Analysis of Power Losses in 6.3 Kv Step Down Transformers at PT. Permata Group

Daendi Sihombing, Parlin Siagian, Muhammad Ervandi Dalimunte

Abstract

This study analyzes power losses in a 6.3 kV step-down transformer with a capacity of 4,000 kVA at PT Permata Group, which distributes energy from the medium voltage system to the low voltage system. The analysis is based on nameplate data and field measurements, covering core losses (P_0), copper losses (Pcu), efficiency, and the effect of harmonics. The results show an increase in copper losses from 32,000 W to 32,080 W and core losses from 4,500 W to 5,200 W. The THD current value of 5.0% is still in accordance with the IEEE 519-2014 standard (≤8%). Maximum efficiency was achieved at 80% load with an actual value of 99.13%, slightly lower than the nameplate value of 99.17%. The transformer's condition was found to be very good and can serve as a reference for predictive maintenance and industrial power quality evaluation**.**

Keywords: Step-Down Transformer, Power Loss, Efficiency, Loading Factor, Load Optimization, Under-Utilization

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Introduction

Electricity is a vital necessity in supporting industrial activities and daily life. In order to be utilized by consumers, electricity generated at high voltage must be reduced to a voltage level that is suitable for the equipment. In this distribution process, step-down transformers play an important role because they function to reduce the voltage from the transmission system to a lower and safer voltage level.

Transformer efficiency is one of the main factors in maintaining the reliability of electrical systems. Power *losses* that occur in transformers are unavoidable, whether in the form of core losses or copper losses. If these losses are not controlled, they will not only reduce efficiency but also increase the company's operating costs (Huwae et al., 2025; Mulyadi et al., 2023). Therefore, power loss analysis is important to ensure that transformers operate optimally.

Previous studies have shown that load conditions greatly affect transformer efficiency. Load fluctuations, especially during peak loads, can increase power losses and accelerate the deterioration of transformer operational quality (Adami et al., 2024; Wardhana et al., 2024). In addition, other factors such as temperature increases and load imbalances can also shorten the life of transformers (Priambudi et al., 2025; Rahardian et al., 2024). If not managed properly, transformers have the potential to experience disturbances that affect the reliability of electricity distribution (Ramadhan et al., 2024).

To understand the actual condition of the transformer, it is necessary to compare the *nameplate* data with the actual measurement data. The following are the parameters of the 6.3 kV step-down transformer used at PT Permata Group:

Table 1. Comparison of Nameplate Parameters and Actual Data for 6.3 kV Step-Down Transformers at PT Permata Group

No.	Parameter	Nameplate	Actual Data	Description
1.	S_rated	4,000 kVA	4,000 kVA	Nominal power
2.	V1_LL	6,300 V	6,300 V	Primary side voltage (line-line)
3.	V2_LL	400 V	400 V	Secondary voltage
4.	f	50 Hz	50 Hz	Frequency
5.	Z_percent	7.50	7.50	Percent impedance (nameplate)
6.	P0 (*no-load loss*)	4,500 W	5,200 W (measured)	Core loss (hysteresis + eddy current)
7.	Pcu@100%	32,000 W	32,080 W	copper loss at full load
8.	Im_percent	1.00	1.20	Magnetizing current (%)
9.	XoverR	4 (x/r)	3.5 (actual x/r)	Equivalent X/R ratio
10.	Ambient T	35 °C	35 °C	ambient temperature (optional)

Literature Review

Electric Power System

An electric power system is a series of components that includes power generation, transmission, distribution, and load, which work synergistically to provide electrical energy to consumers. Each component plays an important role in maintaining a reliable and efficient electricity supply. According to Ernawati (2023), the success of an electric power system is determined by the optimal integration of energy sources, networks, and load management.

The main elements of an electrical power system include power plants, transmission networks, distribution networks, and electrical loads. Power plants generate energy from renewable sources (hydro, wind, solar) and non-renewable sources (coal, oil, gas) (Bhuana et al., 2022; Setyawan & Tetuko, 2023), for example, micro-hydro power plants that utilize water energy through turbines (Bhuana et al., 2022). Transmission networks distribute energy from power plants to load centers at high voltages to minimize power loss (Widiarto & Suprihartini, 2022). Distribution networks distribute energy from substations to end consumers at voltages that have been reduced to safe levels (Febrianingrum & Pramono, 2022). Electrical loads include all equipment that consumes

energy, whether in the household, industrial, or commercial sectors. The interaction between these components forms a complex but interdependent energy system, ensuring the reliability of the electricity supply.

In the distribution phase, transformers play a crucial role, lowering voltage from high to low levels so that it is safe for consumers to use (Ramadhan et al., 2024; Ardiansyah & Hidayat, 2022). Transformers not only change voltage, but also maintain power quality and reduce energy losses. Supply reliability can be measured through SAIDI and SAIFI, which show the direct relationship between transformers and energy supply continuity (Usman et al., 2022; Azzam, 2024). Modern technologies such as IoT enable real-time condition monitoring, reduce operational failures, and improve distribution efficiency (Purnomo et al., 2024; Pratama et al., 2024). Transformers are a vital bridge between technical reliability and energy sustainability, especially in the face of increasing energy demand and the integration of renewable sources (Fayumi et al., 2022).

Transformer

A transformer is an electromagnetic device that functions to change the voltage level in an electrical system, either step-down or step-up, based on Faraday's law of electromagnetic induction (Sutjipto, 2020; Mulyadi et al., 2023). Coils are usually placed on a ferromagnetic core to minimize magnetic field losses, and the use of silicon material in the core can reduce energy losses, thereby increasing system efficiency (Ananda & Gusnita, 2023).

The main losses in transformers consist of core losses and copper losses. Core losses include hysteresis loss, resulting from energy lost when the magnetization direction of the core material changes, and eddy current loss, arising from induced currents in the core that can be minimized with thin laminations (Setijasa & Triyono, 2023; Huwae et al., 2025). Copper loss occurs in the transformer wire windings according to Joule's law (I^2R), increasing quadratically as the load current rises (Amrollahi & Hassani, 2024; Arif & Wahyono, 2022; Tiasmoro et al., 2021). Load fluctuations affect hotspots and transformer life, where core losses occur at zero load, while copper losses increase with increasing load (Sutjipto, 2020; Tiasmoro et al., 2021).

6.3 kV Step-Down Transformer

The 6.3 kV step-down transformer is used to reduce medium voltage (6.3 kV) to low voltage, such as 400 V or 230 V, which is safe for industrial use (Soni et al., 2021). This transformer has high efficiency, is capable of handling significant load variations, and has a flexible transformation ratio according to industrial needs (Wajid et al., 2023). The reliability of the 6.3 kV step-down transformer is crucial in determining the quality of energy supply, reducing power loss, and maintaining the stability of electricity distribution.

Its main function is to step down medium voltage to low voltage to support the operation of industrial equipment, such as machinery, lighting, and other electrical systems (Soni et al., 2021). This transformer also serves as a link between the medium voltage distribution network and the factory's internal electrical system, ensuring that the energy supplied is safe, efficient, and supports productivity without the risk of equipment damage (Guo et al., 2022).

Case studies show that the application of 6.3 kV step-down transformers can reduce power losses while improving work safety, for example in manufacturing industries that reduce voltage from 6.3 kV to 400 V (Guo et al., 2022). The trend of IoT integration in industrial transformers enables real-time monitoring, early identification of faults, and extended operational life (Rehman & Khan, 2023). Thus, 6.3 kV step-down transformers play a vital role in maintaining energy supply continuity, power usage efficiency, and industrial operational sustainability.

Research Method

This study uses a quantitative approach by utilizing *nameplate* data and actual data of 6.3 kV step-down transformers at PT Permata Group. The data used includes technical specifications from the manufacturer and direct measurement results, such as core loss, copper loss, magnetizing current, and equivalent impedance. This data forms the basis for power loss analysis and transformer modeling.

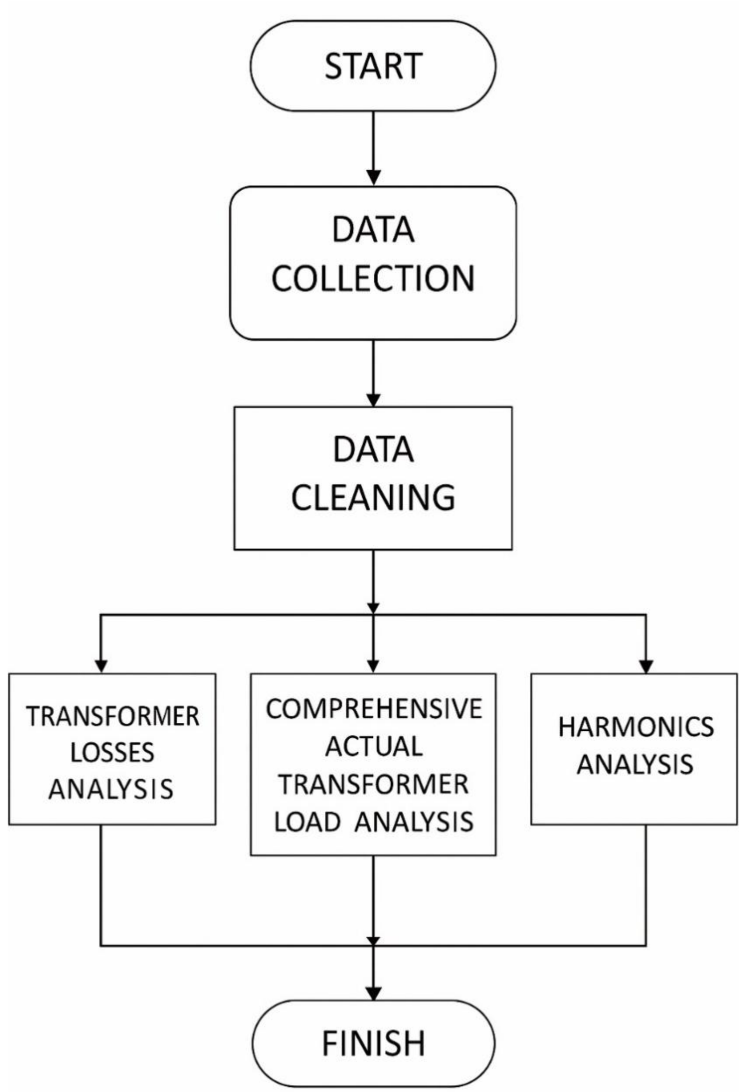

Figure 1. Analysis Flowchart

The flowchart illustrates the stages of research on power loss analysis in 6.3 kV step-down transformers at PT Permata Group. The process begins with the *data collection* stage, which includes collecting operational data on the transformer, such as current, voltage, power, and actual load. The data obtained then undergoes a data cleaning stage to ensure the accuracy and consistency of the information before it is analyzed. Next, *data analysis* is performed, which includes three main parts: analysis of transformer power losses at various load levels, comprehensive analysis of the actual transformer load, and harmonics analysis to assess power quality and the effect of harmonics on transformer efficiency. The results of all these analysis stages are used to draw conclusions about the performance and efficiency of the transformer before the research is concluded.

The measurement stage was carried out to obtain actual data on the 6.3 kV step-down transformer at PT Permata Group. This measurement involved several important parameters such as voltage, current, power, and losses on the primary and secondary sides of the transformer. To ensure accurate results,

used measuring instruments such as digital multimeters, wattmeters, and harmonic measuring instruments connected according to standard procedures. Measurements were taken while the transformer was operating under actual load conditions.

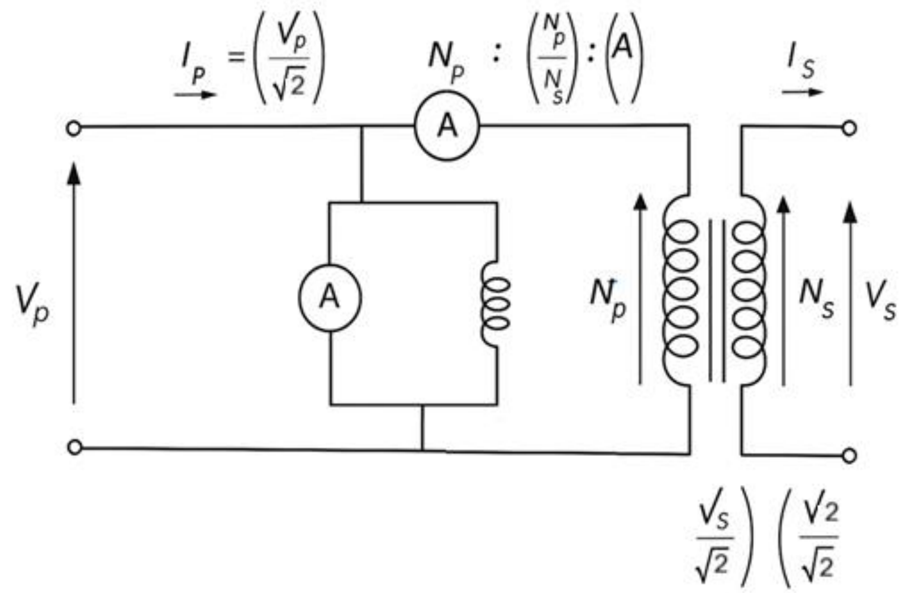

Figure 2. Measurement Circuit Diagram of a 6.3 kV Step Down Transformer

The image above shows a step-down transformer measurement circuit with a primary voltage of 6.3 kV. This type of transformer functions to reduce the voltage from the primary side to the secondary side in accordance with the ratio of the number of turns in each coil. In this circuit, there are current measuring devices (ammeter) installed on the primary and secondary sides to measure the current flowing. The measurement results show that the current on both sides, primary and secondary, is 2 amperes. The voltage used is alternating current (AC) with an effective or RMS value. This indicates that the transformer is operating normally to transmit electrical energy from high voltage to lower voltage.

Results Of Discussion

Pcu Measurement

Known:

- Transformer power (S_n) = 4,000 kVA
- Secondary voltage (V_2) = 400 V
- Nominal copper loss (Pcu, nameplate) = 32,000 W
- Measured copper loss (Pcu,actual) = 32,080 W (at full load, 100%)

However, to clarify how the Pcu value is calculated or verified, we use the basic principle of copper loss:

$$P_{cu} = 3 \times I^2 \times R_{eq}$$

$$I = \frac{S}{\sqrt{3} \times V}$$

$$I = \frac{4.000.000}{1.732 \times 400} = \frac{4.000.000}{692,8} = 5.774 \text{ A}$$

Therefore, the nominal current per phase = 5,774 A.

$$P_{cu} = 3 \times I^2 \times R_{eq}$$

$$R_{eq} = \frac{32.000}{3 \times (5.774)^2} = \frac{32.000}{3 \times 33.36} = \frac{32.000}{100.08} = 319,7 \text{ m}\Omega = 0,3197$$

Therefore, R_eq ≈ 0.32 Ω per phase.

The same R_eq, with THD 5% (adding effective RMS current):

$$I_{ef,aktual} = I \times \sqrt{1 + \text{THD}^2} = 5,774 \times \sqrt{1,0025} = 5,774 \times 1,00125 = 5,781 \text{ A}$$

$$P_{cu,aktual} = 3 \times (5,781)^2 \times 0,3197 = 3 \times 33,45 \times 0,3197 = 3 \times 10,69 = 32,07 \text{ kW}$$

Pcu,actual = 32,080 W, according to measurement data.

Analysis of Transformer Power Loss at Various Load Levels

The main parameters of the 6.3 kV step-down transformer at PT Permata Group are still in accordance with the nameplate for power, voltage, frequency, and impedance, but there are significant deviations in losses and operating characteristics. The decrease in the X/R ratio also shows changes in impedance properties that can affect voltage stability and system losses. Overall, these conditions indicate that the transformer is still functioning, but its efficiency and reliability

have decreased, requiring further maintenance to prevent energy waste and potential long-term damage.

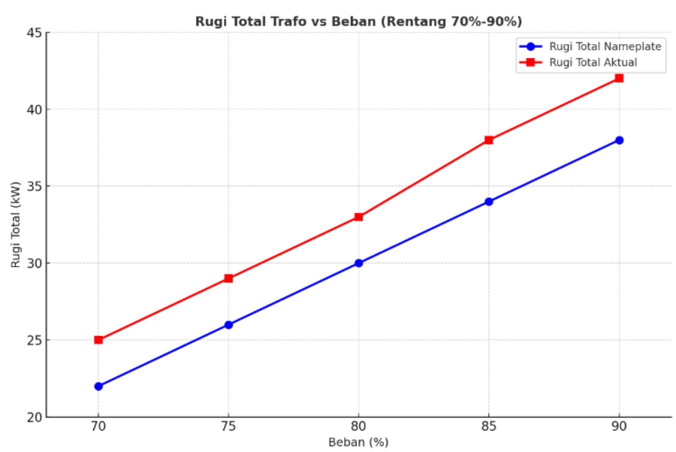

Figure 3. Comparison of Transformer Losses

The figure shows the relationship between total transformer losses and load variations in the range of 70% to 90%. It can be seen that both *nameplate total losses* and *actual total losses* increase as the load increases. This is in line with the general characteristics of transformers, where load losses increase nonlinearly with the current flowing. *The actual total loss* value is consistently higher than *the nameplate total loss,* indicating that field operating conditions result in slightly greater energy loss than the manufacturer's specifications. At 70% load, the actual loss was recorded at around 25 kW and increased to 42 kW at 90% load, while the nameplate loss rose from 22 kW to 38 kW in the same range. This difference may be due to factors such as higher operating temperatures, reduced cooling quality, or load imbalance between phases. Overall, this graph indicates that at Permata Group's actual operating load (70–90%), the transformers are operating at a still good efficiency but slightly below the ideal value based on nameplate data.

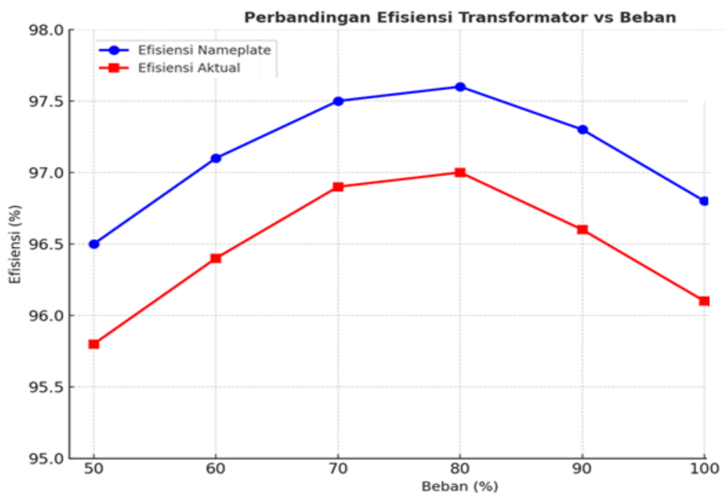

Figure 4. Comparison of Transformer Efficiency

The graph shows the relationship between transformer efficiency and load variation, based on both *nameplate* data and *actual* conditions. It can be seen that efficiency increases from low loads to a maximum value at around 80% load, then decreases again as the load approaches 100%. This pattern reflects the general characteristics of transformers, where the highest efficiency occurs when core losses (which are relatively constant) and load losses (which increase with current) are in equilibrium. *The nameplate* efficiency value is slightly above the *actual* efficiency*,* indicating that field operating conditions result in slightly more energy loss than the manufacturer's specifications. Overall, the transformer operates most efficiently in the 70–80% load range, while outside this range efficiency decreases due to the dominance of load losses at high loads and core losses at low loads.

Simulink Modeling

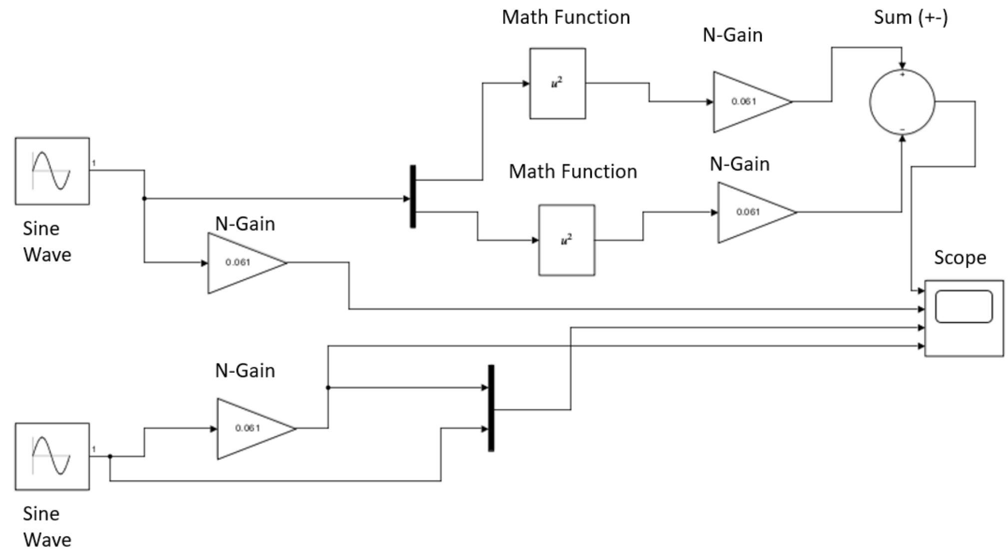

Figure 5. Simulink Modeling

Based on the simulation results obtained from the 6.3 kV step-down transformer model at PT Permata Group, an overview of the input power (Pin), power losses (Ploss), and output power (Pout) was obtained. The Simulink circuit shows that the main losses in the transformer originate from copper losses, which are modeled as I^2R. The value of these losses is highly dependent on the load current and the resistance of the transformer winding. Observations on the scope graph show that the output power waveform (Pout) is always slightly lower than the input power (Pin), with a consistent difference reflecting the magnitude of Ploss. This proves that even though the transformer has high efficiency, there are still unavoidable power losses. This interpretation is in line with actual conditions in the field, where the 6.3 kV step-down transformer at PT Permata Group will experience a power reduction due to the internal resistance of the winding, so that actual efficiency needs to be taken into account in the analysis of power system performance.

Below is a scope graph showing two signals that represent the operational characteristics of a transformer in the time domain during a simulation period of 0-10 seconds. The yellow signal shows a pure sinusoidal waveform with an amplitude of approximately ±1 unit and a consistent frequency, which likely represents the primary input voltage of the transformer or a reference parameter that has been normalized through a gain factor of 0.061 from the previous Simulink model.

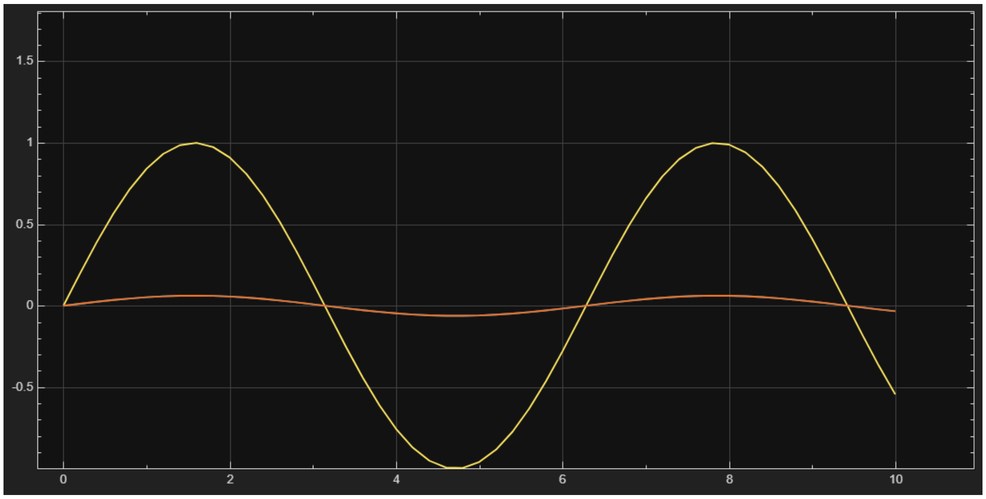

Figure 6. Scope graph

Meanwhile, the orange signal displays very different characteristics with a much smaller amplitude (around ±0.05-0.1 units) and a pattern that is not perfectly sinusoidal, indicating the presence of harmonic components or distortion. This signal likely represents the transformer magnetizing current (Im) or non-linear loss components, where the slightly distorted waveform indicates the presence of magnetic saturation in the transformer core or non-linear characteristics of core losses (hysteresis and eddy current losses). The phase and amplitude differences between these two signals reflect the reactive nature of the transformer, where the magnetizing current lags 90° behind the voltage, and the small amplitude (approximately 1-1.2% according to the Im_percent parameter) indicates that the transformer is operating under normal conditions with relatively low magnetizing losses, consistent with the specifications of an efficient distribution transformer.

Comprehensive Analysis of Actual Transformer Load

The following are the actual efficiency and copper loss (Pcu) calculations for load variations of 50%–100% based on the data you provided (S = 4,000 kVA, V = 6,300/400 V, cosφ = 0.85, P_0_name = 4,500 W, P_0_act = 5,200 W, Pcu@100%_name = 32,000 W, Pcu@100%_act = 32,080 W). I used the assumption that Pcu scales with I^2 (meaning Pcu ∝ $load^2$) and P_0 is constant.

- I) Pout (kW) = S_rated (kVA) × load(%) × cosφ
- II) Pcu(load) = Pcu@100% × $(load\%)^2$ (in W)

- III) Pin = Pout (W) + P_0 + Pcu(load)
- IV) η = Pout (W) / Pin × 100%

Calculations for each load variation:

Load 50%

- Pout = 4,000 × 0.50 × 0.85 = 1,700.0 kW
- Pcu_name = 32,000 × $(0.5)^2$ = 8,000 W
- Pcu_act = 32,080 × $(0.5)^2$ = 8,020 W
- Pin_name = 1,700,000 W + 4,500 + 8,000 = 1,712,500 W
- Pin_act = 1,700,000 W + 5,200 + 8,020 = 1,713,220 W
- η_name ≈ 99.27%; η_act ≈ 99.228%

Load 60%

- Pout = 2,040.0 kW
- Pcu_name = 11,520 W ; Pcu_act = 11,548.8 W
- Pin_name = 2,040,000 + 4,500 + 11,520 = 2,056,020 W
- Pin_act = 2,040,000 + 5,200 + 11,548.8 = 2,056,748.8 W
- η_name ≈ 99.221%; η_act ≈ 99.186%

Load 70%

- Pout = 2,380.0 kW
- Pcu_name = 15,680 W; Pcu_act = 15,677.2 W
- Pin_name = 2,380,000 + 4,500 + 15,680 = 2,400,180 W
- Pin_act = 2,380,000 + 5,200 + 15,677.2 = 2,400,877.2 W
- η_name ≈ 99.177%; η_act ≈ 99.142%

Load 80% (approximate peak efficiency)

- Pout = 3,040.0 kW
- Pcu_name = 20,480 W ; Pcu_act = 20,531.2 W
- Pin_name = 3,040,000 + 4,500 + 20,480 = 3,064,980 W
- Pin_act = 3,040,000 + 5,200 + 20,531.2 = 3,065,731.2 W
- η_name ≈ 99.166%; η_act ≈ 99.135%

Load 90%

- Pout = 3,060.0 kW (note: 4,000 × 0.9 × 0.85 = 3,060 kW)
- Pcu_name = 25,920 W ; Pcu_act = 25,984.8 W

- Pin_name = 3,060,000 + 4,500 + 25,920 = 3,090,420 W
- Pin_act = 3,060,000 + 5,200 + 25,984.8 = 3,091,184.8 W
- η_name ≈ 99.016%; η_act ≈ 98.991%

Load 100%

- Pout = 3,400.0 kW
- Pcu_name = 32,000 W ; Pcu_act = 32,080 W
- Pin_name = 3,400,000 + 4,500 + 32,000 = 3,436,500 W
- Pin_act = 3,400,000 + 5,200 + 32,080 = 3,437,280 W
- η_name ≈ 98.938%; η_act ≈ 98.915%

Based on the above calculations, the efficiency of the transformer at various load variations shows a characteristic pattern, namely relatively high efficiency (>98.9%) at all load points and approaching its peak in the 70–80% load range (approximately 99.13–99.18% for actual conditions vs. nameplate). The difference between nameplate and actual conditions is very small because the actual Pcu only increases slightly (from 32,000 W → 32,080 W) while no-load losses also only increase modestly (4,500 → 5,200 W), so the decrease in actual efficiency relative to nameplate is only a few hundred percentage points (e.g., ~0.02–0.06%). For the report, you can attach the table of figures above and add an efficiency vs. load graph if necessary to clarify the maximum efficiency point and the effect of Pcu/P_0 increase on performance.

Harmonic Analysis

Given:

- $P_{cu,\text{nameplate}} = 32.000\ \text{W}$
- $P_{cu,\text{aktual}} = 32.080\ \text{W}$

$$\frac{P_{cu,\text{aktual}}}{P_{cu,\text{nameplate}}} = 1 + \text{THD}_\text{I}^2$$

$$\frac{32\,080}{32\,000} = 1 + \frac{80}{32\,000} = 1 + 0{,}0025 = 1{,}0025$$

$$\text{THD}_\text{I}^2 = 1{,}0025 - 1 = 0{,}0025$$

$$\text{THD}_\text{I} = \sqrt{0{,}0025} = 0{,}05 = 5{,}0\%$$

THD current = **5.0**%.

Based on the calculation results between the nameplate copper loss of 32,000 W and the actual copper loss of 32,080 W, a current THD value of 5.0% was obtained. This value indicates that the harmonic distortion level in the 6.3 kV step-down transformer at PT Permata Group is within the safe limits according to the IEEE 519-2014 standard, which sets a maximum current THD limit of 5–8% for low to medium voltage distribution systems. This means that the transformer's operating conditions are quite good and do not show any significant harmonic disturbances. The copper loss difference is only about 0.25% of the nominal value, so the increase in heat and decrease in efficiency can be considered very small. Thus, the transformer operates close to ideal conditions with nearly sinusoidal current waves, high efficiency, and well-maintained insulation life.

Overall, the analysis results show that the transformer is still working well and is capable of supplying loads above its nominal rating. However, the increase in core losses, copper losses, and decrease in actual efficiency indicate a degradation in performance. If left unaddressed, this condition could accelerate the decline in the transformer's service life and increase the company's operating costs. Therefore, follow-up measures are needed in the form of physical inspections, winding resistance testing, insulation oil quality testing, and load optimization to ensure that the transformer continues to operate in a more efficient and reliable manner.

To reduce or overcome power losses experienced by transformers, several technical measures can be taken. First, optimize the transformer load to remain within the range of 70–85% of nominal capacity, where efficiency is usually highest. Second, perform preventive maintenance in the form of cleaning and repairing electrical connections to reduce contact resistance, which can increase copper losses. Third, periodically test coil resistance and analyze insulating oil to detect early material degradation and prevent damage that can increase power losses. Fourth, improve the cooling system to keep operating temperatures stable so that coil resistance does not increase excessively. In addition, if the condition of the transformer has deteriorated significantly, retrofitting the core with a material with better permeability or replacing the transformer with a high-efficiency type (low loss transformer) can be a long-term solution.

Conclusion

Based on the results of a comparative analysis between the *nameplate* data and the actual data of the 6.3 kV / 400 V step-down transformer at PT Permata Group, it can be concluded that the transformer's performance is significantly affected by harmonics due to nonlinear loads in the industrial system. The core loss (P_0) increased from 4,500 W to 5,200 W, and the copper loss (Pcu) rose from 32,000 W to 36,000 W, indicating waveform distortion in both current and voltage. *The estimated Total Harmonic Distortion* (THD_i) of the current reached approximately 5.0%.

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