Analysis of Loading and Phase Current Imbalance in Distribution Transformers at ULP Haurgeulis

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***Abstract*—The ever-increasing demand for electrical energy necessitates that power distribution systems operate optimally in terms of both reliability and efficiency. Within these systems, distribution transformers play a crucial role in delivering electricity to customers. However, in actual field conditions, inter-phase load imbalances are frequently encountered, which can negatively impact transformer performance and the quality of electricity delivery. This issue prompted a study to analyze transformer loading levels and phase current imbalances during daytime load conditions in the service area of PT PLN (Persero) ULP Haurgeulis. The research involved direct observation, field measurements, and the processing of current and voltage data from five distribution substations. The parameters analyzed included phase currents, neutral current, transformer loading percentage, load imbalance, and power losses. The analysis revealed that the highest loading level occurred at the HRKC substation (52.64%), while the highest load imbalance was observed at the HRKI substation (65.12%). The HRKE substation exhibited the highest neutral current (49 A) and the greatest power losses (1,642.39 W). These results indicate significant load imbalances across several distribution substations; consequently, measures to balance inter-phase loads and implement periodic monitoring are required to enhance the efficiency and reliability of the power distribution system.**

Keywords*— *Distribution transformer, Neutral current, Loading, Unbalance

I. INTRODUCTION

With the rising demand for electrical energy across various sectors, electric power distribution systems are required to operate reliably, efficiently, and sustainably [1],[2]. Distribution transformers are key components of the distribution system, serving to deliver electrical energy from the medium-voltage network to the low-voltage level for end-user consumption [3]. Optimal transformer performance is significantly influenced by loading conditions and the level of current balance across the phases [4],[5].

In a three-phase electric power system, the ideal condition is balanced loading across each phase [6]. However, in actual field conditions, load imbalance frequently occurs due to uneven customer distribution, variations in load types, and changes in electricity consumption patterns [7]. This imbalance results in unequal currents across the phases and generates a neutral current which, under balanced conditions, should be close to zero [8],[9]. The resulting impacts include increased power losses, reduced transformer efficiency, and the potential for equipment overheating [10],[11].

Load imbalance conditions tend to be more apparent during specific times—such as the daytime load period—when activities across residential, small business, and office sectors occur simultaneously [12],[13]. The active energy consumption patterns during this period result in uneven load distribution across phases, necessitating a more comprehensive analysis to determine the actual state of the distribution system [14].

Transformer loads are not constant; rather, they fluctuate over time in accordance with customers' electricity usage patterns. Daytime load patterns, for instance, tend to differ from those at other times, making this a key factor to consider when evaluating load imbalance in distribution transformers [15]. Increased customer activity during the day typically drives up electricity consumption. This situation often results in uneven loading across phases, which in turn affects the current levels in each phase as well as the current flowing through the transformer's neutral wire [16].

When such load imbalances occur, the neutral current tends to rise, leading to increased power losses. Consequently, the degree of load imbalance during daytime hours requires further analysis to gain a clearer understanding of the transformer's actual loading conditions [17]. Furthermore, the magnitude of load imbalance is closely linked to increased power losses and reduced transformer operating efficiency. In other words, load imbalance affects not only current distribution but also determines the transformer's overall performance [18].

Beyond power losses, load imbalance can also cause the transformer's operating temperature to rise. If this persists over an extended period, there is concern that the elevated temperature could compromise the transformer's reliability and shorten its service life [19],[20].

Based on these issues, this study was conducted to analyze transformer loading levels and phase current imbalances during daytime load conditions within the service area of PT PLN (Persero) ULP Haurgeulis. The analysis utilized current and voltage measurement data obtained from distribution substations. The parameters examined included phase currents, neutral current, and the percentage of transformer loading. The findings are expected to provide an overview of the actual state of the distribution system and serve as a basis for efforts to improve the efficiency and reliability of electrical energy distribution.

II. MATERIALS AND METHODS

This study was conducted to evaluate transformer loading levels and current imbalances within the three-phase electric power distribution system managed by PT PLN (Persero) ULP Haurgeulis. Data collection focused on daytime load conditions, representing a period of relatively

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high electricity consumption driven by customer activity. The study aimed to assess the actual state of the distribution system—specifically regarding transformer loading and inter-phase current distribution—and to identify the resulting impacts on network performance. The research involved direct observation and field measurements at several distribution substations, gathering data on phase currents, neutral current, and system voltage. This data was subsequently processed and analyzed to determine load balance levels and transformer operating conditions. The analysis results are expected to provide relevant information to support efforts to enhance the efficiency and reliability of the electric power distribution system.

A. *Research Location and Subject*

This study was conducted within the service area of PT PLN (Persero) Customer Service Unit (ULP) Haurgeulis, Indramayu Regency, West Java. The subject of the study was a three-phase distribution transformer at a distribution substation, observed under daytime load conditions. The selection of the research subject was based on indications of phase load imbalance, which has the potential to generate neutral current, increase power losses, and affect transformer performance.

B. *Data Collection Techniques*

The data collection methods used in this study include:

1. Observation

Direct observations were conducted on the operational conditions of the distribution substations and transformers serving as the research subjects. These observations aimed to assess the physical and operational state of the substations and to identify the parameters required for data collection. The research subjects comprised five distribution substations: HRKI, HRKF, HRKE, HRKG, and HRKC.

2. Measurement

Measurements were conducted directly in the field under daytime load conditions using a clamp meter. Readings were taken at each distribution substation by measuring the current in each phase—R, S, and T—as well as the current in the neutral conductor. The phase current data were used to determine the average current and to analyze the transformer's loading level and load imbalance. Meanwhile, the neutral current data served to quantify the current resulting from inter-phase load imbalance. In addition to current readings, voltage and transformer capacity data were utilized as supporting information for calculating transformer loading. All measurement results were recorded for each distribution substation for subsequent processing and analysis.

3. Literature Review

A literature review was conducted by examining various scholarly sources regarding distribution transformers, three-phase electric power systems, transformer loading, load imbalance, neutral current, and power losses. This review served as the basis for determining research parameters and calculation methods, as well as a reference for analyzing and discussing the measurement results obtained in the field.

C. *Research Parameters*

The parameters analyzed in this study encompass several key aspects related to the operational conditions of distribution transformers. Observations were conducted on the current in each phase—specifically phases R, S, and T—to determine the load distribution within the three-phase system. These current values were then used to calculate the average current, serving as a benchmark for assessing the level of load balance. Additionally, the transformer loading percentage was calculated to determine the extent of capacity utilization during operation. The degree of load imbalance was also analyzed by comparing inter-phase currents against the average value. Neutral current was monitored as an indicator of system imbalance. Finally, all these parameters were used to evaluate transformer performance under actual operating conditions within the electric power distribution network.

D. *Data Analysis Method*

1. Average Current Analysis

The average current is used as a reference to evaluate the current balance condition between phases [4].

$$I_{avg} = \frac{I_R + I_S + I_T}{3} \quad (1)$$

2. Transformer Loading Analysis

The magnitude of the load's apparent power is calculated to determine the transformer's loading level. This analysis is used to determine the transformer's capacity utilization rate [4].

$$S = \sqrt{3}.V.I_{avg} \quad (2)$$

The loading percentage is calculated using the equation:

$$\%Load = \frac{S_{load}}{S_{transformer}} x100\% \quad (3)$$

3. Load Imbalance Analysis

The degree of unbalance is determined based on the largest current deviation from the average current. This analysis is used to evaluate the extent of deviation from a balanced condition [4].

$$\%Imbalance = \frac{Deviasi_{max}}{I_{avg}} x100\% \quad (4)$$

4. Neutral Current Analysis

Neutral current is analyzed as an indicator of the impact of load imbalance on the distribution system [14].

5. Analysis of Power Losses Due to Neutral Current

Power losses in the neutral conductor are analyzed using the equation [14].

$$P_N = I_N^2.R_N \quad (5)$$

This analysis is used to evaluate the impact of neutral current on potential power losses in the distribution system.

6. Transformer Performance Evaluation

This study evaluates transformer performance by examining the interrelationships among key parameters: loading level, load imbalance, and the neutral current present in the system. The loading level reflects the utilization of the transformer's capacity during operation, while load imbalance indicates the current distribution across the phases. The presence of neutral current serves as an indicator of imbalance that can affect the transformer's operating conditions. These three aspects are analyzed collectively to understand their impact on operational efficiency, including potential increases in power losses and equipment performance degradation. The evaluation aims to provide a realistic picture of the transformer's operational status and serve as a basis for determining necessary improvement measures.

E. Research Stages

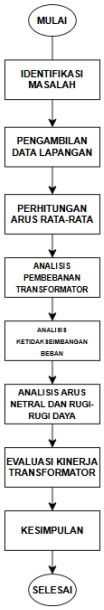


Fig. 1. Diagram Block diagram of research stages

Fig. 1 illustrates the research stages, ranging from problem identification, data collection, and the analysis of loading parameters and load imbalance, to transformer performance evaluation and the drawing of conclusions. Each stage is carried out sequentially to obtain analysis results regarding loading and phase current imbalance in distribution transformers.

1. Problem Identification
The problem identification stage is conducted to determine the specific issues serving as the research focus: transformer loading conditions and inter-phase current imbalance at the distribution substation. This identification is based on the characteristics of the distribution system under study, enabling the determination of parameters requiring measurement and analysis specifically phase currents, neutral current, voltage, transformer capacity, loading percentage, and load imbalance.

2. Field Data Collection
Field data collection was conducted directly at the five distribution substations serving as the research subjects HRKI, HRKF, HRKE, HRKG, and HRKC—under daytime load conditions. Data were obtained by measuring the current in each phase (R, S, and T) and the current in the neutral conductor using a clamp meter. Additionally, voltage and transformer capacity data were recorded to support the loading analysis. All measurement results were logged for each substation to be used subsequently in the data processing and analysis stages.

3. Average Current Calculation
Current data for phases R, S, and T, obtained from measurements, is used to calculate the average current for each distribution substation. This average current calculation serves as the basis for determining transformer loading conditions and acts as a parameter for load unbalance analysis. The calculation results are then utilized in the subsequent stage of analysis.

4. Transformer Loading Analysis
Transformer loading analysis is conducted using average current values and transformer capacities to determine the apparent power and loading percentage for each substation. The analysis results are used to assess the loading level of each transformer and compare it with the transformer's nominal capacity.

5. Load Imbalance Analysis
Load unbalance analysis is conducted based on the deviation of current values in phases R, S, and T from the average current value. The magnitude of the unbalance is calculated for each distribution substation to identify the substation with the highest level of load unbalance. The results of this analysis are used to illustrate the inter-phase load distribution conditions for each transformer.

6. Neutral Current and Power Loss Analysis
An analysis of neutral current was conducted using measured current data from the neutral conductor to determine the magnitude of the current resulting from inter-phase load imbalance. Subsequently, this data was used to calculate power losses in accordance with established equations. The analysis results were used to assess the neutral current conditions and the magnitude of power losses at each distribution substation.

7. Transformer Performance Evaluation
Transformer performance evaluation is conducted by comparing the results of analyses regarding loading, load imbalance, neutral current, and power losses at each distribution substation. The evaluation aims to assess the operational condition of the transformers based on the analyzed parameters and to identify substations that require closer attention regarding their loading conditions.

8. Conclusion

The final stage is drawing up conclusions based on the data processing and analysis. The conclusions contain the main research findings regarding transformer loading levels, interphase current imbalance, neutral current, and power losses at each distribution substation, and provide an overview of the transformer's performance based on the analyzed parameters.

III. Results and Discussion

In its first stage, this study analyzes transformer loading conditions within the electric power distribution system of the study area. The discussion focuses on evaluating transformer loading levels based on current data obtained from field measurements. This analysis aims to determine the extent to which transformer capacity is utilized during operation, particularly during the daytime load period.

Next, the discussion focuses on analyzing the phase-to-phase load imbalance occurring in a three-phase system. This imbalance is examined by comparing the current in each phase against the average value, thereby determining the extent of the load deviation. Additionally, the neutral current is analyzed as an indicator of imbalance within the distribution system.

In the final stage, transformer performance is evaluated by correlating the results of the analysis regarding loading, load imbalance, and neutral current. This evaluation aims to understand the impact of these conditions on operational efficiency and the potential for increased power losses. The findings are expected to provide an overview of the distribution system's actual condition and serve as a basis for determining necessary improvement measures.

A. *Current Measurement Results for Each Phase*

Based on measurement results from five distribution substations, data on phase currents and neutral current were obtained, as shown in Table 1.

TABLE I. Current Measurement Results for Each Phase

Substation	***Transformer Capacity***	***IR (A)***	***IS (A)***	***IT (A)***	***IN (A)***
HRKI	50 kVA	15	5	23	7
HRKF	100 kVA	12	8	14	8
HRKE	160 kVA	128	129	44	49
HRKG	50 kVA	10	15	12	7
HRKC	100 kVA	35	41	38	6

Table I reveals variations in inter-phase loading across several distribution substations. The most significant current imbalances occur at the HRKE and HRKI substations, evidenced by substantial differences in current between phases. This condition indicates uneven load distribution and the potential for neutral current generation.

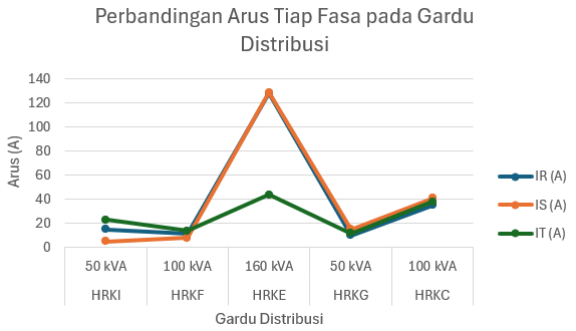


Fig. 2. Graph comparing the current of each phase at the distribution substation

Fig. 2, reveals inter-phase current differences at several distribution substations, particularly at HRKE and HRKI. The most significant imbalance is observed at the HRKE substation, where the current in phase T is lower than in the other two phases. This condition indicates that the load distribution across phases is uneven signifying a load imbalance—which has the potential to generate neutral current and increase power losses in the transformer.

B. *Transformer Loading Analysis*

The loading analysis was conducted by calculating the average current value using equation (1) and then determining the apparent power at each substation. Subsequently, the loading percentage for each substation was calculated using equation (3). The results of the loading percentage for each substation are presented in Table II.

TABLE II. Loading Calculation Results

Substation	***Iavg (A)***	***% Beban***
HRKI	14.33	19.86
HRKF	11.33	7.85
HRKE	100.33	43.44
HRKG	12.33	17.08
HRKC	38.00	52.64

Based on the calculation results, substation HRKE has the highest loading level at 52.64%, while substation HRKF has the lowest at 7.85%. Although all transformers are operating below their nominal capacity, the difference in loading levels indicates a variation in transformer capacity utilization.

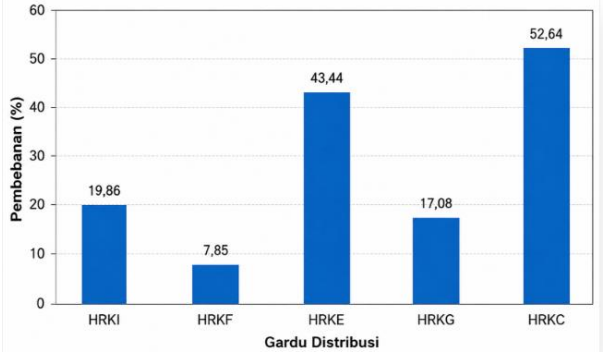


Fig. 3. Graph of tranformer loading percentage

Fig. 3 shows that substation HRKC has the highest loading level, while HRKF has the lowest. All transformers remain below their nominal capacity; the variation in loading also indicates differences in the transformer capacity utilization levels across the substations.

C. Load Imbalance Analysis

The load unbalance analysis is derived from calculations using Equation (4); this involves first calculating the average current using Equation (1) and subsequently determining the maximum deviation value for each phase. The results of the load unbalance calculations are presented in Table III.

TABLE III. LOAD UNBALANCE CALCULATION RESULTS

Substation	*Imbalance (%)*
HRKI	65.12
HRKF	29.41
HRKE	56.15
HRKG	21.62
HRKC	7.89

Based on the calculation results, the greatest imbalance occurs at the HRKI substation (65.12%), followed by the HRKE substation (56.15%). This condition indicates a significant current deviation from a balanced state, potentially leading to increased neutral current and power losses.

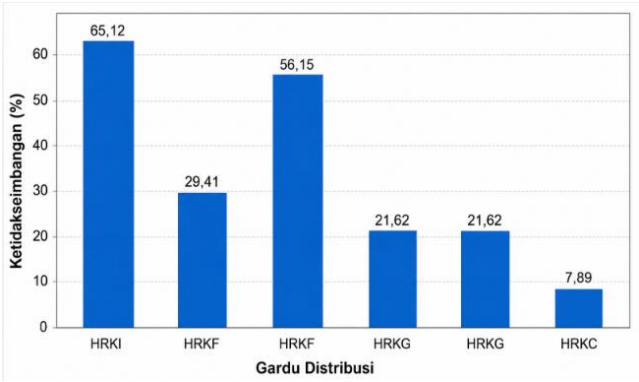


Fig. 4. Load imbalance percentage graph

Fig. 4 shows that the highest levels of imbalance occur at the HRKI and HRKE substations. This condition is characterized by a significant current deviation from the balanced state, which can affect transformer operating efficiency and increase the neutral current.

D. Neutral Current and Power Loss Analysis

The analysis of neutral current and power losses is derived from the measured neutral current (IN) values in Table I and power loss calculations using equation (5). Based on a conductor resistance of 0.6842 ohms, the calculated power losses are presented in Table IV.

TABLE IV. NEUTRAL CURRENT AND POWER LOSS RESULTS

Substation	*Neutral Current (A)*	*Power Losses (W)*
HRKI	7	33,53
HRKF	8	43,79
HRKE	49	1642,39
HRKG	7	33,53
HRKC	6	24,63

Based on the calculation results, the HRKE substation exhibits the highest potential for power losses compared to the other substations, amounting to 1,642.39 W. This indicates that load imbalance contributes to increased losses and potentially reduces the transformer's operating efficiency.

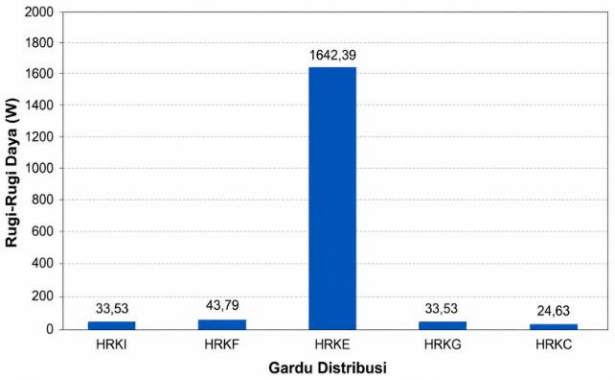


Fig 5. Power loss percentage graph

Fig. 5 shows that the highest level of power loss occurs at the HRKE substation. The highpower loss at the HRKE substation is due to the substation's highest neutral current value. Transformer Performance.

E. Transformer Pefromance Evaluation

Based on an analysis of loading, load imbalance, neutral current, and potential power losses, the HRKE substation was found to be in the most critical operating condition compared to the other substations. This is evidenced by a combination of the highest loading, significant imbalance, and the highest neutral current. Consequently, periodic inter-phase load balancing is required to enhance the operational efficiency and reliability of the distribution transformer.

IV. CONCLUSION

Based on the research results and analysis, it can be concluded that the transformer loading at the observed distribution substations remains below maximum capacity—with the highest load recorded at the HRKC substation at approximately 52%—thereby classifying the units as underloaded. However, significant inter-phase load imbalance was detected, particularly at the HRKI substation, where the imbalance reached approximately 65%. This imbalance generates neutral current within the system, resulting in power losses along the neutral conductor. The highest power loss occurred at the HRKE substation—approximately 1,642 W—correlating with the magnitude of the flowing neutral current. These findings demonstrate that

load imbalance directly influences the increase in neutral current and the amount of energy lost within the system. Therefore, measures to balance inter-phase loads and implement periodic monitoring are necessary to ensure optimal transformer performance and maintain the efficiency of the distribution system.

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