THE IMPACT OF LOADING, LOAD IMBALANCE, AND AMBIENT TEMPERATURE ON THE DETERMINATION OF DISTRIBUTION TRANSFORMER AGING

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ABSTRAK

In the operation of distribution transformers, it is expected that they can operate continuously and at maximum capacity. However, this can impact the lifespan of the transformer, as it will gradually decrease over time. One of the key factors contributing to the reduced lifespan of transformers is loading, along with other factors such as load imbalance and ambient temperature. Based on these factors, the author conducted a study on the impact of loading, load imbalance, and ambient temperature on the determination of the aging rate of distribution transformers. The research method involves collecting load current and ambient temperature data from four transformers to calculate the aging rate and remaining life of the transformers using IEEE and IEC standards. The study reveals that the loading factor is the most significant contributor to the aging of distribution transformers. The calculation results indicate that the lowest estimated aging rate occurs in Transformer 1, at 0.0052 hours per day (24 hours), resulting in the highest estimated remaining life of the transformer at 11.997 years, with a life difference of 0.003 years compared to the normal remaining life of 12 years, based on a standard life expectancy of 20 years. Conversely, the highest estimated aging rate occurs in Transformer 2, at 0.276 hours per day (24 hours), resulting in the lowest estimated remaining life of the transformer at 14.8275 years, with a life difference of 0.1725 years compared to the normal remaining life of 15 years, based on the standard life expectancy of 20 years. The impact of loading is more dominant than load imbalance and ambient temperature in accelerating transformer aging.

Keyword: *Distribution Transformer Aging Factors IEEE And IEC Standards Peak Load Current Transformer Life.*

INTRODUCTION

Distribution transformers are electrical devices used to transfer electrical power from medium voltage to low voltage at the same frequency to consumers. Distribution transformers operate at maximum capacity and continuously. This can certainly impact the lifespan of the transformer, as over time, the transformer's lifespan will gradually decrease each year. The factors contributing to the reduction in the lifespan of transformers include loading, load imbalance, and ambient temperature.

Loading refers to the amount of electrical current supplied to consumers such as households, industries, and public service facilities. There are three types of loads: the base load, which is the minimum level of electricity demand; the intermediate load, which is the medium level of electricity demand required during the day; and the peak load, which is the highest electricity demand during a certain period.

Load imbalance refers to a condition where one or all phases of the transformer experience differences. These differences can be observed from the magnitude of the current or voltage and the angle of each phase of the transformer. Each phase of the transformer is considered balanced if it meets the condition that the three current vectors of each phase (R, S, T) have the same magnitude and the phase angle difference between the three vectors is each 120° [1]. According to IEEE Standard 446-1995, the percentage value for load imbalance is between 5% and 20%. If the percentage of load imbalance exceeds 20%, it does not comply with the standard.

The ambient temperature used for the study of aging impact is the air temperature measured around the transformer. The operation of distribution transformers according to IEC standards is intended for an average annual temperature of 20 °C and a monthly average temperature of 30 °C. If the air temperature exceeds the IEC standards, the aging rate of the insulation of transformers operating in Indonesia is relatively faster due to insulation failure [2].Among the factors influencing loading, load imbalance, and ambient temperature described above, there is a commonality: the heat generated during the operation of distribution transformers leads to aging. However, each influencing factor has a different level of heat. Indications or signs of aging, such as deterioration of windings and insulation aging, will occur more rapidly if the insulation operates at temperatures exceeding the allowable limits (In this case, it refers to the hot spot temperature, which is the highest temperature occurring within the transformer windings, specifically at the point with the highest heat accumulation. This hot spot is typically located at the innermost part of the winding, where cooling is most difficult, and the current density (current concentration) is the highest). According to IEC 60354, which has also become the current standard for PLN, a transformer will experience a normal lifespan under hot spot temperature conditions of 98°C with continuous loading and an ambient temperature of 20°C. If the transformer experiences a hot spot temperature greater than 98°C, its aging will accelerate, thereby shortening its lifespan from the expected duration.

Transformers in Indonesia are designed to operate at ambient temperatures not exceeding 40°C, with a monthly average temperature of 30°C and an annual average temperature of 20°C. The IEC establishes that the lifespan of a transformer is approximately 20 years, or equivalent to 7,300 days, when loaded at 100% of the transformer's rated power at an ambient temperature of 20°C, resulting in a normal aging rate of 0.0137% per day. Various researchers do not fully agree on the aging of transformers at specific temperatures. However, they concur that within the range of 80°C to 140°C, the aging rate of transformers doubles for every 6°C increase in temperature, and this value is used as the basis for research [3].Based on the background above, to determine the aging and remaining life of distribution transformers due to loading, load imbalance, and ambient temperature, further studies are needed. This is an interesting area for research as it can serve as a parameter for evaluating transformer performance. By determining the aging and remaining life of the transformer, it is expected to help reduce transformer damage, the impact of power supply disruptions, and improve operational efficiency.

LITERATURE REVIEW

In a previous study conducted by Anggy Eri Sodilesmana at Universitas Peradaban Bumiayu, titled “Analysis of Loading and Load Imbalance on the Determination of Distribution Transformer Aging,” the research focused on analyzing the full load values of transformers, the percentage of load imbalance, and the calculation of transformer aging and remaining life. Based on the results and discussion, it can be concluded that the full load values of transformers during the day and night show that transformers with capacities of 100 kVA and 160 kVA are loaded above 70%, while transformers with a capacity of 200 kVA are loaded below 50%. The percentage of load imbalance in transformers with capacities of 100 kVA and 200 kVA from the TRAFINDO brand during the day and night does not meet the standard, as the load imbalance exceeds 20%. The calculation of aging and remaining life for all transformers loaded above 80% shows that aging is still within normal limits and does not significantly affect the transformer's lifespan, with an estimated remaining life of over 20 years. Therefore, all transformers operating at PT. PLN (Persero) Rayon Bumiayu are still in compliance with the standard [3]. There is also a study conducted by Fadly Azhar from Universitas Negeri Malang, titled “Estimation of Distribution Transformer Life Based on Load Growth and Ambient Temperature in Bolo Feeder of PLN Rayon Woha, Bima Regency,” which states that distribution transformers in the Bolo feeder of PLN Rayon Woha operating at an average ambient temperature of 29°C will experience normal aging when loaded at 91.6% of the transformer's rated power.

The BO001 transformer has an estimated remaining life of 7 years from a normal remaining life of 11 years, with load growth ranging from 58.53% to 104.83% of the transformer's rated power. Meanwhile, the BO043 transformer has an estimated remaining life of 3 years from a normal remaining life of 13 years, with load growth ranging from 83.12% to 110.16% of the transformer's rated power [4]. The next previous research was conducted by Rocki Mahendra from Universitas Tanjungpura, titled “Analysis of the Impact of Loading on Transformer Efficiency and Lifespan at the Bengkayang 2 × 50 MW Coal-Fired Power Plant of PT. PLN (Persero) UPK Singkawang,” states that the impact of loading on transformer efficiency is that the greater the load, the higher the transformer's efficiency, and the smaller the load, the lower the transformer's efficiency. The impact of loading on transformer lifespan is that the greater the load, the faster the aging process experienced by the transformer, thereby shortening its remaining lifespan

[5]. Then the research conducted by Yoga Pirniawan from Universitas Tanjungpura, titled “Analysis of Distribution Transformer Lifespan Based on Load at PT. PLN (Persero) Pontianak,” states that distribution transformers experience shorter lifespans due to unstable load usage, while distribution transformers have longer lifespans when operating under stable (constant) conditions [6].From the previous studies that have been discussed, the difference in this research is that it is conducted in a different location, specifically at the Faculty of Engineering, Universitas Tanjungpura. Furthermore, in the final results, the researcher will compare the outcomes of the three factors that influence the aging of distribution transformers.

METHOD

In this research, the material used for study is the distribution transformer located within the Faculty of Engineering at Tanjungpura University. The research method involves collecting data on specifications, phase current, load, and ambient temperature, carried out on four transformers. The following includes measured data on peak load current (amperes) during the day and night, along with ambient temperature data over a 24-hour period for the four transformers currently installed at the Faculty of Engineering.

Tabel 1. Peak load current measurement data

Name	Peak current per phase (A)		
		Day	Night
Transformer 1	R	77.5	5.6
	S	56.5	6
	T	47.6	2.1
Transformer 2	R	142.5	14.2
	S	109.2	4.4
	T	160.4	12.2
Transformer 3	R	155.5	56.4
	S	145.7	37.3
	T	180.5	37.2
Transformer 4	R	72	56.4

	S	55.5	37.3
	T	52.4	37.2

Table 2. Ambient temperature measurement data over 24 hours

Jam	Ambient Temperature (°C)			
	Transformer 1	Transformer 2	Transformer 3	Transformer 4
01.00	24	25	24	25
02.00	24	25	24	24
03.00	24	25	24	24
04.00	24	24	24	24
05.00	24	24	24	24
06.00	24	24	24	24
07.00	25	25	25	24
08.00	27	25	25	24
09.00	28	26	26	24
10.00	29	27	27	25
11.00	30	28	28	26
12.00	31	29	29	26
13.00	31	30	30	28
14.00	32	31	31	28
15.00	31	31	30	28
16.00	30	29	27	29
17.00	27	28	27	27
18.00	27	27	26	27
19.00	26	26	26	27
20.00	26	25	26	26
21.00	26	25	26	26
22.00	25	25	26	26
23.00	25	24	25	26
00.00	24	25	24	25

Insulation deterioration accelerates when the insulation operates at temperatures exceeding the allowable limit (in this case, the hot spot temperature). According to IEC 60354 standards, which have also been adopted as PLN's current standard (SPLN 17 A: 1979), a transformer is expected to have a normal lifespan under conditions of a "hot spot temperature of 98°C with continuous loading" at an ambient temperature of 20°C.

If the transformer experiences a hot spot temperature exceeding 98°C, its aging rate will accelerate, thereby shortening its expected lifespan. IEC 60354 provides a continuous loading factor that will produce a hot spot temperature of 98°C across various ambient temperatures and for each cooling type, making it possible to calculate continuous loading capacity based on ambient temperature as referenced in Table 3. (IEC 60354, 1991: 09).

Table 3. Permissible loading at different ambient temperatures

Ambient temperature (°C)			-25	-20	-10	0	10	20	30	40
Hot-spot temperature rise (K)			123	118	108	98	88	78	68	58
K_{24}	Distribution	ONAN	1,37	1,33	1,25	1,17	1,09	1,00	0,91	0,81
	Power transformer	ON	1,33	1,30	1,22	1,15	1,08	1,00	0,92	0,82
		OF	1,31	1,28	1,21	1,14	1,08	1,00	0,92	0,83
		OD	1,24	1,22	1,17	1,11	1,06	1,00	0,94	0,87

According to SPLN, transformers in Indonesia are designed to operate at ambient temperatures not exceeding 40°C, with a monthly average of 30°C and an annual average of 20°C. The IEEE standard specifies that a power transformer has a lifespan of up to

180,000 hours, or 20.55 years (equivalent to 7,500 days) when loaded at 100% of its rated capacity at an ambient temperature of 20°C, resulting in a normal aging rate of 0.0137% per day [7]. Meanwhile, IEC standards do not specify a precise lifespan, though it is generally expected to reach up to 30 years, depending on the aging rate determined by the hot spot temperature [8].

The aging rate due to hot spot temperature can be seen in Table 4. Researchers have not fully agreed on transformer aging rates at specific temperatures. However, they concur that within the 80°C–140°C range, the aging rate of a transformer doubles with every 6°C increase in temperature, a value used as the basis for this study as referenced in Table 4. (IEC 60076-7, 2005: 12)

Table 4. Aging rate due to temperature rise according to IEC 60076-7 [9].

Winding Temperature (°C)	80	86	92	98	104	110	116	122	128	134	140
Aging Rate	0.125	0.25	0.5	1	2	4	8	16	32	64	128
Estimated Age (Years)	>20	>20	>20	20	10	5	2.5	1.25	0.625	0.5125	0.15625

The calculation stage is carried out to obtain data on the aging and remaining life of distribution transformers, so that the most influential factors affecting transformer aging can be analyzed. The following are the steps involved in the calculation process.

A. Calculating the full load current, load percentage, and winding temperature of the distribution transformer during the day and night. To calculate the full load current [10]:

$$I_{FL} = \frac{S}{\sqrt{3}\ .\ V} \tag{1}$$

Where :

I_{FL} = Full load current (A)

S = Transformer power (kVA)

V= Secondary voltage of transformer (kV)

Determining the average current, loading percentage, and resulting winding temperature can be calculated using the following equations:

a. Average current

To calculate the average current, data for "I" _"R" "," "I" _"S" "," "I" _"T" "," are needed, which are obtained from field measurements [10].

$$I_{Average} = \frac{I_R + I_S + I_T}{3} \tag{2}$$

b. (%) Loading

$$(\%)\ \text{Loading} = \frac{I_{Average}}{I_{FL}} \times 100\ \% \tag{3}$$

c. Winding temperature due to loading

$$\theta_h = (\%)\ \text{Loading} \times 107{,}7°C \tag{4}$$

The winding temperature produced at 100% loading of the transformer's rated capacity is 107.7°C. A transformer will have a normal lifespan under a hot spot temperature condition of 98°C according to the SPLN standard, which specifies transformer operation at an ambient temperature of 30°C. Referring to Table 3, with an ambient temperature of 30°C, a winding temperature of 98°C for an ONAN-cooled transformer will be reached at a loading factor of 0.91 (91%) of the transformer's rated capacity. To achieve a winding temperature of 107.7°C, the following calculation is applied:

$\frac{98^{\circ}C}{0,91} \times (100\ \%) = 107,7\ ^{\circ}C$

B. Determining the coefficient value and the percentage of load imbalance in the transformer during the day and night.

To find the magnitude of load imbalance based on the coefficient equations a, b, and c, it is determined by comparing the phase currents R, S, and T with the average current. It should be noted that the average current ("I" _"average") will equal the phase currents in a balanced state (where a, b, and c equal 1), and can be calculated using the following equation [10]:

$$I_R = a \times I_{average}\text{, thus } a = \frac{I_R}{I_{average}} \tag{5}$$

$$I_S = b \times I_{average}\text{, thus } b = \frac{I_S}{I_{average}} \tag{6}$$

$$I_T = c \times I_{average}\text{, thus } c = \frac{I_T}{I_{average}} \tag{7}$$

Where :

$I_{average}$ = Average Current (A)

I_R , I_S , I_T = Phase Current R, S, T (A)

a = The comparison coefficient of phase current R to the average current is expressed as follows:

b = The comparison coefficient of phase current S to the average current is expressed as follows:

c = The comparison coefficient of phase current T to the average current is expressed as follows:

To determine the percentage of load imbalance and the winding temperature in the transformer, the calculations can be performed using the following equations [10] **:**

$$(\%)\ \text{Load imbalance} = \frac{\{|a-1| + |b-1| + |c-1|\}}{3} \times 100\% \tag{8}$$

C. Calculating the aging and estimated remaining life of the distribution transformer due to the effects of loading and load imbalance.

To obtain the relative aging rate at each hot spot above the normal temperature (98°C) under nominal load and increased winding temperature, the design of the transformer is based on the IEC 60354 standard. The relative value of the operating life depends on the hot spot temperature. This temperature relationship operates in an ambient temperature of 30°C at the nominal power rating of the transformer, resulting in a hot spot temperature increase of 98°C. In transformers, the relative aging process rate can be approximately expressed by the following equation [9] [11]:

$$V = 2^{\left(\frac{\theta_h - 98^{\circ}C}{6^{\circ}C}\right)} \tag{9}$$

Where :

V= Relative aging for loading and load imbalance

θ_h = Hot spot winding temperature (°C)

$98^{\circ}C$ = Design temperature for reasonable lifespan (20-30 years)

The loading over a day (24 hours) is assumed to consist of 14 hours during Peak Load Time (PLT), reflecting daytime loads as evidenced by the phase currents in the transformer increasing from 6:00 AM to 8:00 PM, and 10 hours during Off-Peak Load Time (OPLT), reflecting nighttime loads as shown by the phase currents in the transformer decreasing from

8:00 PM to 6:00 AM. In calculating the reduction in lifespan, an equation is provided to determine the extent of the aging loss, which is as follows [12] :

$$\text{24-Hour aging rate} = \left(t_{plt} \times V_{plt} \right) + \left(t_{oplt} \times V_{oplt} \right) \qquad (10)$$

Dimana :

t_{oplt} = Measurement time outside peak load hours (hours)

t_{plt} = Measurement time during peak load hours (hours)

V_{oplt} = Relative aging rate outside peak load hours

V_{plt} = Relative aging rate during peak load hours

Since the loading of the transformer varies daily and is not continuous, making it difficult to determine a daily loading pattern, this study assumes that the daily loading pattern is uniform [3].

The estimation of the transformer lifespan in this research only takes into account the effects of insulation degradation of the windings, without considering other influencing factors [13].

$$\text{Estimated remaining life} = \frac{\text{8760 hours - (24-Hour aging rate} \times \text{365)}}{\text{8760 hours}} \times$$

$$(\, 20 - n \,) \qquad (11)$$

Where :

n = Duration of transformer operation (years)

8760 = Annual hour conversion (hours/year)

D. Calculating the hot spot temperature of the windings on the thermal diagram based on the effects of the ambient temperature surrounding the distribution transformer.

To calculate the increase in hot spot temperature under continuous load, various sources of thermal characteristics can be utilized. The results of specific temperature rise tests, including direct measurements of the hot spot or upper oil temperature within the windings, can typically be provided by the manufacturer's menu. Additionally, normal temperature rise test results and assumptions regarding temperature rise at rated current are considered. The following thermal characteristics are commonly used as references according to international standards, as outlined in the table 5. (IEC 60354 Loading guide for oil-immersed power transformers).

Table 5. Thermal characteristics used for calculations [14].

	Symbol	**Distribution transformers**	**Medium and large power Transformers**		
		ONAN	**ON**	**OF**	**OD**
Oil exponent	x	0,8	0,9 1,6 1,3 2,5	1,0 1,6 1,3 1,5	1,0 2,0 1,3 1,5
Winding exponent	y	1,6			
Loss ratio	R	5			
Hot-spot factor	H	1,1			
Oil time constant	τ_o (h)	3,0			
Ambient temperature	θ_a (°C)	20	20	20	20
Hot-spot rise	$\Delta\theta_{hr}$ (K)	78	78	78	78
Average winding rise	$\Delta\theta_{Wr}$ (K)	65	63	63	68
Hot-spot to top-oil gradient	Hg_r (K)	23	26	22	29
Average oil rise	$\Delta\theta_{imr}$ (K)	44	43	46	46
Top-of-winding oil rise[1)]	$\Delta\theta_{ir}$ (K)	55	52	56	49
Bottom-oil rise	$\Delta\theta_{br}$ (K)	33	34	36	43
[1)] For ON cooling, $\Delta\theta_{ir}$ is taken to be equal to $\Delta\theta_{or}$					

For ON cooling, the hot spot temperature at a load with K as the load factor is obtained by dividing the load power by the transformer rating power. The top oil temperature depends on the ambient temperature conditions, which can be calculated using the following equation [14].

$$\theta_h = \theta_a + \Delta\theta_{or}\left[\frac{1 + RK^2}{1 + R}\right]^x + Hg_r \times K^y \qquad (13)$$

Dimana :

θ_h = Hot Spot Temperature (°C)
θ_a = Ambient temperature (°C)
$\Delta\theta_{or}$ = Top-oil temperature rise (K)
R= Loss ratio
K= Load factor
x = Oil exponent
y = Winding exponent
Hg_r = Hot-spot to top-oil gradient (K)

E. Calculating the aging and estimating the remaining life of distribution transformers due to the influence of ambient temperature.

The aging factor or the rate of change in the life of a transformer for each increase in hot spot temperature above the normal temperature (98 °C) can be calculated using the following equation [7].

$$V_n = 2^{\left(\frac{\theta_h - 98^\circ C}{6^\circ C}\right)}$$

Dimana :

V_n = Relative aging rate of transformer usage life
θ_h = Hot spot temperature (°C)

Aging can be expressed in monthly, daily, or hourly units. If the load and ambient temperature remain constant over a given period, the relative aging of the transformer life is equal to V × t over that specific period. N is obtained from the total number of time intervals, which is 24 hours, and t_n is obtained from the-n time interval, which is 1 hour. The relative aging over a specific duration can be calculated using the following equation [9].

$$L = \sum_{n=1}^{N} V_n \times t_n \qquad (15)$$

Dengan:

L = Aging rate (hours)
N= Total number of time intervals (24 hours)
V_n = Relative aging rate of transformer usage life
t_n= 1-Hour interval time
n = Interval number (n)

To estimate the remaining life of the transformer, the following equation can be used [13].

$$\text{Estimated remaining life} = \frac{8760 - (L \times 365)}{8760} \times (20 - n) \qquad (16)$$

Where :

Base life = 20 years
n = Transformer operation duration (years)
8760 = Annual hour conversion (hours/year)

HASIL DAN PEMBAHASAN

1. Data Results of the Calculation of Aging and Remaining Life of the Transformer

The overall results of the aging and remaining life calculations of the transformer can be seen in the following table:

Table 6. Calculation results of aging and remaining life due to loading effects

	Transformer loading (%)				Relative aging		Aging rate (hours)	Estimated remaining life (years)
	Day		Night		Day	Night		
	(%)	(°C)	(%)	(°C)				
Transformer 1	26.21	28.22	1,97	2.12	0,0003	0,00001	0,0043	16,996
Transformer 2	59,47	64,04	4,44	4,78	0,0197	0,00002	0,276	14,8275
Transformer 3	55,62	59,90	15,11	16,27	0,0122	0,00007	0,1722	11,9139
Transformer 4	25,96	27,95	18,89	20,34	0,0003	0,0001	0,0052	11,997

In this study, the primary focus is on the factors influencing the aging and remaining life of transformers, which are vital components in electrical power distribution systems. The transformers used as research subjects include four units with capacities of 160 kVA (installed in 2021), 160 kVA (installed in 2019), 200 kVA (installed in 2016), and 160 kVA (installed in 2016). This analysis adheres to the IEC 60354 standard, which states that a transformer will have a normal lifespan under conditions of a hot spot temperature of 98°C at 100% of its rated load capacity, with an ambient temperature of 20°C. Data collection was conducted during both daytime and nighttime over a period of seven days. The loading for a 24-hour day is assumed to consist of 14 hours during Peak Load Time (PLT), following the daytime load, as evidenced by the phase currents in the transformers that increase from 6:00 AM to 8:00 PM, and 10 hours during Off-Peak Load Time (OPLT), corresponding to the nighttime load, as shown by the phase currents in the transformers that decrease from 8:00 PM to 6:00 AM. The load data is assumed to be constant, and the phase currents used for calculations during peak daytime and nighttime loads are taken into account.

Based on the data and calculations regarding the load factor, the lowest loading percentage was observed in Transformer 4, which registered 25.96% during the daytime with a winding temperature of 27.95°C, and 1.97% at nighttime in Transformer 1 with a winding temperature of 2.12°C. Conversely, the highest loading percentage occurred in Transformer 2, with 59.47% during the daytime and a winding temperature of 64.04°C, while Transformer 4 had 18.89% at night with a winding temperature of 20.34°C. Regarding relative aging, the lowest calculated value was found in Transformer 1, with a relative aging of 0.0003 during the day and 0.00001 at night. The highest relative aging value was noted in Transformer 2 during the daytime at 0.0197, while Transformer 3 recorded 0.00007 at night. From the impact of the load, the estimated lowest aging, which only considers the effect of insulation deterioration, occurred in Transformer 4 at 0.0052 hours per day (24 hours), leading to an estimated remaining life of 11.997 years, which is 0.003 years short of the normal remaining life of 12 years, based on the standard lifespan of 20 years. Conversely, the highest estimated aging occurred in Transformer 2 at 0.276 hours per day (24 hours), resulting in an estimated remaining life of 14.8275 years, with a difference of

0.1725 years from the normal remaining life of 15 years, also based on the standard lifespan of 20 years.

Table 7. Results of aging rate and remaining life calculations due to load imbalance

	Load imbalance of the transformator (%)				Relative aging		Aging rate (hours)	Estimated remaining life (years)
	Day		Night		Day	Night		
	(%)	(°C)	(%)	(°C)				
Transformer 1	19	20.46	35.6	38.34	0,00012	0,0010	0,0117	16,991
Transformer 2	13,3	14,32	38	40,92	0,00006	0,0013	0,0138	14,991
Transformer 3	8,6	9,26	19,6	21,10	0,00003	0,0001	0,0017	11,9991
Transformer 4	13,6	14,64	19,6	21,10	0,00006	0,0001	0,00184	11,9990

From Table 7 above, load imbalance in transformers refers to a condition where one or all phases experience differences in electrical load currents. According to IEEE Standard 446-1995, the acceptable load imbalance percentage ranges from 5% to 20%; any value exceeding 20% is considered non-compliant with the standard and can lead to a decrease in the efficiency of transformer performance. Based on the data and calculations regarding the load imbalance factor, the lowest load imbalance percentage was observed in Transformer 3, which recorded 8.6% during the daytime with a winding temperature of 9.26°C and 19.6% at nighttime with a winding temperature of 21.10°C. This is considered normal since it does not exceed 20%. In contrast, the highest load imbalance percentage was found in Transformer 1, which registered 19% during the daytime with a winding temperature of 20.46°C, while Transformer 2 experienced 38% at nighttime with a winding temperature of 40.92°C. This is classified as abnormal since it exceeds 20%. Regarding relative aging, the lowest calculated value was recorded in Transformer 3, with a relative aging of 0.00003 during the daytime and 0.0001 at night.

In contrast, the highest relative aging was observed in Transformer 1, which recorded a relative aging of 0.00012 during the daytime, while Transformer 2 experienced 0.0013 at nighttime. From the influence of load imbalance, the lowest estimated aging loss, taking into account only the impact of insulation degradation, occurred in Transformer 3, with a value of 0.0017 hours. The highest estimated remaining life occurs in Transformer 3, at 11.9991 years, with a life difference of 0.0009 years compared to the normal remaining life of 12 years based on a standard life expectancy of 20 years. Conversely, the lowest estimated aging rate occurs in Transformer 2, at 0.0138 hours per day (24 hours), resulting in an estimated remaining life of 14.991 years, with a life difference of 0.009 years compared to the normal remaining life of 15 years based on a standard life expectancy of 20 years.

Table 8. Results of aging rate and remaining life calculations due to ambient temperature

	Hot spot temperature (°C)	Relative aging	Aging rate (hours)	Estimated remaining life (years)
Transformer 1	56,8717	0,0086	0,1197	16,9152
Transformer 2	62,8287	0,0171	0,2494	14,8441
Transformer 3	64,7266	0,0214	0,3031	11,8484
Transformer 4	56,4152	0,0082	0,1367	11,9316

In calculating the aging loss and remaining life due to environmental temperature effects, data on the ambient air temperature surrounding the transformer installation was utilized over a 24-hour period, with the highest temperature recorded each day being taken as an example for the calculations. The lowest hot-spot winding temperature was recorded in Transformer 4, at 56.4152°C, while the highest hot-spot winding temperature was observed in Transformer 3, at 64.7266°C. The lowest relative aging rate was calculated in Transformer 4, at 0.0082, whereas the highest relative aging rate was found in Transformer 3, at 0.0214. The aging rate calculation, derived from the summation of relative aging over 24 hours, yielded a value of 0.1197 hours for Transformer 1, categorized as low. On the other hand, the highest aging rate occurred in Transformer 3, at 0.3031 hours. Based on these calculations, the lowest remaining life was determined to be 14.8441 years, with a difference of 0.1559 years compared to the normal remaining life of 15 years based on a standard life expectancy of 20 years, occurring in Transformer 2. Meanwhile, the highest remaining life was found in Transformer 4, at 11.9316 years, with a difference of 0.0684 years from the normal remaining life of 12 years based on the standard life expectancy of 20 years.

2. Graph of Calculated Aging Loss and Remaining Life of Transformer

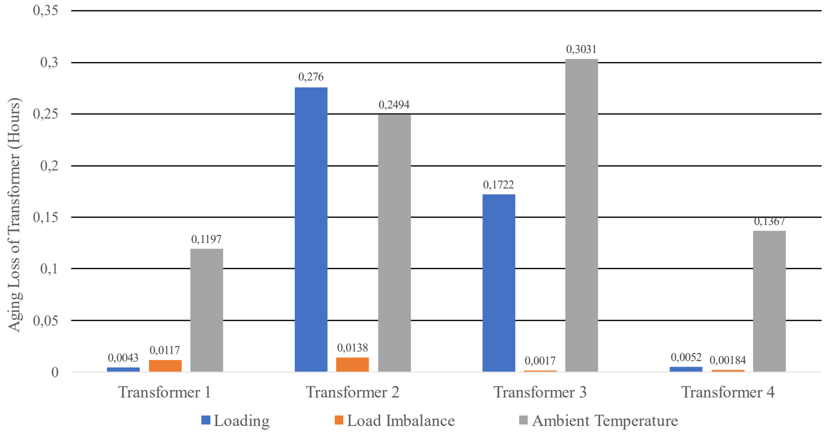

Figure 1. Graph of Transformer Aging Loss

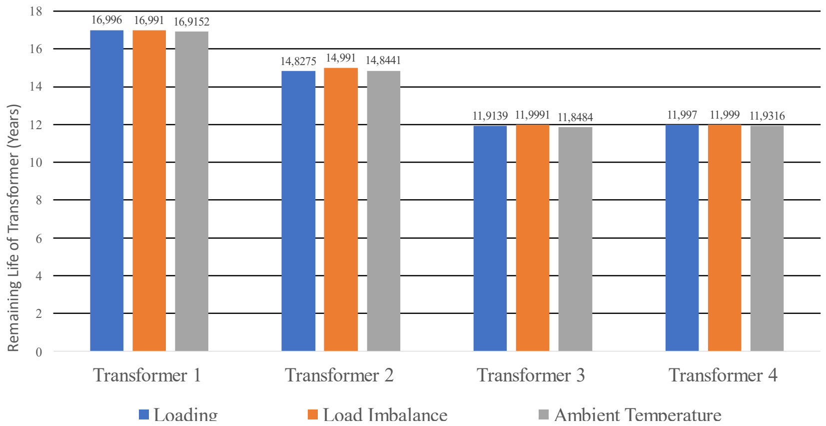

Figure 2. Graph of Transformer Remaining Life

3. Analysis of the Comparison of the Effects of Loading, Load Imbalance, and Ambient Temperature

In the previous analysis, the results of the aging and remaining life from each factor were detailed, and the comparison of these three factors can be explained as follows:

Loading refers to the amount of electrical current drawn by the load from the transformer. Its impact on aging is significant, as a high load current increases I^2R losses (resistive losses), which in turn raises the winding temperature. This temperature increase accelerates the aging of the transformer's paper insulation and oil, ultimately reducing its lifespan. However, based on the calculations and studies, the load remains within normal limits, ensuring that the transformer's performance is still optimal. The transformer's remaining life is not significantly reduced from its expected life span, but the calculated remaining life from the loading factor is more dominant than other factors, as shown by the lowest remaining life occurring in Transformer 2.

Load imbalance occurs when the phases in a three-phase system do not receive equal loads, causing neutral currents and additional losses in the transformer. Load imbalance results in higher localized heating in certain parts of the windings. Although its impact is not as immediate as loading, chronic load imbalance can lead to uneven thermal stress and accelerated aging in specific areas. While load imbalance does affect transformer lifespan, its impact is generally smaller compared to direct loading. This is because imbalance typically causes smaller and slower losses. Calculations and studies indicate that while load imbalance exists, it does not significantly affect transformer aging, and the remaining life of the transformers remains within normal limits.

Ambient temperature around the transformer affects its cooling capability. High ambient temperatures reduce cooling efficiency, increasing the transformer's internal temperature. Elevated ambient temperatures accelerate the degradation of the transformer's oil and paper insulation. However, the impact tends to be more stable and dependent on climatic conditions rather than operational variables. The influence of ambient temperature is generally less significant compared to loading. This is because ambient temperature typically does not experience extreme short-term fluctuations, making its effect on transformer life more predictable and manageable with adequate cooling systems. Calculations and studies show that ambient temperature has minimal impact on aging, and the transformers' remaining life remains within normal limits.

Nonetheless, based on the calculations, it can be concluded that the studied transformers are still within normal operating conditions. The influence of loading remains within reasonable limits, not exceeding 100% of the transformer's rated capacity and not exceeding the normal temperature condition of 98°C, with relative aging remaining below 1.0, ensuring aging is still normal. For load imbalance, some transformers exceed the 20% standard, particularly Transformers 1 and 2; however, this does not significantly impact aging. The influence of ambient temperature produces hot-spot temperatures that can also be considered normal, as they do not exceed the transformer's normal temperature of 98°C, thus not accelerating aging.

CONCLUSION

Based on the results of calculations and analyses regarding the effects of loading, load imbalance, and ambient temperature on determining the aging and remaining life of distribution transformers, the following conclusions can be drawn:

Loading has proven to be the most significant factor in the aging of distribution transformers. This is evidenced by calculation results showing that the lowest remaining transformer life, influenced by loading, occurred in Transformer 2, with an estimated remaining life of 14.8275 years, a difference of 0.1725 years compared to the normal remaining life of 15 years based on the standard life expectancy of 20 years.

Load imbalance also influences the acceleration of aging, primarily through the uneven increase in winding temperatures across the transformer phases. However, compared to overall loading, load imbalance has a smaller impact. Nevertheless, imbalances exceeding 20% of the standard can still cause accelerated aging in transformers. From the influence of load imbalance, the lowest estimated aging loss, taking into account only the impact of insulation degradation, occurred in Transformer 3, with a value of 0.0017 hours. The highest estimated remaining life occurs in Transformer 3, at 11.9991 years, with a life difference of 0.0009 years compared to the normal remaining life of 12 years based on a standard life expectancy of 20 years. Conversely, the lowest estimated aging rate occurs in Transformer 2, at 0.0138 hours per day (24 hours), resulting in an estimated remaining life of 14.991 years, with a life difference of 0.009 years compared to the normal remaining life of 15 years based on a standard life expectancy of 20 years.

Ambient temperature also affects transformer performance, especially if it exceeds the established normal operating limits. However, the impact of ambient temperature on accelerated aging is lower than that of loading. Nonetheless, controlling operating temperature remains important for maintaining the stability of transformer operation. The effect of ambient temperature results in the highest remaining lifespan occurring in transformer 4, which is 11.9316 years, with a lifespan difference of 0,0684 years from the normal remaining lifespan of 12 years compared to the normal standard lifespan of 20 years.

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