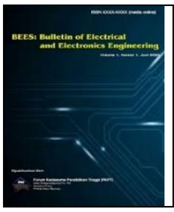

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The Impact of Load Unbalance on Neutral Conductors Losses and Transformer Efficiency

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A B S T R A C T

The transformer is a crucial component in the electrical energy distribution system. Therefore, strict supervision is necessary to ensure that the electricity supply network is maintained and safe during operational processes. This research aims to measure the transformer load installed at PT. Sunrise Steel to determine the values of loading, imbalance, power losses, and efficiency of the loaded transformers. This measurement is important to ensure that the values resulting from operational processes do not exceed predetermined limits. Observations over 10 days show that the peak load value during operational time is 66.08%, which can still be categorized as quite good. The load imbalance reached a maximum value of 10.13%, which is categorized as poor since SPLN regulations state that a good imbalance should be below 10%. The percentage of power loss has a maximum value of 0.33%, and the best transformer efficiency reaches 97.17%, which is the highest efficiency value considering several other loss parameters.

Kata Kunci: Efficiency; Load Unbalanced; Neutral Conductor Losses; Transformer

1. INTRODUCTION

Electrical energy is the most important human need to help all kinds of human activities in daily life. With the development of the times and technology in Indonesia, energy providers are required to provide stable electricity needs to help the development and development process in Indonesia [1][2][3]. The distribution system is an important means of distributing electrical energy to consumers or end users. In the distribution of electrical energy to consumers there is electrical power equipment, namely distribution transformation which is useful for reducing the medium voltage of 20 kV (primary side) to low voltage (secondary side) between the phases 380 V - 400 V and the neutral phase 220 V which can used by consumers [4]. This transformer plays an important role in ensuring a stable and reliable electricity supply to end users [5][6]. However, in the process of distributing electrical energy to consumers, transformers often face load imbalance problems. Because in this case, electricity use does not coincide within a certain period of time [7]. If there is a load imbalance between the phases, current will flow in the neutral conductor. The value of the neutral current depends on how big the load imbalance factor is on each phase. The emergence of neutral current in this transformer causes power losses [8]. In a transformer there are core losses and copper losses, where these losses affect the decrease in transformer efficiency [9]. The level of transformer efficiency value is determined by the amount of power losses, where the higher the power loss value, the lower the efficiency value of a transformer [10]. According to research conducted by Budiyasa [11], the imbalance of load between phases causes neutral current in the transformer, with an imbalance tolerance of 20% of the transformer capacity by PLN. Load balancing is carried out in the LVMDP panel of three-phase customers to reduce imbalance, which has an impact on neutral current and losses. The measurement results show a daytime load imbalance of 29.9% and 26.6%, and at night of 62.6% and 31%. The greater the neutral current flowing, the greater the losses in the transformer neutral conductor.

According to Pelawi [12], the secondary distribution system is used to distribute electric power from the distribution substation to the loads at the consumer. Because the load is supplied through a single-phase system, an imbalance in the load in an electric power distribution system always occurs. Eventually it will cause current to flow in the transformer neutral, resulting in losses in the neutral conductor. If the neutral current (leakage current) flowing in the neutral conductor is too large, the resulting power losses will be greater. If the system is truly balanced, the power losses will only occur in the R, S and T channels. After analysis, it was found that if there is a load imbalance of 4.67%, the neutral current that appears is 20,43 A, and the losses due to the neutral current to the ground are 1,27%.

Other research Mufizar [13] conducted an analysis on the distribution transformer owned by PT. PLN ULP Selayar which will then be done several calculations with a predetermined formula to determine the effect of load imbalance on neutral current and power loss in the transformer. This calculation is then used as the basis for analyzing the effect of load imbalance on neutral current and power loss in the transformer and its impact on customers. Based on the calculations that have been done, the percentage of load imbalance exceeds 14% during the day and 27% at night. This study also calculates losses caused by the emergence of neutral current flowing through the neutral conductor of 4,49 W and flowing to the ground of 0,86 W and also found overvoltage at customers. The impact of decreasing transformer efficiency can affect the performance of the electricity distribution system on a transformer, because the power output is different from the power entering. If the load imbalance between phases on a transformer is continuously ignored, it will have an unfavorable impact, which can cause losses for energy providers and consumers. Distribution transformers play an important role in carrying out the role of distributing electrical power to meet the supply of daily needs, both for the industrial sector and the needs of the household sector. Thus, the process of carrying out energy operational activities for consumers requires a transformer with fairly good performance. What can be categorized as good is that it does not exceed the limits of the PLN standard (SPLN) provisions in Table 1.

Table 1. PLN Standart (SPLN)

Characteristics		Health Index			
		Good	Average	Poor	Bad
Load Analysis	Unbalanced current between phase	<10%	10% - <20%	20% - <25%	≤25%
	The amount of neutral current TR (% of transformer load current)	<10%	10% - <15%	15% - <20%	≤20%
	Transformer loading (% of capacity)	<60%	60% - <80%	80% - <100%	≤100%

The electrical power distribution process inherently produces a three-phase imbalance. This causes the voltage and current in the R, S, T phases along the distribution feeder to become unbalanced. An unbalanced situation will cause extra line power losses, reduced operating efficiency in the distribution system and shorter transformer life [14]. Power losses in transformers are divided into constant iron core losses not affected by load, copper losses affected by changing load currents, and power losses due to neutral currents. Neutral current power loss is caused by neutral current flowing in the transformer conductor [15]. Three-phase imbalance is a serious problem in distribution networks because it affects the quality of the power supply and the economic operation of distribution networks [16]. Efforts that can be made to handle load imbalances on transformers, namely load transfer, redistribution and phase change of user loads, reactive compensation [17].

Research on the impact of load imbalance on neutral conductor losses and transformer efficiency at PT. Sunrise Steel has high urgency. Energy efficiency is an important factor, because power losses in neutral conductors and low transformer efficiency can lead to inefficient energy use and higher operating costs. In the context of ever-increasing energy costs, increased efficiency can result in significant savings for the company. In addition, the reliability of the electrical system is very important to prevent overheating in neutral conductors and transformers that can cause component damage and power outages. By understanding the impact of load imbalance, PT. Sunrise Steel can improve system reliability and reduce unwanted downtime. Excessive load imbalance also poses safety risks, such as potential fires. Therefore, this research is very important to ensure a safe working environment for employees.

However, there is a significant research gap in this context. Local empirical data on the impact of load imbalance on the steel industry in Indonesia is still limited. Many existing studies have been conducted in other regions or industries, so that specific and relevant data for PT. Sunrise Steel is still lacking. In addition, many studies only focus on general aspects of load imbalance without exploring in depth how specific load imbalance affects neutral conductors and transformer efficiency in a specific industry context. Differences in measurement and analysis methodologies used in previous studies also cause gaps in the application of these research results to the specific conditions of PT. Sunrise Steel. Furthermore, many studies may only identify problems without providing practical solutions that can be implemented by the industry to overcome load imbalance and improve transformer efficiency. Thus, this study aims to fill this gap and offer practical solutions that can be implemented in the steel industry in Indonesia. This research aims to calculate the load, load imbalance, power losses and efficiency of PT. Sunrise Steel transformers. So it is hoped that the results of this research can help companies reduce power losses caused by imbalance, because the consequences of load imbalance also affect transformer efficiency.

2. RESEARCH METHODOLOGY

2.1 Research Stages

The first step in starting research is to look for references in journals, books or articles that are relevant to the topic of load imbalance in distribution transformers. Data collection on distribution transformers at PT. Sunrise Steel, in the form of transformer specification data which includes transformer brand, primary voltage, secondary voltage, power, copper conductor resistance (*Rcu*), neutral wire conductor resistance (R_N), power factor, iron core loss and measurement data The transformer consists of R phase current, S phase current, T phase current, neutral current, R phase voltage, S phase voltage and T phase voltage.

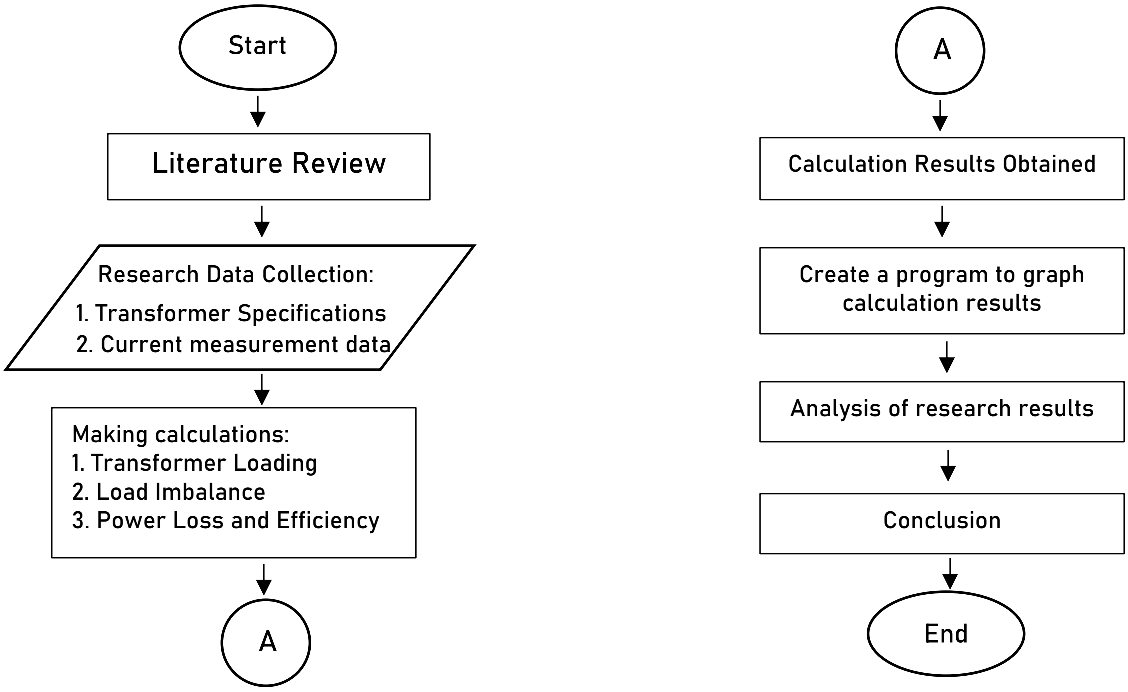

Figure 1. Flowchart

Figure 1 shows a flowchart explaining the research process related to transformer loading, load imbalance, and power losses and efficiency. The process begins with the "Start" stage which is continued by conducting a literature review to collect existing knowledge and background information. After that, research data is collected in two categories: transformer specifications and current measurement data. The next step is to perform calculations covering three aspects: transformer loading, load imbalance, and power losses and efficiency. The results of these calculations are then obtained and continued with the creation of a program to visualize the results of the calculations in the form of graphs. Analysis of the research results is carried out based on the graphs that have been made, so that conclusions can be drawn from the analysis. The end of this process is marked by the "End" step which indicates that the entire series of research has been completed.

2.2 Determination of Transformer Loading

The use of transformers in power systems allows for the selection of suitable and cost-effective voltage levels for various needs, such as high voltage for transmitting electrical power over long distances. The simplicity and reliability of transformers enable the appropriate and economical voltage to be chosen for each requirement, which is a key reason why alternating current is extensively used for the generation and distribution of electrical power. To calculate the full load current, you can use the following equation [18]:

$$I_{FL} = \frac{S}{\sqrt{3}\, V_{L-L}} \quad (1)$$

Where,
I_{FL} = Full Load Current (Ampere)
S = Active Power (VA)
V_{L-L} = Line to Line Voltage (Volt)

In calculating the loading percentage of a transformer, it can be determined using the following equation [18]:

$$\%\text{Loading} = \frac{I_{Avg}}{I_{FL}} \quad (2)$$

Where,
I_{Avg} = Average Current (Ampere)
I_{FL} = Full Load Current (Ampere)

Load imbalance between each phase of the transformer (Phase R, Phase S, and Phase T) causes current to flow on the neutral side of the transformer.

2.3 Load Unbalance Calculation

For example, real power (P) is distributed through a channel with a neutral conductor. If in this power distribution the current in each phase is in a balanced state, then the amount of power can be expressed as follows [18]:

$$P = 3 \times V \times I \times Cos\varphi \quad (3)$$

Where,
P = Real Power (Watt)
V = Line to Netral Voltage (Volt)
I = Nominal Current (Ampere)

The distributed power will be smaller than the actual power value (P) calculated due to losses in the lines. The nominal current (I) represents the magnitude of the phase current in power distribution under balanced conditions. Therefore, in the same power distribution under unbalanced conditions, the magnitude of the phase currents can be expressed by the coefficients a, b, and c as follows [18]:

$$I_{Avg} = \frac{I_R + I_S + I_T}{3} \quad (4)$$

$$I_R = a \times I_{Avg} \qquad I_S = b \times I_{Avg} \qquad I_T = c \times I_{Avg} \quad (5)$$

With I_R, I_S, and I_T respectively are the currents in the *R*, *S*, and *T* phases. If the power factor in the three phases is considered the same even though the magnitude of the current is different, the amount of power distributed can be expressed as:

$$P = (a + b + c) \times V \times I \times Cos\varphi \quad (6)$$

Where in a balanced state, the value a = b = c = 1. Thus, to determine the average load imbalance percentage, the following equation can be used [18].

$$\%Unbalaced = \frac{\{|a-1| + |b-1| + |c-1|\}}{3} \times 100\% \quad (7)$$

2.4 Neutral Current Calculation

To calculate the 3-phase neutral current if the R, S and T phases are known, you can calculate the amount of current flowing in the neutral phase using the equation below [18]:

$$I_N = I_R + I_S + I_T \quad (8)$$

Where,
I_N = Neutral Current (Ampere)
I_R, I_S, I_T = Phase Current (Ampere)

As a result of the load unbalance between each phase on the secondary side of the transformer (R-S-T phase), current flows in the neutral conductor of the transformer. This current causes losses in the neutral conductor. These losses can be formulated as follows [18]:

$$P_N = I_N^2 \times R_N \quad (9)$$

P_N = Neutral Wire Losses (Watt)
R_N = Neutral Wire Resistance (Ohm)
I_N = Neutral Current Resistance (Ampere)

2.5 Transformer Efficiency

The efficiency of the transformer itself is obtained from the comparison between the output of the power used and the input of total power. Because the input to the transformer is the same as the power output used plus the losses. From this comparison, we can determine the overall performance and functionality of the transformer. By analyzing these inputs and outputs, one can gauge how efficiently the transformer is operating. From this, we can understand how optimally a tool component works. Thus, the value of the efficiency calculation can be obtained using the equation. This equation is crucial in determining the precise efficiency, allowing for better optimization and maintenance of the transformer to ensure its longevity and effectiveness in power transmission.

$$\eta = \frac{P_{out}}{Pin} \times 100\% \quad (10)$$

Where,
η = Transformer efficiency
P_{out} = Output Power (Watt)
P_{in} = Input Power (Watt)

3. RESULT AND DISCUSSION

This research aims to determine several key parameters related to transformer performance. Firstly, it seeks to establish the value of the transformer loading percentage, which is critical in assessing how much of the transformer's capacity is being utilized. Secondly, the research aims to evaluate the load imbalance percentage value on the transformer, an important factor that indicates the degree of uneven distribution of the electrical load across the transformer's phases. Load imbalance can lead to inefficiencies and potential damage to the transformer over time. Lastly, the research aims to ascertain the transformer efficiency percentage value after being loaded. This efficiency metric is vital as it indicates the transformer's ability to convert input electrical power to output power effectively, minimizing losses. To provide a comprehensive analysis, the research utilizes a transformer with specific characteristics tailored to the research objectives. Below are the detailed specifications of the transformer used as the current research material, which will serve as the basis for measuring and analyzing the aforementioned parameters.

These specifications include the transformer's rated capacity, voltage levels, frequency, and other relevant technical details that influence its performance and efficiency under various loading conditions. Understanding these values is essential for optimizing transformer performance, ensuring reliable power delivery, and extending the lifespan of the equipment. The findings from this research could also provide valuable data for improving transformer design and maintenance practices, contributing to more robust and efficient electrical power systems.

Table 2 shows the specifications of a transformer. The capacity of this transformer is 3500 KVA with an operating frequency of 50 Hz. The design standard used is IEC76. This transformer has an impedance of 7% and uses ONAN (Oil Natural Air Natural) cooling type. The primary voltage of the transformer is 20 kV, while the secondary voltage is 0.4 kV. The resistance value of this transformer is 0.6842 ohms. This specification shows that this transformer is designed for operation on a power grid with high voltage on the primary side and low voltage on the secondary side. This transformer is designed to meet the needs of industry or distribution networks with large power capacity. The ONAN cooling type indicates that the cooling system uses oil to cool the transformer core and then the heat is dissipated through the air naturally. The 7% impedance value indicates the relative resistance to current flow, which is important in determining voltage regulation and the overall performance of the transformer in the electrical system.

Table 2. Transformer Specification

Parameter	Value
Transformer Capacity	3500 [KVA]
Frequency	50 [Hz]
Design Standard	IEC76
Impedance	7%
Cooling Type	ONAN
Primary Voltage	20 [kV]
Secondary Voltage	0,4 [kV]
Resistance	0,6842 [ohm]

3.1. Calculation of Loading Percentage

Calculating the load percentage is a process for determining the extent to which the total capacity of an equipment or system is used. It measures the proportion of actual load used compared to the full load capacity available. Load percentage provides important information about efficiency and resource utilization, and helps in identifying whether equipment or systems are working within safe and optimal limits or not. To determine the percentage load on a transformer, we must know how to calculate the full load current (I_{FL}). Can be found using equation (1)**:**

$$I_{FL} = \frac{S}{\sqrt{3}\, V_{L-L}} \tag{1}$$

$$I_{FL} = \frac{3500\ [VA]}{\sqrt{3}\ \times 400[V]} = 5051{,}8\ [A]$$

After determining the current at full load (I_{FL}), then determine the percentage of load given to the distribution transformer at PT. Sunrise Steel, using equation (2) the loading percentage value can be calculated as follows:

$$I_{AVG} = \frac{I_R + I_S + I_T}{3} \tag{4}$$

$$I_{AVG} = \frac{3362\ [A] + 3219[A] + 3112[A]}{3} = 3231\ [A]$$

$$\%\text{Loading} = \frac{I_{AVG}}{I_{FL}} \tag{2}$$

$$\%\text{Loading} = \frac{3231[A]}{5051{,}8[A]} \times 100\% = 63{,}95\%$$

By calculating the full load current and using it to determine the percentage load, we can effectively assess the operational status of the transformer and ensure it is functioning within the specified range for optimal performance and longevity. Figure 2 explains the results of the calculation of the load percentage assessment of a transformer with a capacity of 3500 kVA. We can conclude that during the 10 days of observation activities, the load percentage was still categorized as a good value according to the provisions of the PLN Standard (SPLN), which stipulates that the load percentage should not be below 40% or above 80%.

From the modeling graph in Figure 2, it is evident that the highest peak operational load reaches 66.08%, while the lowest operational load is recorded at 61.77%. This evaluation clearly demonstrates that the transformer is functioning within an optimal range, which is crucial for ensuring both efficiency and longevity of the equipment.

Operating the transformer within this specified load percentage range is vital as it helps to prevent both overloading and underutilization. Overloading can lead to excessive heat generation, which may cause insulation degradation, reducing the transformer's lifespan and increasing the risk of failure. Conversely, underutilization can result in inefficiencies, as the transformer may not be operating at its optimal performance level, leading to unnecessary energy losses. Maintaining the load within these limits is a key aspect of effective transformer management.

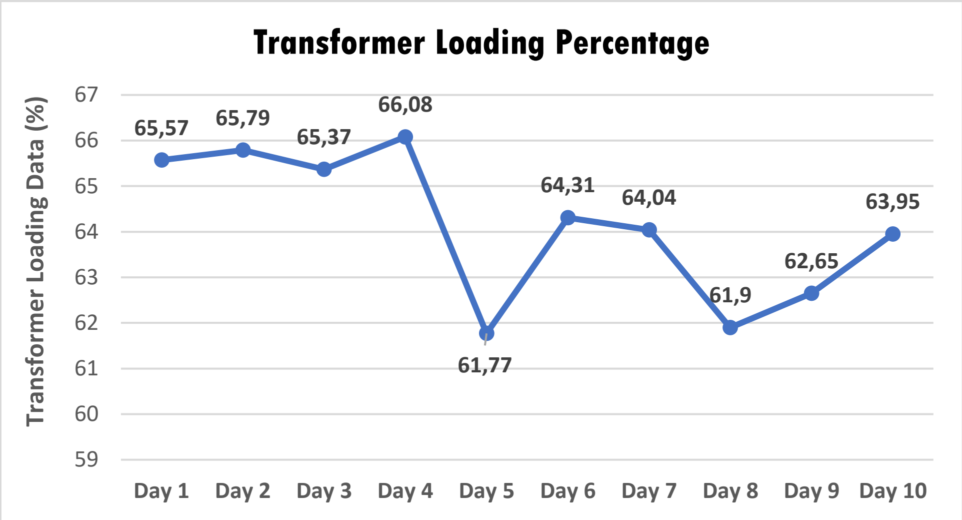

Figure 2. Percentage of PT. Sunrise Steel transformer loading for 10 days

3.2. Transformer Load Unbalance Analysis

To analyze the imbalance that occurs in the transformer, you can use the equation (5). After knowing the magnitude of the imbalance value for each phase, proceed to the percentage stage which uses the equation of (7).

$$I_R = a \times I_{Avg} \qquad I_S = b \times I_{Avg} \qquad I_T = c \times I_{Avg} \tag{5}$$

$$a = \frac{3368\ [A]}{3200\ [A]} = 1{,}05 \qquad b = \frac{3215\ [A]}{3200\ [A]} = 1{,}04 \qquad c = \frac{3018\ [A]}{3200\ [A]} = 0{,}97$$

$$\%Unbalaced = \frac{\{|a-1|+|b-1|+|c-1|\}}{3} \times 100\% \tag{7}$$

$$\%Unbalaced = \frac{\{|1{,}05-1|+|1{,}04-1|+|0{,}97-1|\}}{3} \times 100\% = 6\%$$

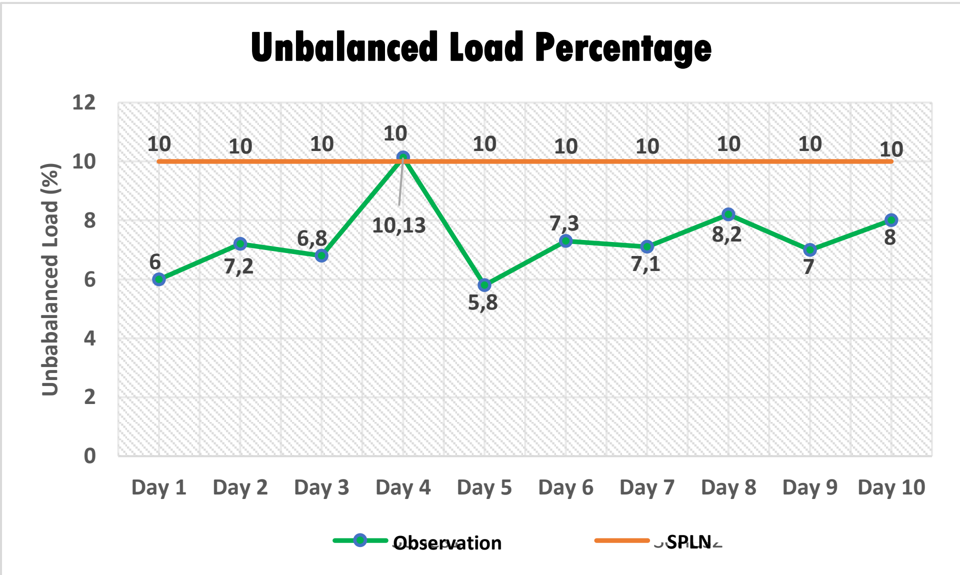

Figure 3. Percentage of Unbalance in PT. Sunrise Steel transformers for 10 days

In Figure 3, the results of the modeling graph above show that one day, on the fourth day, the imbalance value was deemed not to be in accordance with the provisions of the PLN standard (SPLN) because it touched a value of 10.13%. If we review the terms and conditions, it should be stated that the resulting load imbalance percentage value must not exceed the limit of 10%. This can be used as an evaluation in the future to minimize the percentage of imbalance with the aim of minimizing the magnitude of power losses due to neutral current.

3.3 Analysis of Power Losses Due to Neutral Current in the Neutral Conductor of the Transformer

Calculating power losses due to unbalanced loading resulting in current in the neutral conductor can be done using equations (x) and (y)

$$P_N = I_N^2 \times R_N \quad (9)$$

$P_N = (397{,}52)^2[A] \times 0{,}6842\ [ohm] = 108{,}48\ [Watt]$
Where the active power in the transformer is calculated using the formula:
$P = S \times Cos\varphi$
$P = 3500[VA] \times 0{,}94 = 3290\ [Watt]$

Thus, the percentage of losses due to current in the neutral conductor of the transformer can be calculated using the equation:

$$\%P_N = \frac{P_N}{P} \times 100\%$$

$$\%P_N = \frac{108{,}48\ [Watt]}{3290\ [Watt]} \times 100\% = 0{,}32\%$$

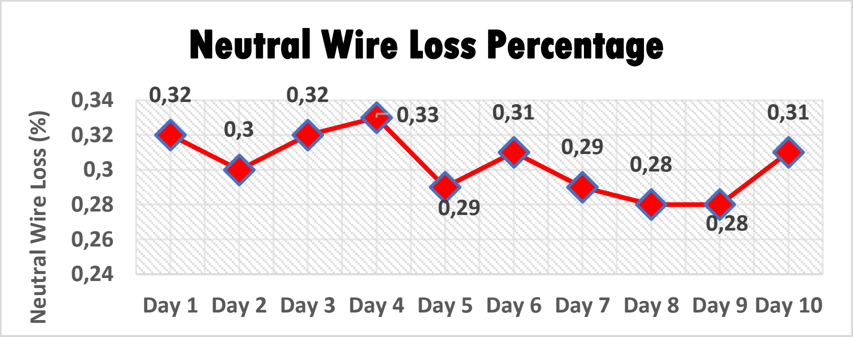

Figure 4. Neutral Wire Loss Percentage

In Figure 4, we can conclude that current losses to the neutral current occurred on the fourth day with a value of 0.33%. This observation indicates that there is a small but noticeable loss of current in the neutral phase, which can have implications for the overall efficiency and performance of the electrical system. The emergence of these power losses is primarily attributed to the imbalance in the network installation. This imbalance occurs because the current in the neutral phase cable is not equally distributed among the phases, which is a common issue in installations where factory equipment is involved. An imbalance in the network can arise from various factors, such as unequal loading on the phases, different power consumption patterns of the connected devices, and potential faults in the installation.

To delve deeper, it's essential to understand that the neutral current losses, although seemingly minor at 0.33%, can accumulate over time, leading to significant energy wastage and potential damage to the electrical infrastructure. These losses can cause overheating of cables and connectors, which, if left unaddressed, might result in insulation failure and possible electrical fires. The performance of sensitive equipment could also be affected, as imbalances can introduce noise and disturbances in the electrical supply, leading to malfunction or reduced operational life of the machinery. The unbalance in the network often stems from several underlying causes. Unequal loading on the phases is one of the most prevalent issues, where certain phases are burdened more than others. This situation can be exacerbated in factories where heavy machinery and equipment are operated intermittently or cyclically, causing fluctuating loads that are not evenly spread across all phases. Additionally, the diverse power consumption patterns of various connected devices contribute to the imbalance. For example, some devices may have higher inrush currents or varying operational cycles, leading to temporary or sustained unbalances.

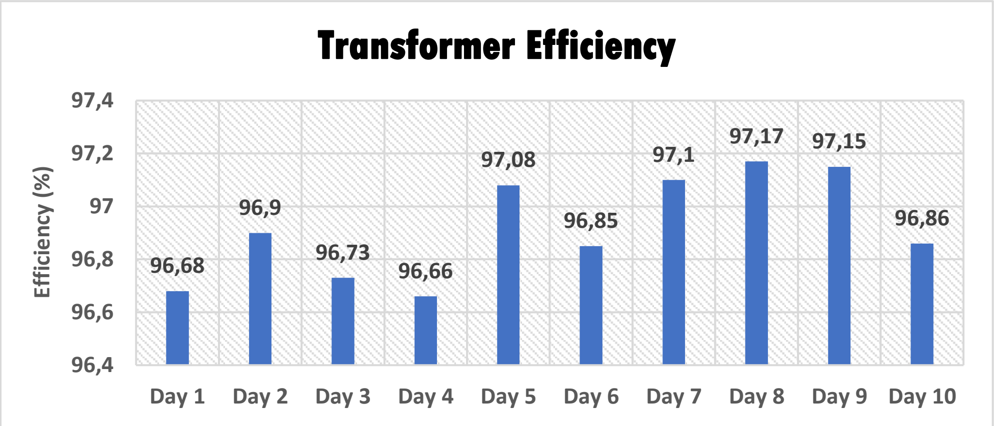

Figure 5. Percentage Transformer Efficiency

After carrying out calculations regarding the loading percentage, the percentage of imbalance and power losses caused by neutral currents. Next is the percentage of transformer efficiency after load. In Figure 5, we can see the highest percentage with a value of 97.17% on the eighth day. And the lowest point of efficiency was the fourth day with a percentage value of 96.66%. This can be categorized as inefficient and the installation of the electrical installation network on factory machines should be reviewed. Because this efficiency percentage is influenced by the load imbalance between phases. So, in the future it is recommended that improvements be made by mapping or recalibrating, or by adding a capacitor bank with the aim of minimizing the emergence of power losses and unbalaced. When factory equipment is installed, it often leads to uneven distribution of loads across the three phases, causing a higher current flow in one or more phases compared to the others. This discrepancy results in a compensatory current in the neutral cable, which manifests as power loss [19]. Addressing these imbalances is crucial for maintaining the efficiency of the electrical system. It involves careful planning and installation of equipment to ensure that loads are evenly distributed across all phases. Regular monitoring and maintenance are also necessary to detect and correct any emerging imbalances that could lead to increased power losses. By minimizing these losses, the overall reliability and efficiency of the electrical network can be improved, leading to cost savings and better performance of the installed factory equipment [20][21]. Moreover, understanding the causes and effects of current losses in the neutral phase helps in designing more robust electrical systems. Engineers can use this knowledge to implement better load management strategies, employ advanced balancing techniques, and integrate technologies that can automatically adjust and compensate for any detected imbalances [22][23]. These measures can significantly reduce the occurrence of power losses, thereby enhancing the longevity and stability of the electrical infrastructure.

4. CONCLUSION

Research on the percentage of loading at PT. Sunrise Steel Transformer for 10 days under peak load conditions shows that the highest value of 66.08% occurred on the fourth day at 01.00 PM. This indicates that the distribution transformer is still categorized as sufficient and can still add more loading value. However, the load unbalance on the PT. Sunrise Steel transformer is 10.13%, whereas according to the provisions, the load imbalance value is categorized as good if it is less than 10%. Therefore, it is necessary to review the network installation on factory machines to minimize load imbalances. Apart from that, power losses resulting from neutral current have the highest value of 0.33%. From the results of calculating the efficiency value for 10 days, the highest point of efficiency percentage that can be achieved is 97.17%, while the lowest value is 96.66%. This shows that efficiency is still less than optimal due to the fairly large imbalance value which can affect the efficiency of a transformer that is already overloaded.

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