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Optimization of Three-Phase Load Balancing to Improve the Efficiency and Reliability of Power Transformers at the Tanjung Morawa Substation

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ABSTRACT

Three-phase load imbalance in power transformers is one of the main problems that can reduce efficiency, increase power losses, accelerate the increase in winding temperature, and reduce the life of transformer insulation. This condition often occurs in distribution systems due to uneven load growth between phases. This study aims to optimize three-phase load balancing to improve the efficiency and reliability of power transformers at the Tanjung Morawa Substation. The research method uses a quantitative approach based on transformer operational data, including measuring the current of each phase, calculating the percentage of load imbalance, analyzing copper losses, and evaluating efficiency and reliability indices. The optimization model is carried out by simulating load redistribution between phases using a mathematical approach to minimize current deviations from the average current. Evaluation parameters include reducing power losses, increasing transformer efficiency, and improving the value of the imbalance factor according to IEC and IEEE standards. The results show that before optimization, the level of load imbalance was in the moderate to high category, which resulted in increased power losses and increased operating temperatures. After the load balancing optimization process, there was a significant decrease in the percentage of imbalance, a decrease in power losses, and an increase in transformer efficiency. Furthermore, the estimated insulation life shows an improvement due to reduced thermal stress. This study demonstrates that a systematic, data-driven three-phase load balancing optimization strategy can sustainably improve the performance, efficiency, and reliability of power transformers. The proposed model can be implemented as part of an asset management and preventive maintenance strategy in electric power systems.

Keywords: Load Unbalance; Optimization; Transformer Efficiency; Power Losses; Power System Reliability.

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1. INTRODUCTION.

Power transformers are the primary equipment in an electric power system, transforming voltage levels to ensure the continuity and quality of electrical energy distribution. Transformer reliability significantly determines system stability, particularly in substations that connect the transmission and distribution systems. In the electricity system managed by PT PLN (Persero), power transformers play a strategic role in maintaining voltage quality, power distribution efficiency, and continuity of service to customers. Three-phase load imbalance is a common problem in electric power distribution systems. This condition occurs due to uneven load distribution across each phase, resulting in significant current differences between phases. According to (Stevenson 1994), an unbalanced three-phase system will generate neutral currents and increase power losses in conductors and transformers. Furthermore, (Gonen 2014) states that load imbalance can cause increased copper losses proportional to the square of the current, thus directly impacting the efficiency of the distribution system.

The impact of load imbalance is not only limited to increased power losses, but also affects the thermal aspects of the transformer. The IEEE C57.91 standard explains that increasing transformer winding temperatures can significantly accelerate the insulation aging process and reduce the transformer's service life (IEEE, 2011). This is in line with the International Electrotechnical Commission standard IEC 60076 which emphasizes the importance of controlling operating temperatures to maintain the reliability of power transformers (IEC, 2018). Theoretically, load imbalance analysis can be performed using the symmetrical components method introduced by Fortescue, where the unbalanced system is represented by positive, negative, and zero sequence components (Grainger & Stevenson, 1994). This approach allows for a quantitative evaluation of the level of imbalance and its impact on power system performance.

Several previous studies have shown that systematic interphase load redistribution can reduce power losses and increase transformer efficiency (Short, 2014). However, most of these studies are still evaluative and have not integrated a mathematical optimization approach based on actual operational data. Therefore, this study proposes a three-phase load balancing optimization model through current redistribution simulation to minimize deviations from the average current, thereby achieving measurable increases in the efficiency and reliability of power transformers. Based on this description, this study aims to: (1) analyze the level of three-phase load imbalance in power transformers, (2) evaluate its impact on power losses and efficiency, and (3) formulate a load balancing optimization model to continuously improve transformer performance and reliability.

2. LETERATURE REVIEW.

2.1. Substation

Substations are a crucial component of the electrical power system, serving as the central control center for the flow of electrical energy from the transmission system to the distribution system. Substations also play a role in voltage transformation, load regulation, and power system protection, ensuring safe and reliable distribution. Within the national electricity system managed by PT PLN (Persero), substations play a strategic role in maintaining the continuity of electricity supply to industrial, commercial, and residential customers. According to standards set by the International Electrotechnical Commission, a substation is an electrical installation consisting of primary equipment such as power transformers, circuit breakers, disconnect switches, protection systems, and measuring equipment, all of which function to regulate and control the flow of electrical power within the power system (IEC, 2018). Substations also serve as system safety points to protect the network from disturbances such as short circuits, overloads, and voltage fluctuations.

In general, substations have several main functions, namely as a voltage transformation center, a power distribution control center, and a power system protection center. (Grainger & Stevenson 1994) explain that substations enable electrical energy transmitted at high voltage to be reduced to medium or low voltage so that it can be distributed efficiently to consumers. Furthermore, the presence of substations also allows for the regulation of electrical power flow so that the power system can operate stably and efficiently. Based on their function, substations can be classified into several types, including step-up substations, step-down substations, distribution substations, and switching substations. Step-down substations are generally used to reduce the voltage from the transmission system to distribution voltage before being distributed to customers. According to (Gonen 2014), distribution substations play an important role in maintaining voltage quality and balancing the load on the distribution network so that the system can operate optimally.

In operation, substations are equipped with various main equipment such as power transformers, circuit breakers, isolators, relay protection systems, and measurement and control equipment. Power transformers are the main components that function to change voltage levels, while circuit breakers function to interrupt the flow of current when a disturbance occurs in the system. In addition, relay protection systems are used to detect disturbances quickly so that damage to equipment can be minimized (Chapman, 2012). Substation reliability is significantly influenced by the load conditions on power transformers. Load imbalances in the distribution system can lead to increased power losses, increased transformer temperatures, and decreased power system efficiency. Therefore, load management and monitoring the operational conditions of transformers in substations are crucial for maintaining overall power system performance. Thus, substations not only serve as connecting points between transmission and distribution systems but also as control centers for electric power system operations. Proper substation management will improve the efficiency of electrical energy distribution and maintain long-term power system reliability.

2.2 Power Transformer

Power transformers are the primary equipment in an electric power system, converting the voltage from one level to another without changing the frequency. In substations, power transformers are used to step down the high voltage from the transmission system to a medium or low voltage suitable for the distribution system and consumer loads. At the Tanjung Morawa Substation, power transformers operate continuously to serve varying load requirements over time. Therefore, transformers must operate with a high level of reliability and efficiency. One of the problems that often occurs in power transformers is interphase load imbalance, which can cause increased power losses, the emergence of neutral currents, overheating, and reduced transformer insulation life. Power transformers generally operate in three-phase systems with certain winding connection configurations, such as Y–Y, Δ–Δ, or Δ–Y, according to system requirements. Current imbalance in each phase indicates uneven load distribution, so that the transformer's performance is not at optimal conditions.

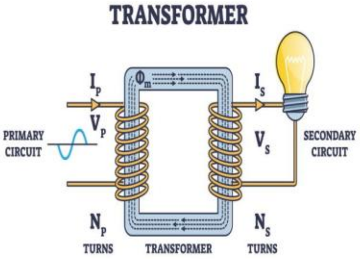

Figure 1. Transformer Circuit

The working principle of a transformer is based on the law of electromagnetic induction (Faraday's Law), namely that changes in magnetic flux in the transformer core will induce an electromotive force (EMF) in the coil. When an alternating voltage is applied to the primary coil, an alternating current will flow and produce a changing magnetic flux in the iron core. This magnetic flux then connects the secondary coil, thus creating an induced EMF on the secondary side. The relationship between the primary voltage and the secondary voltage is directly proportional to the ratio of the number of turns in each coil, so that the transformer can be used to increase or decrease the voltage according to the needs of the electric power system. In addition, under ideal conditions, the electrical power entering the primary side will be the same as the power leaving the secondary side, ignoring the losses that occur in the transformer. Under real-world operating conditions, transformers experience various losses, including core losses (hysteresis and eddy currents) and copper losses due to winding resistance. In a three-phase system, if the load on each phase is unbalanced, the current flowing in each phase will also be unequal. This imbalance causes neutral currents and increases power losses and heating in the transformer, which can reduce efficiency and shorten the life of the transformer's insulation. Therefore, understanding the working principles of transformers based on the law of electromagnetic induction is an important basis for analyzing the effect of load imbalance on the performance of power transformers in substations.

2.3. Load Imbalance

Load unbalance is a condition where the loading on a three-phase system is uneven, so that the current or power in each phase (R, S, and T) is not the same. In an ideal balanced three-phase system, the current in all three phases is the same and the phase angle is 120° apart. However, in distribution systems in the field, a balanced condition is difficult to achieve due to variations in load types, the dominance of single-phase loads, and changes in electrical energy consumption that are not the same in each phase. Load unbalance generally occurs on the distribution side, especially in medium voltage (20 kV) and low voltage (380/220 V) networks. Many household customers, MSMEs, and some commercial loads use single-phase supplies, so the distribution of customers to the R, S, and T phases greatly affects load balance. If the placement of single-phase customers is more dominant in one phase, the current in that phase will increase compared to the other phases, thus causing an imbalance. **Some** causes of load imbalance include:

1) Uneven distribution of single-phase customers.
2) Changes in load usage patterns at certain hours.
3) Addition of new loads without phase equalization.

4) Disturbances or abnormal conditions in one of the phases.
5) Mismatch between connections and network conditions.
The three-phase average current is calculated using the equation:

$$I_{\mathrm{avg}} = \frac{\mathrm{IR} + \mathrm{IS} + \mathrm{IT}}{3}$$

PThe percentage of load imbalance is calculated using the formula:

$$\%\mathrm{Keseimbangan} = \frac{|I_{\mathrm{MAX}} - I_{\mathrm{avg}}|}{I_{\mathrm{avg}}} x100\%$$

2.4. Power Losses and Efficiency in Transformers

Power losses in transformers consist of two main components, namely core losses and copper losses. Core losses occur due to hysteresis and eddy current phenomena in the iron core of the transformer, while copper losses occur due to the resistance in the transformer coils through which the electric current passes (Chapman, 2012).
Copper loss can be calculated using the equation:

$Pcu=I^2R$
Where:
Pcu = copper loss
I = current flowing in the coil.
R = coil resistance

Under load imbalance conditions, the current value in one phase can increase significantly, causing increased copper losses and reducing transformer efficiency. Transformer efficiency is the ratio of output power to input power. Mathematically, transformer efficiency is expressed as:

$$\eta = \frac{Pout}{Pin} \text{ x } 100\%$$

Where:
η = transformer efficiency.
Pout= output power.
Pin = input power

According to (Stevenson 1994), transformer efficiency is greatly influenced by loading conditions. Load imbalance can increase power losses, thereby reducing the overall transformer efficiency.

2.5. The Effect of Load Unbalance on Transformer Reliability

Load imbalance can cause an increase in the operating temperature of a transformer. High temperatures accelerate the thermal aging process of transformer insulation materials. According to the International Electrotechnical Commission standard IEC 60076, excessive winding temperature increases can accelerate insulation degradation and reduce the transformer's service life (IEC, 2018). Furthermore, the IEEE C57.91 standard explains that a temperature increase of 6–8°C can accelerate the rate of insulation aging by up to twofold (IEEE, 2011). Therefore, controlling load distribution is a crucial step in maintaining long-term transformer reliability. Load balancing optimization is a method for distributing electrical loads evenly across each phase to minimize current deviation and reduce power losses. According to Short (2014), load balancing can be done by redistributing load connections on the distribution network or using a mathematical simulation approach to determine the optimal load configuration.
This optimization approach aims to:

1. Reduce the current difference between phases.
2. Reduce power losses in transformers.
3. Improve the efficiency of the distribution system.
4. Extend the operating life of the transformer.

By implementing operational data-based optimization methods, the power distribution system can operate more efficiently and reliably.

3. METHOD

This research uses a quantitative approach with a technical analysis method based on power transformer operational data. The purpose of the research is to analyze the level of three-phase load imbalance and optimize load balancing to improve the efficiency and reliability of power transformers at the Tanjung Morawa Substation operated by PT PLN (Persero). The research method is carried out through several stages including data collection, data processing, load imbalance analysis, and load balancing optimization simulation. This research uses a descriptive quantitative method with an electric power system analysis approach. This approach is used to identify transformer loading conditions based on current data on each phase and evaluate the impact of unbalance on power losses and transformer efficiency. The analysis method used refers to transformer evaluation standards issued by the IEEE and the International Electrotechnical Commission regarding power transformer performance. The research was conducted at the Tanjung Morawa Substation in North Sumatra. This substation is a crucial component of the power distribution system, channeling electrical energy from the transmission grid to the distribution grid. Data collection was conducted through field observations and the collection of transformer operational data over a specific observation period.

The data used in this study consists of two types, namely primary data and secondary data.

1. Primary data, obtained through direct measurements at the substation, includes:

- Current in each phase (R, S, and T)
- Three-phase system voltage
- Power transformer capacity
- Load connected to the transformer

2. Secondary data, obtained from operational reports and technical documentation of the substation, which includes:

- Transformer technical specifications
- Transformer loading data
- Distribution system operating data

Data collection techniques in this study were carried out using the following methods:

1. **Field observation.**

Observations were carried out to determine the operational conditions of the power transformer and distribution system at the Tanjung Morawa Main Substation.

2. **Documentation**

   Documentation is carried out by collecting transformer technical data and operational records available on the substation monitoring system.

3. **Literature study.**

Literature studies were conducted by studying references from books, scientific journals, and technical standards related to transformers and electric power distribution systems.

Data analysis in this study was carried out through several stages as follows:

1. Calculation of Three-Phase Average Current

The average current is calculated using the equation:

$$Iavg= \frac{Ir+Is+IT}{3}$$

Where:

IR= phase current R

IS= phase current S

IT = phase current T

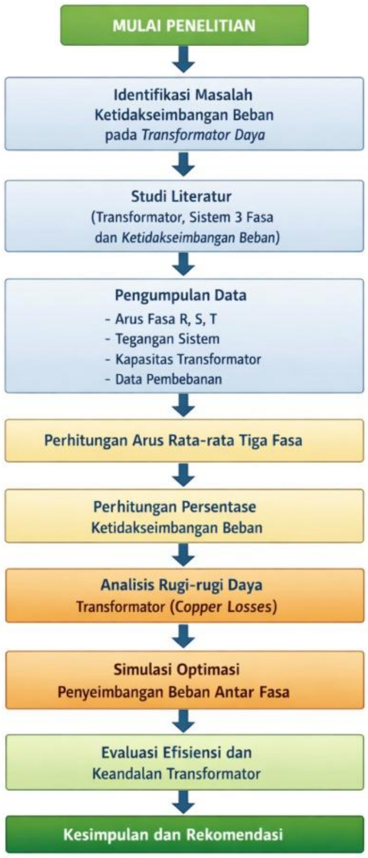

Figure 2. Research Flow

The percentage of load imbalance is calculated using the formula:

$$\%Imbalance = \frac{Imax-Iavg}{Iavg} \text{ x } 100\% \ \frac{Imax-Iavg}{}$$

Where:
Imax = the largest current of the three phases.
Iavg = three-phase average current.

Copper losses are calculated using the equation:
Pcu=I2R
Where:
Pcu = copper loss.
I = current in the coil.
R = transformer coil resistance
Transformer efficiency is calculated using the equation:

$$\eta = \frac{Pout}{Pin} \text{ x } 100\%$$

Where:
η = transformer efficiency.
Pout = output power.
Pin = input power

The optimization phase involves mathematically redistributing the load between phases to minimize the current difference relative to the average current. This process aims to achieve a more balanced loading condition, thereby minimizing power losses and increasing transformer efficiency.

In general, the research stages can be described as follows:

1. Identify load imbalance problems in transformers.
2. Collection of operational data of transformers at substations.
3. Calculation of the level of unbalance of three-phase loads.

4. Analysis of power losses and transformer efficiency.
5. Simulation of load balancing optimization between phases.
6. Evaluation of optimization results on transformer efficiency and reliability.
7. Drawing conclusions and recommendations for system improvements.

4. RESULT.

4.1. Three-Phase Transformer Loading Results.

The analysis was conducted based on operational data of power transformers at the Tanjung Morawa Substation operated by PT PLN (Persero). The data analyzed included the currents in each phase, namely the R phase, the S phase, and the T phase. The measurement results showed differences in current values in each phase, which indicated a load imbalance in the power transformer. The current measurement data on the power transformer at the Tanjung Morawa Substation are shown in the following table:

Table 1. Transformer loading conditions before load balancing optimization is carried out.

Phase	Current (A)
R	777
S	816
T	772

Based on this data, it can be seen that the currents in the three phases are not equal. The largest current is in phase S, while the smallest current is in phase T. This indicates a load imbalance in the three-phase system.

The three-phase average current is calculated using the equation:

$$I_{\text{avg}} = \frac{\text{IR} + \text{IS} + \text{IT}}{3}$$

$$I_{\text{avg}} = \frac{777 + 816 + 772}{3}$$

$$I_{\text{avg}} = \frac{2365}{3} = 788{,}33A$$

The largest current is in the S phase, so:

$$I_{\max} = 816A$$

The percentage of load imbalance is calculated using the formula:

$$\%\text{ketidakseimbangan} = \frac{[I_{\max} - I_{\text{avg}}]}{I_{\text{avg}}} x100\%$$

$$\%\text{ketidakseimbangan} = \frac{[861 - 788{,}33]}{788{,}33} x100\%$$

$$\%\text{ketidakseimbangan} = \frac{27{,}67}{788{,}33} x100\% = 3{,}51\%$$

4.2. Analysis of Calculation Results

Based on the calculation results, the load imbalance percentage value was obtained at 3.51%. This value indicates that the loading conditions of the power transformer at the Tanjung Morawa Substation are in a relatively balanced condition. The current difference between phases is still within acceptable limits, so it does not have a significant impact on transformer performance. However, the current difference between phases R, S, and T still needs to be considered so that the imbalance does not increase under certain operating conditions, such as during peak loads. The load imbalance that occurs in the power transformer at the Tanjung Morawa Substation is influenced by the load distribution in the distribution network connected to the transformer. Phase S has the largest current, which indicates that the load connected to that phase is more dominant than phases R and T.

Even though the load imbalance is relatively small, this condition still has the potential to cause neutral currents and increased copper losses if uneven load increases in the future. Therefore, regular load monitoring is essential to maintain optimal transformer performance.

4.3. Transformer Power Loss Analysis

Power losses in transformers are primarily influenced by copper losses, which are proportional to the square of the current flowing through the transformer coils. Based on the analysis, several measures that can be taken to maintain balanced load conditions include:

1. Conduct periodic monitoring of incoming transformer current via measuring panel or SCADA.
2. Perform load equalization between phases in the distribution network if an increase in current difference is found.
3. Using historical loading data as a basis for evaluating and planning transformer operations.

To reduce load imbalance, a simulation of load redistribution between phases was performed to more evenly distribute the current across each phase. After optimization, the transformer's power losses decreased because the current across each phase became more balanced. This resulted in a more even current distribution across the transformer coils, minimizing copper losses.

In addition, reducing power losses also has an impact on increasing transformer efficiency.

4.4. Discussion

The results of the study indicate that three-phase load imbalance can significantly impact the performance of power transformers. This imbalance causes increased power losses and increases the transformer temperature, which can accelerate insulation degradation. Through the load balancing optimization process, the current distribution between phases can be improved so that the current difference becomes smaller. This condition can reduce power losses and increase the overall efficiency of the transformer. The results of this study indicate that the load balancing strategy is an effective method for improving the efficiency of the electric power distribution system. Implementation of this method in substations can help improve the reliability of the power system and extend the operational life of power transformers. Based on the analysis results, several efforts that can be made to maintain balanced load conditions include:

- Monitor the incoming transformer current periodically via the measuring panel or SCADA.
- Equalize the load between phases in the distribution network if an increase in the current difference is found.
- Using historical loading data as a basis for evaluating and planning transformer operations.

CONCLUSION.

5.1. Conclusion

Based on the results of research and analysis of load imbalance on power transformers at the Tanjung Morawa Substation, several conclusions can be drawn as follows:

1. The incoming current measurement data from the transformer shows that there is a difference in current in each phase, namely the R phase is 777 A, the S phase is 816 A, and the T phase is 772 A.
2. The average three-phase current value is 788.33 A, with a load unbalance percentage of 3.51%.
3. Based on these values, the transformer loading conditions are still in the relatively balanced category and are below the general tolerance limit for current imbalance (< 5%).
4. Phase S is the phase with the largest load, so it has the potential for higher copper losses than other phases.
5. Although the imbalance is relatively mild, this condition still has the potential to cause neutral currents and local temperature increases if there is an uneven increase in load in the future.

Overall, the power transformers at the Tanjung Morawa Substation are still operating in a safe and stable condition, however, regular load monitoring is still required to maintain the reliability and technical lifespan of the equipment.

4.2. Suggestions

Based on the results of the research that has been carried out, several suggestions that can be given are as follows:

1. Conduct periodic monitoring of three-phase current and neutral current through a monitoring system or SCADA to detect early potential increases in load imbalance.
2. Conducting evaluation and equalization of inter-phase loads in the distribution network if there is a significant increase in current differences.
3. Using historical load data as a basis for planning the operation and development of electric power systems.

4. Further research is recommended to analyze load imbalance over longer time periods (daily, weekly, and peak loads), and examine its impact on temperature increase and transformer efficiency.

With continuous evaluation and control, it is hoped that the performance of power transformers can remain optimal and support the reliability of the electric power system as a whole.

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