a maximum rating of 60 MVA installed at the 150 kV Surabaya Barat substation.

II. METHOD

A. Transformer Age Prediction Using the Linear Trend

To calculate the lifetime, multiple equations must be employed to estimate how much life the transformer has left. The first stage is to determine the loading ratio of 60 MVA power transformer using the equation below [20]:

$$K = \frac{S}{Sr} \tag{1}$$

Where,

K = Loading ratio of power transformer

S = Loading percentage of power transformer

Sr = Percentage of maximum loading

After obtaining the loading ratio, use a linear trend to anticipate the load for the following year. Equations (2) and (3) may be used to calculate the values of a and b. [20].

$$b = \frac{n\sum XY - \sum XY}{n\sum X^2 - \sum X^2} \tag{2}$$

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

Where,

ΣY = Total transformer load percentage

ΣX = Number of time periods (t)

a = Constant

b = Coefficient

n = Amount of data

After finding the values a and b then these values are substituted using equation (4) [20]

$$Y_i = a + bX_i \tag{4}$$

Where,

Yt = Length of loading period (t)

Xt = Time period

a = Constant value of Yi at Xi is equal to zero

b = Coefficent or the change in the Y value over time

The next step is to determine the transformer load prediction results for the following year using a linear trend, then determine the transformer losses using equation (5) [20]

$$d = \frac{P_{Cu}}{P_{Core}} \tag{5}$$

After identifying the transformer losses, use equation (6) to determine the top oil temperature rise [20].

$$\Delta\theta_b = \Delta\theta_{br}\left(\frac{1 + dK^2}{1 + d}\right)^x \tag{6}$$

Where,

$\Delta\theta b$ = Transformer top oil temperature increase value

$\Delta\theta br$ = 40°C (off condition), 55°C (on condition)

d = Transformer loss value

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

k = Load prediction value

Following the findings of calculating the rise in top oil temperature, the next step is to calculate the increase in hotspot temperature using equation (7). [20].

$$\Delta\theta_H = \Delta\theta b + (\Delta\theta_{cr} - \Delta\theta_{br})K^{2(y)} \tag{7}$$

Where,

$\Delta\theta H$ = Hotspot temperature increase value

$\Delta\theta b$ = Transformer top oil temperature increase value

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

$\Delta\theta cr$ = 78°C (Maximum temperature under loading conditions)

$\Delta\theta br$ = 55°C (Temperature under normal conditions)

K = Transformer loading prediction results

After calculating the increase in hotspot temperature, the next step is to determine the difference between the hotspot and insulation temperature using equation (8) [20].

$$\Delta\theta_{OU} = (\Delta\theta_{cr} - \Delta\theta_{br})K^{2y} \tag{8}$$

Where,

$\Delta\theta ou$ = Hotspot and oil temperature difference

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

$\Delta\theta br$ = 55°C (Temperature under normal conditions)

$\Delta\theta cr$ = 78°C (Maximum temperature under loading conditions)

K = Transformer loading prediction results

After that, calculate the hotspot temperature linearly using equation (9).

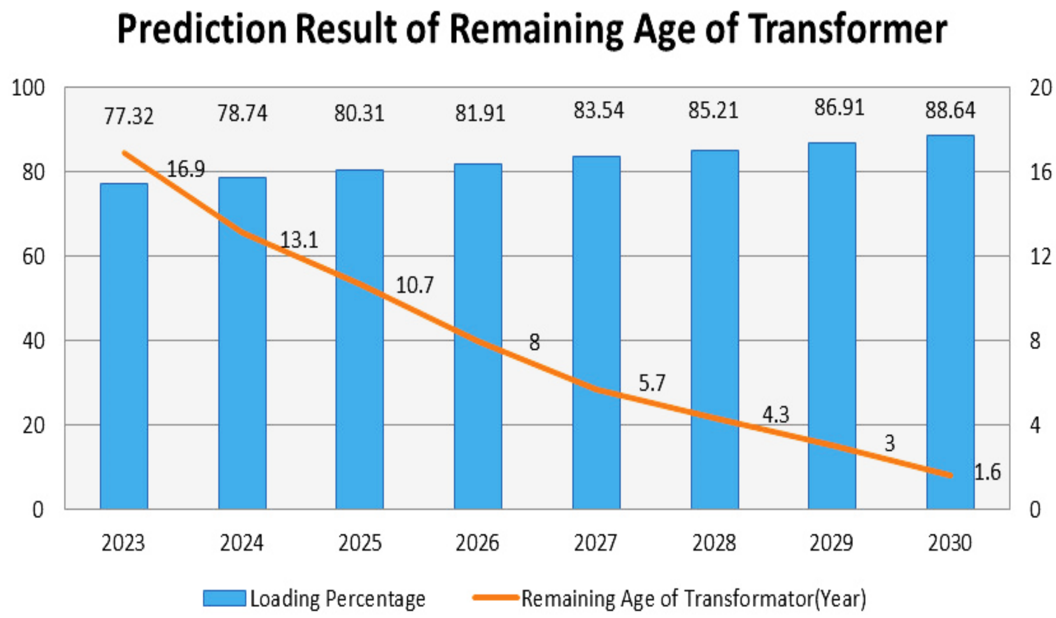

Fig. 1. Forecasting of remaining age of a 60 MVA power transformer

$$\theta_H = \theta_a + \Delta\theta_H + \Delta\theta_{OU} \quad (9)$$

Where,

θH = Hotspot temperature in transformer

θa = Ambient temperature in transformer

$\Delta\theta ou$ = Hotspot temperature difference and oil insulation

$\Delta\theta H$ = Increased of hotspot temperature in transformer

Next, determine the comparative value of the remaining lifetime of the power transformer to forecast each year of the power transformer's lifespan (p.u.) using equation (10) [20].

$$V = 2\,\frac{\theta_H - 98^\circ\text{C}}{6} \quad (10)$$

Where,

V = Prediction result

θH = Hotspot temperature

The last process is to use equation to anticipate the transformer service life according to increased load, which impacts temperature, after calculating the relative value of the transformer's remaining life (11) [20].

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

Where,

n = The remaining operating life of the transformer

III. RESULT AND ANALYSIS

In this research, the power transformer under investigation has a maximal capacity of 60 MVA, as depicted in Figure 2. The loading data were collected from historical peak load records spanning from 2020 to 2022 at the 150 kV Surabaya Barat main substation. Data collection occurred every 3 months during this period.

The linear trend approach is used to forecast the transformer's anticipated remaining life depending on its loads.

A. Prediction due to Loading Percentage

The results of the correlation analysis of the influence of time variables on loading were found to be 80%, therefore calculations were carried out using the linear trend method. Table I shows that the transformer loading an uneven increase.

TABLE I
LOADING DATA ON TRANSFORMER

Year of Observation	Periods (X)	A Daytime Load		
		Loading (Y)	(X^2)	(XY)
2021	1	55,8	1	55,8
	2	57,1	4	114,2
	3	61,1	9	184,6
	4	58,3	16	233,2
2022	1	63,3	1	63,3
	2	65,6	4	131,2
	3	70	9	210
	4	66,6	16	266,4
2022	1	71,8	1	718
	2	71,6	4	143,2
	3	73,3	9	219,9
	4	79	16	316
Total	30	794	90	2009,6

Fig. 2. Transformer 60 MVA at Surabaya Barat Substation

To obtain the load forecasting findings, first seek for constants and coefficients in equations (2) through (4). Table II shows the load forecast results after obtaining the constant and coefficient values for the following year.

TABLE II
LOAD PREDICTION RESULTS ON TRANSFORMERS

Year	Loading Percentage (%)
2023	77,32
2024	78,74
2025	80,32
2026	81,91
2027	83,54
2028	85,21
2029	86,91
2030	88,64

TABLE III
REMAINING AGE OF THE TRANSFORMER

Year	Load Prediction (%)	θH (℃)	V (p.u)	Prediction of Age Transformer (year)
2023	77,32	92,2	0,53	16,9
2024	78,74	93,2	0,61	13,1
2025	80,31	94	0,65	10,7
2026	81,91	95	0,75	8
2027	83,54	96,5	0,87	5,7
2028	85,21	97,2	0,93	4,3
2029	86,91	98,2	0,97	3
2030	88,64	99,6	1,2	1,6

Table II explains that the percentage of transformer load over the next 4 periods per year will increase by 2% during the peak load each year and could possibly be more than 2% if seen from the previous load increase. The percentage of load on a 60 MVA transformer in 2030 is predicted to reach 88,64%. Figure 1 is a graph of the predicted service life of a 60 MVA transformer which started operating in 2011 at a 150 kV Surabaya Barat Substations, which indicates that the use of the transformer is still in accordance with standards.

So the results of calculations using the linear trend method show that the useful life of a 60 MVA transformer in 2030 predicts load usage reaching 88,64%, where the life of the transformer has decreased, which means that the predicted useful life of the transformer is 1.6 (1 year 6 months) remaining in in 2030.

B. Linearity Analysis with SPSS

The model summary results explain the size of the correlation value (R), which is 0,984. The output findings show a coefficient of determination (R Square) of 0,967, indicating that the independent variable (total loading) has a 96,2% effect on the dependent variable (transformer life loss). Table 4 shows the results of the statistical tests performed on the model summary data.

TABLE IV
MODEL SUMMARY

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.984[a]	0.967	0.962	0.4325

a. Predictors: (Constant), Loading (p.u)

The ANOVA test outcomes clarify the significance of the F value, indicating that the regression model is applicable for predicting the transformer age loss variable. In essence, variable (X) affects variable (Y), as demonstrated in Table V.

TABLE V
ANOVA ANALYSIS
ANOVA[a]

Model		Sum of Squares	df	F	Sig.
1	Regression	0.332	1	177.502	0.000[b]
	Residual	0.011	6		
	Total	0.343	7		

a. Dependent Variable: Remaining Age (Year)
b. Predictors: (Constant), Loading (p.u)

In the coefficients, the constant parameter (a) is -3,719, while the overall loading value (b) is 0,005, reflecting a negative sign because the value decreases with the transformer's decreasing useful age, as shown in Table VI.

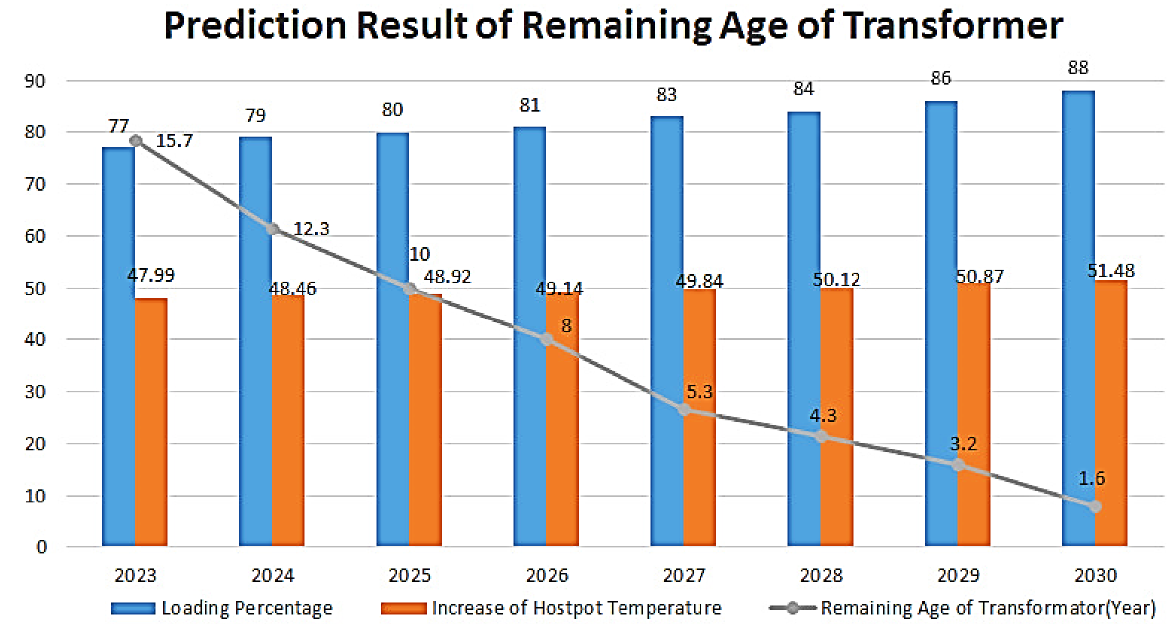

Fig. 4. Prediction of remaining age of a transformer

TABLE VI
COEFFICIENTS RESULT
Coefficients[a]

	Model	Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Std. Coefficients Beta	t	Sig.
1	(Constant)	-3.719	0.341		-10.920	0.000
	Loading (p.u)	0.055	0.004	0.984	13.323	0.000

a. Depent Variable: Remaining Age (Year)

In Figure 3 is a graph of transformer life loss using SPSS to quickly find out how much transformer life remains compared to calculating manually using the existing formula. It can be seen in Figure 4 that the predictions from year to year are linear and the data is very normal because the distribution is not far from the linearity line.

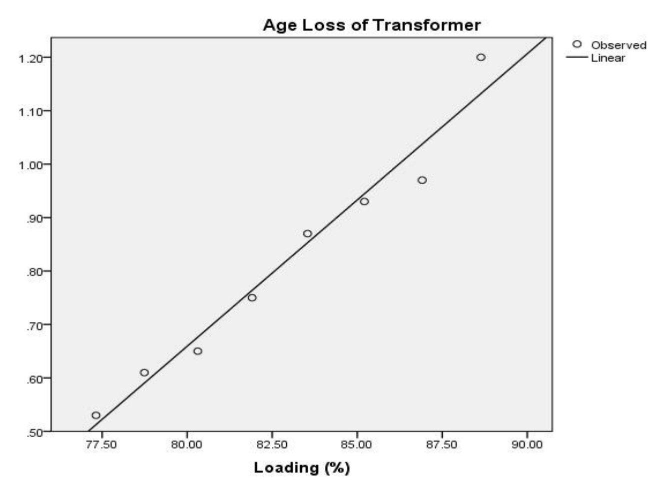

Fig. 3. Linearity test of the lifetime of the power transformer

Based on the expected life expectancy of transformers with loads that is still less than 80%, it is estimated that a 60 MVA transformer at the West Surabaya substation will last 1 year and 6 months, with a life loss value of 1,2 p.u. in 2030.

C. *Predictions Based on Increasing Hotspot Temperatures*

The correlation analysis indicated that time variables have an 80% influence on transformer loading. Consequently, calculations were performed using the linear trend. Table VII illustrates that the transformer experienced an irregular or uneven increase in loading over the analyzed period.

TABLE VII
LOADING AND TEMPERATURE HOTSPOT INCREASE DATA

Year	Periods	Percentage of Loading (%)	$\Delta\theta_H$
2020	1	55	41.50
	2	58	42.35
	3	60	42.99
	4	56	41.90
2021	1	61	43.32
	2	65	44.41
	3	67	44.93
	4	63	43.71
2022	1	71	45.92
	2	76	47.69
	3	79	48.55
	4	73	46.66

Table VIII presents transformer loading data, initially projected due to an increase in hotspot temperature as measured during daylight. To derive load forecasting results, begin by identifying constants and coefficients from equations (2) to (4). Once these data are established, forecast the load for the future year. Table IX shows the forecast results based on these equations.

TABLE VIII
LOADING DATA BASED ON INCREASE IN HOTSPOT TEMPERATURE

Year of Observations	Periode (X)	A Daytime Loading		
		Loading (Y)	(X^2)	(XY)
2021	1	55	1	55
	2	58	4	116
	3	60	9	180
	4	56	16	224
2022	1	61	1	61
	2	65	4	130
	3	67	9	201
	4	63	16	252
2022	1	71	1	71
	2	76	4	152
	3	79	9	237
	4	73	16	292
Total	30	784	90	1871

TABLE IX
LOAD PREDICTION RESULTS ON TRANSFORMERS

Year	Loading Percentage (%)	$\Delta\theta_H$
2023	77,32	47,99
2024	78,74	48,46
2025	80,32	48,92
2026	81,91	49,14
2027	83,54	49,84
2028	85,21	50,12
2029	86,91	50,87
2030	88,64	51,48

TABLE X
REMAINING AGE OF THE TRANSFORMER

Year	Load Prediction (%)	θH (°C)	V (p.u)	Prediction of Age Transformer (year)
2023	77	47,99	92,8	15,7
2024	79	48,46	94	12,3
2025	80	48,92	94,7	10
2026	81	49,14	95,4	8
2027	83	49,84	96,8	5,3
2028	84	50,12	97,3	4,3
2029	86	50,87	98,7	3,2
2030	88	51,48	100	1,6

The transformer's load is projected to increase by 2% annually during peak periods over the next four years. Additionally, considering past trends, this increase could potentially exceed 2%. By 2030, the loading of the 60 MVA transformer is forecasted to reach 88%. Figure 4 depicts the predicted operational lifespan of a 60 MVA transformer that commenced operation in 2011 at the 150 kV Surabaya Barat substation, showing that its usage adheres to standards.

So, the results of calculations using the linear trend method show that the useful life of a 60 MVA transformer in 2030 predicts load usage reaching 88%, where the life of the transformer has decreased, which means that the predicted useful life of the transformer is 1 year 6 months.

D. Hotspot Temperature Linearity Analysis with SPSS

A summary analysis model elucidates the correlation coefficient (R) value of 0.968. An R Square value of 0.937 was attained, indicating that the independent variable (maximum loading) influenced the dependent variable (transformer age loss) by 92,6%, as shown in Table XI.

TABLE XI
MODEL SUMMARY

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.968[a]	0.937	0.926	0.5527

b. Predictors: (Constant), Loading (p.u)

ANOVA analysis clarifies the significance of the F value, indicating that the regression model can estimate the transformer life loss variable. In simpler terms, it shows that variable (X) influences variable (Y), as presented in Table XII.

TABLE XII
ANOVA ANALYSIS
ANOVA[a]

Model		Sum of Squares	df	F	Sig.
1	Regression	0.272	1	88.987	0.000[b]
	Residual	0.018	6		
	Total	0.290	7		

a. Dependent Variable: Remaining Age (Year)
b. Predictors: (Constant), Loading (p.u)

In the results of the Coefficients test, it is known that the constant parameter (a) is –3,556, while the total loading value (b) is 0,005, where there is a negative effect (-) because the value decreases as the transformer's service life decreases, which can be seen in Table XIII. In Figure 5 is a graph of transformer life loss using SPSS to quickly find out how much transformer lifetime compared to calculating manually using the existing formula. It can be seen in Figure 5 that the predictions from year to year are linear and the data is very normal because the distribution is not far from the linearity.

TABLE XIII
COEFFICIENTS RESULT
Coefficients[a]

Model		Unstandardized Coefficients		Std. Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	-3.556	0.466		-7.637	0.000
	Loading (p.u)	0.053	0.006	0.968	9.433	0.000

b. Depent Variable: Remaining Age (Year)

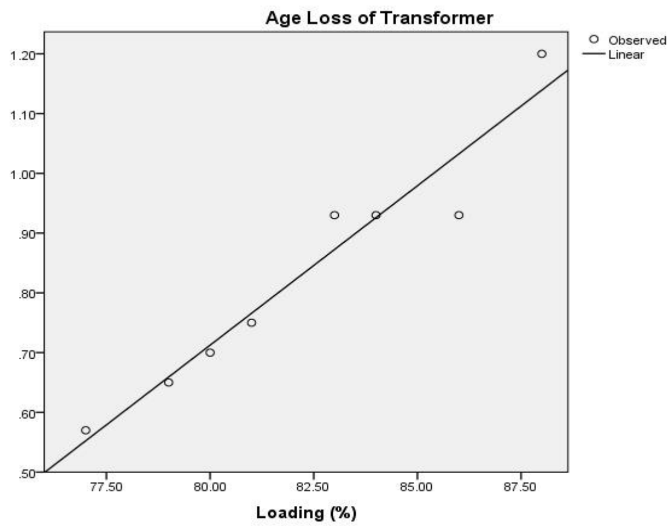

Fig. 5. Linearity test for the transformer's remaining age

From the results of predicted life expectancy of transformers with loading which is still below the limit value of 80%, it is estimated that the life of a 60 MVA transformer at the West Surabaya substation will reach 1 year 6 months, which has a life loss value of 1,2 p.u. in 2030.

IV. CONCLUSION

The data utilized in this study includes loading data from a 60 MVA power transformer at the 150 kV West Surabaya substation from 2020 to 2022 using the linear trend approach, which tries to estimate loading in the next year. Based on a 2% annual load growth, a 60 MVA power transformer's remaining usable life in 2030 is 1 year and 6 months, with an 88,64% load increase and a hotspot temperature increase of up to 51,48℃. Temperature has a significant influence on forecasting the life time of a power transformer because as the load increases, the temperature of the power transformer rises, causing the components in the transformer to be damaged more quickly and causing the transformer's life to be shorter than expected.

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