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Transformer Life Prediction Analysis Based on Thermal Aging at PT Ultra Sumatera Dairy Farm

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A transformer is a vital component in the electrical power distribution system that functions to transfer energy from medium voltage to low voltage. The reliability of a transformer is highly influenced by the thermal condition of its insulation, which determines its service life. This study aims to predict the effective lifespan of a 1250 kVA distribution transformer at PT. Ultra Sumatra Dairy Farm uses the thermal aging method based on the IEEE C57.91-2011 standard. The data used includes nameplate information, daily load profiles, and average ambient temperature. Based on the measurements, the transformer operates at an average load of 422.7 kVA (33.8% of its rated capacity) and an ambient temperature of 23°C. The calculated results show a hottest-spot temperature of 49.55°C with an aging acceleration factor (FAA) of 0.000649. The daily Loss of Life (LOL) value of 0.00000865% indicates that thermal aging occurs very slowly. Based on the Equivalent Aging Factor (FEQA), the theoretical effective lifespan of the transformer reaches approximately 31,660 years. However, in practice, the actual lifespan of the transformer is estimated to range between 25–35 years due to non-thermal factors such as moisture, oil oxidation, and load fluctuations. These results indicate that the thermal condition of the transformer remains very safe and efficient for long-term operation.

Keywords: Transformer, Thermal Aging, IEEE C57.91-2011, Aging Acceleration Factor, Effective Lifespan.

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1. Introduction

Transformers are vital equipment in the power distribution system that functions to channel electrical energy from medium voltage to low voltage (Arismunandar, 2014). Transformer reliability directly affects the continuity of electricity supply, especially in industrial sectors such as PT Ultra Sumatera Dairy Farm, which has an internal electrical system to support the continuous milk production process. Over time, transformers experience a decline in performance due to degradation of the insulation material caused by high operating temperatures and excessive loads. This degradation process is known as thermal aging, where every 6°C increase in temperature can accelerate aging twofold (IEEE C57.91-2011, 2011).

Therefore, it is important to conduct a transformer life prediction analysis to determine the remaining effective life and optimize preventive maintenance. The thermal aging method according to the IEEE C57.91 standard is used to predict the life of a transformer based on the parameters of the hot spot temperature, daily load, and ambient temperature. With this approach, it is hoped that it can be known to what extent the thermal condition of the transformer affects its service life and whether it is still within safe operating limits.

2. Literature Review

Basic Theory of Transformers

A transformer is a static electrical device that functions to transfer electrical energy from one circuit to another circuit through electromagnetic induction (Arismunandar, 2014). The working principle of a transformer follows Faraday's law, where changes in magnetic flux in the primary coil will induce voltage in the secondary coil. A transformer consists of two main parts, namely the coil and the iron core (Zuhal, 1994). The primary coil is connected to a power source, while the secondary coil is connected to the load. Power losses in a transformer consist of core losses (iron losses), which depend on magnetic flux, and copper losses, which depend on load current. Both of these losses generate heat, which increases the temperature of the transformer oil and insulation. Continuously increasing operating temperatures will reduce the durability of the insulation material and accelerate the aging process

Figure 1. 1250 KVA Transformer at PT USDF

Concept of Age and Aging Isolation Transformer life is determined by the thermal conditions of oil and paper insulation (Arismunandar, 2014). Cellulose material in the insulation undergoes chemical degradation due to heat, oxygen, and moisture. This process causes a decrease in dielectric strength and changes in oil viscosity (Susa et al., 2005). According to IEEE C57.91-2011, (2011) the design life of a transformer is 180,000 hours (±20 years) at a hot spot temperature of 110°C. Every increase in temperature of about 6°C will accelerate the aging process twofold, while a decrease in temperature of 6°C will extend the life twofold. Therefore, transformer life analysis can be done by estimating the hot spot temperature during daily operation to assess the rate of acceleration of insulation aging (IEEE C57.91-2011, 2011). The thermal aging method is an analytical approach used to estimate the acceleration of transformer aging due to the influence of temperature. Its basic principle is derived from the Arrhenius equation, which states that the rate of chemical reactions (including cellulose degradation) increases exponentially with increasing temperature. The Aging Acceleration Factor (FAA) equation according to IEEE C57.91-2011, (2011) is written as follows:

$$FAA = e^{\left\{\frac{15000}{383} - \frac{15000}{\theta H + 273}\right\}}$$

Where:

FAA = Aging Acceleration Factor
θH = Hottest-spot temperature in °C
383 (110°C)is the standard reference temperature for the nominal age.
Interpretation of FAA values:

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FAA = 1→ normal aging (at 110°C).
FAA < 1→ aging more slowly than normal (longer lifespan).
FAA > 1→ faster aging (shorter lifespan).

Function of Thermal Aging Method

This method works for:

a. Determines the rate of accelerated aging of insulation based on operating temperature.
b. Predicting the effective life of a transformer by considering load conditions and ambient temperature.
c. Determine the safe limits of transformer operation to prevent premature failure.

Relationship between Temperature and Relative Life of Insulation IEEE Standard C57.91-2011

Table 1. IEEE Standard C57.91-2011

Hot Spot Temperature (°C)	Relative Aging Factor (FAA)	Relative Age (%)
80	0.25	400
90	0.50	200
95	0.75	133
110	1.00	100
120	2.00	50
130	4.00	25
140	8.00	12.5

Table 2.IEEE C57.91-2011 Standard Description

Temperature	Interpretation	Impact on Age
80–90°C	Very good conditions; low temperatures make chemical reactions run slowly.	Lifespan can be 2–4 times the standard (up to 40 years).
95–100°C	Optimal working temperature; transformer operates efficiently without accelerating significant aging.	The age is approximately 1.3 times the design age (±26 years).
110°C	Standard conditions; aging proceeds normally (FAA = 1).	Age according to design (20 years).
120–130°C	High temperature; accelerates the degradation reaction of the insulation.	Age decreases 2–4 times faster (5–10 years).
≥140°C	Critical condition; insulation is rapidly deteriorating.	The lifespan is only about 10–15% of the design (2–3 years).

3. Methods

This research is descriptive quantitative with a single case study approach on a 1250 kVA distribution transformer at PT. Ultra Sumatera Dairy Farm (USDF) located in Pertibi Tembe Village, Merek District, Karo Regency, North Sumatra. The research stages were carried out systematically as shown in Figure 3 below:

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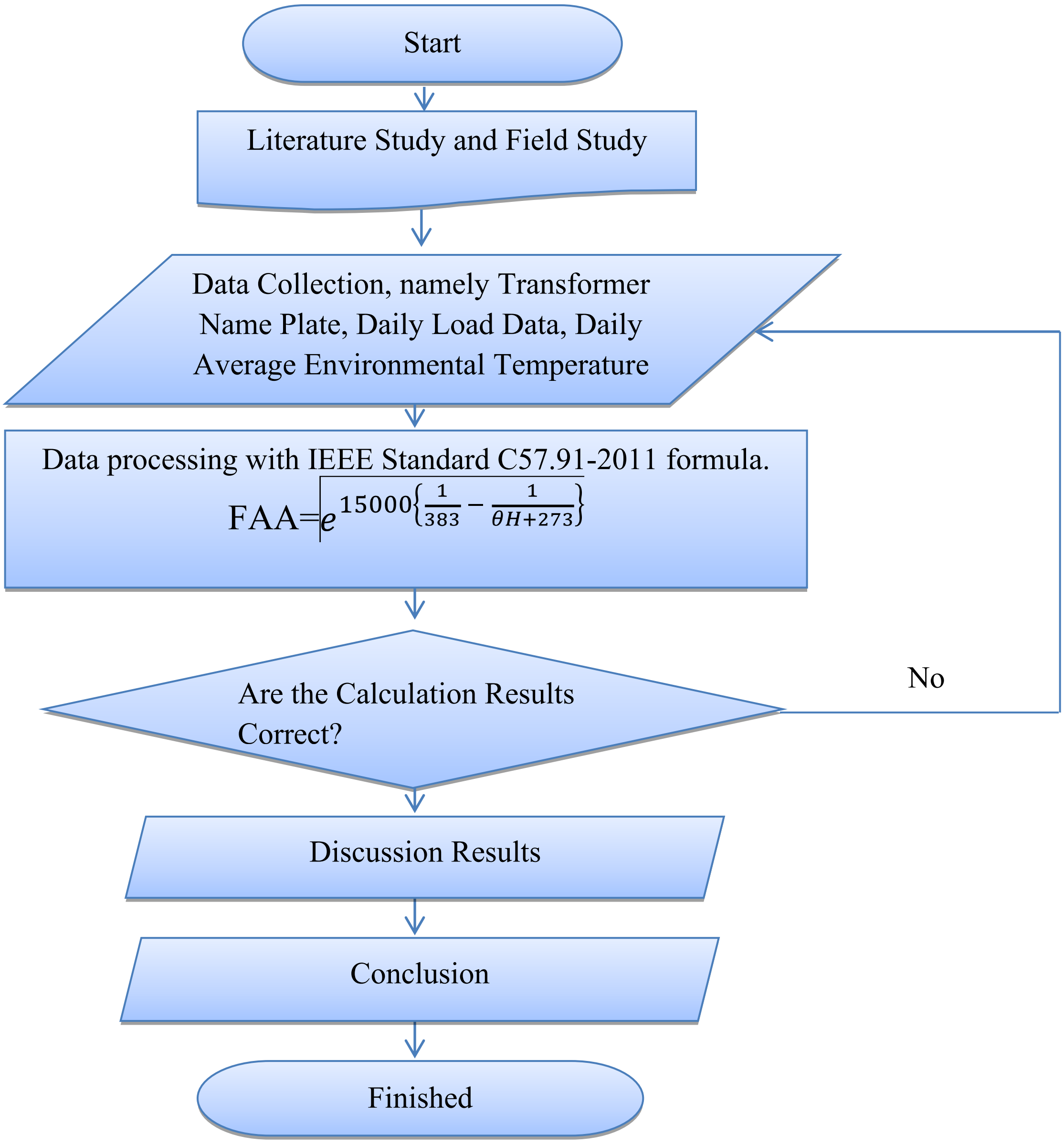

Figure 2. Flow chartStudy
Source: Researcher (2025)

The explanation of the flowchart above is as follows:

1. Start
   The research began by determining the objective, namely analyzing the prediction of transformer life based on thermal aging according to the IEEE C57.91-2011 standard.
2. Literature Study and Field Study
   a. Literature Study
      Reviewing theories related to transformers, thermal aging processes, the effect of temperature on insulation aging, and the calculation of hot-spot temperature and aging acceleration factor (FAA) based on the IEEE C57.91-2011 standard.
   b. Field Study
      Conducting direct observations at the research location, namely PT. Ultra Sumatera Dairy Farm (USDF), to understand the actual conditions of the transformer such as the cooling system, loading patterns, and surrounding environmental conditions.
3. Data collection

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This stage functions to collect all data which is the main input in thermal aging analysis. Data collected includes:

a. Transformer Nameplate Data: capacity, nominal voltage, nominal current, cooling type, and year of installation.
b. Daily Load Data: hourly transformer load in kVA units, taken from operational recording results.
c. Average Ambient Temperature Data:obtained from the results of direct measurements of the area around the transformer.

This data is the main input in calculating hot-spot temperature and aging acceleration factors.

4. Data processing
   The data obtained was processed using the IEEE C57.91-2011 standard formula with the following steps:
   a. Determine the insulation hot spot temperature (θH) with the equation:
      θHθA+$= \Delta\theta TO, R(K^{X}) + \Delta\theta H$,R()$K^{2y}$
      Where :
      θA = ambient temperature (°C)
      ΔθTO= increase in oil temperature at top-oil (°C)
      ΔθH = increase in hot spot temperature above oil temperature (°C)

   b. Calculate the Accelerated Aging Factor (FAA) with the equation:
      FAA=$e^{15000\{\frac{1}{383}-\frac{1}{\theta H+273}\}}$
   c. Determine the Loss of Life (LOL) and Equivalent Aging Factor (FEQA) to estimate the effective life of the transformer using the equation:
      $$\text{LOL} = \frac{FAA \times \Delta t}{180000} \times 100\%$$
      Where:
      Δt= operating time (hours)
      180,000 hours = transformer design life (20 years)
   d. Determining the Equivalent Aging Factor (FEQA)
      Load and temperature data are obtained over a certain time period, the Equivalent Aging Factor value.
   e. Determining Effective Age Estimate
      The effective life of a transformer is calculated by:
      $$\text{Leq} = \frac{180000}{FEQA}$$
      where the results show the estimated actual life (hours) based on field thermal conditions.
5. Calculation Results
   The calculation results are evaluated to ensure there are no input errors. If discrepancies are found, the data is reviewed again at the collection stage for corrections. Once validated, the results are ready for analysis.
6. Research result
   This stage displays the final calculation results in the form of:
   a. Transformer hot spot temperature value.
   b. Aging Acceleration Factor (FAA) and Loss of Life (LOL) values.
   c. Estimated remaining life of transformer based on daily load profile and ambient temperature.

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7. Conclusion

   Conclusions are drawn up based on the results of calculations and analysis, which include:

a. Transformer age estimation at PT. USDF based on thermal aging method.

b. The main factors that accelerate aging, such as high temperatures and excessive loading.

c. Recommendations for maintenance actions, such as inter-transformer load regulation and cooling system repairs to extend the life of the equipment.

8. Finished

   The final stage marks the end of the research process. All analysis, discussions, and conclusions have been compiled into a scientific document ready for publication or use as a reference for transformer maintenance in the field.

4. Analysis and Discussion

Transformer Data

Calculation analysis is taken from transformer data:

Source: Researcher Documentation (2025))

Figure 2. Name Plate 1250 KVA Transformer at PT. USDF

Transformer Data Calculation analysis is taken from transformer data:

Brand	: TRAFINDO
Serial No.	: 17.38.0827
Year	: 2017
Power	: 1250 kVA
Standard	: SPLN/IEC76
Type of coolant	: ONAN
Oil weight	: 643Kg
Winding temperature rise	: 65°C
Oil temperature rise	: 60°C
Frequency	: 50 Hz
Transformer	: 3 Phases
Vector Group/relationship	: dyn5

Type : Outdoor
Heavy : 3079Kg
Primary voltage : 20,000V
Secondary voltage : 400V
Impedance : 5.5%

Load Power (kvA) and Ambient Temperature Measurement

The load power measurement data (kVA) was obtained from the power meter on the control panel and the average ambient temperature of 23°C was obtained from a thermometer attached to the wall.°C

Table 3. 1250 kVA Transformer Daily Load Data

Time	Load (kVA)	% Load to Capacity	Ambient Temperature (°C)
00.00	375	30	21
01.00	375	30	21
02.00	365	29.2	21
03.00	250	20	21
04.00	250	20	20
05.00	250	20	20
06.00	350	28	20
07.00	400	32	22
08.00	425	34	23
09.00	455	36.4	24
10.00	450	36	26
11.00	475	38	27
12.00	475	38	27
13.00	500	40	27
14.00	525	42	27
15.00	525	42	27
16.00	525	42	27
17.00	500	40	24
18.00	500	40	23
19.00	425	34	22
20.00	425	34	22
21.00	525	42	21
22.00	425	34	21
23.00	375	30	21
Average	422.7	33.8	23

Calculation Of Field Study

Based on the field study, transformer data was obtained, the average loading for 24 hours and ambient temperature which will be calculated in the analysis of transformer life based on thermal aging.

- Listed capacity : 1250 kVA
- Average load : 422.7
- Ambient Temperature1 : 23°C
- Oil temperature rise at nominal load$\Delta\theta_{TO}, R)$: 60°C (dari Name Plate
- Hot spot increase in oil at nominal load$\Delta\theta_{H}, R)$: 65°C (dari Name plate)

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- Load loss to no-load loss ratio R: 5 (typical value for distribution transformers)
- Empirical exponent x = 0.8 y = 1.6 (standard value on transformer)

1. Calculating the load factor:

$$K = \frac{Savc}{Sn}$$
$$= \frac{422,7}{1250} kVA$$
$$= 0,338$$

So the transformer operates at 33.8% of the nominal load.

2. Determine the insulation hot spot temperature (θH) with the equation:

K^x = = 0.41 $0,338^{0,8}$

K^{2y} = = 0.03 $0,338^{3,2}$

θHθA+ $= \Delta\theta TO, R(K^{X}) + \Delta\theta H$,R() K^{2y}

$$= 23 + (60 \times 0,41) + (65 \times 0,03)$$
$$= 23 + 24,6 + 1,95$$
$$= 49,55°C$$

So the transformer insulation hot spot temperature is $49,55°C$

3. Calculate the Accelerated Aging Factor (FAA) with the equation:

FAA= $e^{15000\left\{\frac{1}{383} - \frac{1}{\theta H + 273}\right\}}$

θH = 49.55∘Cso the absolute temperature (Kelvin):

T = θH+273 = 49.55+273 = 322.55 K

FA = $e^{\left\{\frac{15000}{383} - \frac{15000}{322,55}\right\}}$

= $e^{\left\{\frac{15000}{383} - \frac{15000}{322,55}\right\}}$

= $e^{\left\{\frac{15000}{383} - \frac{15000}{322,55}\right\}}$

= $e^{15000\ (\ 0.00261149086 - 0.00310029453)}$

= $e^{-7.33205505}$

=0.000649

= 6.49×10−4

then FAA is 0.000649

4. FEQA (Equivalent Aging Factor)

Because it uses a constant average value (θH is the daily average value) then:

FEQA = FAA= 0.000649

5. Daily Loss Of Life (LOL)

$$\text{LOL} = \frac{FAA \times \Delta t}{180000} \times 100\%$$

$$\text{LOL} = \frac{0.000649 \times 24}{180000} \times 100\%$$

$$\text{LOL} = \frac{0.015576}{180000} \times 100\%$$

$$= 8.6533 \times 10^{-8} \times 100\%$$

per day $= 8.65 \times 10^{-8-6}\%$

LOL day = 0.00000865%shows that in one day of operation, the transformer only experiences thermal degradation of 0.00000865% of its total insulation life.

6. Effective Life (L-eq)

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$$Leq = \frac{180000}{FEQA}$$

$$Leq = \frac{180000}{0.000649}$$

O'clock $Leq = 277{,}307{,}952$

Convert to years (1 year = 8760 hours)

$$Leq = \frac{277{,}307{,}952}{8760}$$

$$Leq = 31{,}656 \text{ tahun}$$

So the pure thermal theory yields:

O'clock $Leq = 277{,}307{,}952 \approx 31{,}656 \text{ years}$

Based on the IEEE C57.91 method, the transformer hot spot temperature of 49.55°C indicates a safe thermal condition because it is far below the reference limit of 110°C. The FAA value of 0.000649 and the daily LOL of 0.00000865% indicate that the thermal degradation process is very slow. Mathematically, the theoretical effective life reaches ±31,660 years. These results confirm that thermally, the transformer is still operating in a safe and efficient condition, with a very low risk of aging due to heat.

5. Conclusion

Based on the analysis results of the IEEE C57.91-2011 thermal aging method, the 1250 kVA distribution transformer at PT Ultra Sumatera Dairy Farm operates under very safe and efficient thermal conditions. The hot spot temperature of 49.55°C indicates that the average loading of 422.7 kVA does not cause significant thermal aging. The Accelerated Aging Factor (FAA) value of 0.000649 and daily Loss of Life of 0.00000865% indicate a very slow degradation rate. Theoretically, the effective life of the transformer reaches ±31,660 years, while the actual life is estimated to be 25–35 years considering non-thermal factors. Thus, the transformer is still in optimal condition and has the potential to provide reliable long-term performance. Based on the results of this study, it is recommended that PT Ultra Sumatera Dairy Farm conduct routine monitoring of operating temperature, insulating oil quality, and cooling system to maintain the transformer's thermal efficiency. The implementation of a temperature sensor-based monitoring system will help detect potential anomalies in transformer performance early. Furthermore, the company can consider periodic testing of oil moisture content and breakdown voltage to prevent non-thermal degradation. For future researchers, this study can be expanded by incorporating humidity and environmental factors to estimate transformer lifespan more comprehensively.

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