Analysis of Power Losses Due to Load Imbalance and Loss Calculation in Distribution Transformers: Merauke City Customer Service Unit

Original Article

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Abstract

This study analyzes power losses due to load imbalance and the calculation of losses in distribution transformers at the Merauke City Customer Service Unit (ULP). The results show that most distribution transformers on the Angkasa, Bampel, Parako, Kompi, and Ermasu feeders experienced load imbalances exceeding the 20% tolerance limit according to SPLN D3.002-1:2014 standards, contributing to increased neutral currents and power losses, particularly in transformers with heavy loads and uneven phase distribution. After phase current balancing using ETAB 19, significant reductions in neutral current and losses were observed, with transformer efficiency increasing by an average of 2-5% per unit. A feeder-based, data-driven balancing strategy, involving the redistribution of load from dominant phases to deficit phases along with regular monitoring, proved effective in improving distribution system efficiency, extending transformer lifespan, and enhancing voltage quality for customers. These findings provide an operational basis for PLN ULP Merauke to prioritize distribution network improvements, maintain a minimum bus voltage profile of 93–95%, and reduce operational costs through regular load balancing.

Keywords: Distribution Transformer, Load Imbalance, Network Efficiency, Phase Balancing, Power Losses.

1. Introduction

To meet the growing demand for electrical energy, PT Perusahaan Listrik Negara/PLN (State Electricity Company), as the primary electricity provider in Indonesia, strives to maintain reliability, continuity, and affordability. Load distribution imbalances frequently occur among phases. This issue is largely attributed to the connection pattern of single-phase customer service lines, where new customer installations often disregard the existing phase-loading conditions at the distribution transformer (Pranoto et al., 2020). Initially, the load distribution was balanced (Afrianda et al., 2021). However, changes in energy demand over time have led to load imbalances in 20 kV/380 V distribution transformers, causing unequal phase loading and resulting in increased distribution losses.

Load and current imbalance among phases (R, S, and T) causes neutral current to flow through the distribution transformer, resulting in additional losses for the electricity provider (Aisah et al., 2020). This condition generates real power losses within the distribution network. It may also limit the loading capacity of distribution transformers, keeping it well below their rated capacity. As electrical distribution systems continue to grow in size and complexity, reducing these losses can lead to significant savings for electricity providers.

Previous research has frequently highlighted load imbalance as a significant contributor to increased neutral currents and power losses in distribution transformers (Patilima, 2022), often leading to reduced efficiency and economic setbacks for utility providers. For instance, technical losses, including those from unbalanced loads, significantly impact system efficiency, with lower percentages of losses indicating a more efficient power system (Maulana et al., 2021). The economic consequences of these losses can be substantial, as evidenced by studies quantifying the monetary impact of imbalance, no-load, and on-load losses over extended periods (Liliana et al., 2024).

Earlier work predominantly addresses the aggregate performance of electrical networks in established urban areas, thus less highlighting temporal and spatial load patterns in developing regions with infrastructure under strain. This study fills that gap by analyzing power losses due to load imbalance in distribution transformers in Merauke City. This approach links consumer behavior and load growth in developing regions with specific transformer loss calculations, providing practical insights for network planning and more efficient asset management.

PT PLN (Persero) Customer Service and Network Unit (UP3) Merauke, through Procurement Service Unit (ULP) Merauke City, operates eight feeders as of 2023. This study uses transformer load measurement data from UP3 Merauke to analyze whether power losses occur in the 20 kV network system and evaluate whether distribution transformers operate within the allowable load imbalance limits. The results of this analysis will become the basis for assessing transformer conditions from the load capacity side and power losses in the neutral conductor due to load imbalance.

To ensure that this research achieves its intended objectives, it is necessary to establish clear boundaries so that the calculations and analyses remain within the defined scope of the problem. In this context, the study is limited to the use of measurement data obtained directly from PLN personnel and sourced from PLN UP3 Merauke. The power loss analysis is focused solely on the neutral conductor, and therefore does not include losses within the internal components of the distribution transformers. In addition, all simulation and analytical procedures are carried out using the ETAP software as the primary analytical tool.

This study specifically aims to calculate the degree of load imbalance in the distribution transformers at ULP Merauke City during peak load hours (WBP). Furthermore, it aims to determine the power losses that occur in these transformers under peak load conditions. The findings of this research are expected to provide meaningful contributions to PLN UP3 Merauke as a reference for understanding load imbalance conditions in the distribution transformers at ULP Merauke City. These results may serve as a foundation for planning and implementing future distribution network maintenance activities. Moreover, the study is expected to serve as a reference for electrical engineering students conducting similar research, as well as for further studies focusing on reducing losses and mitigating load imbalance in distribution transformers within the region.

2. Literature Review

2.1. Distribution Network

In general, a complete electric power system consists of four main components. First, a power generation unit, where the electrical energy is produced. The voltage generated by power plants is typically at the medium-voltage level. Second, a transmission system equipped with substations. Due to the long distances involved, high voltage (HV) and/or extra-high voltage (EHV) levels are required. Third, a distribution system, which usually consists of a

primary distribution network operating at medium voltage (MV) and a secondary distribution network operating at low voltage (LV). Fourth, the utilization or consumption component, which includes electrical installation systems. Household installations typically operate at low voltage, while large consumers such as industrial facilities use medium-voltage or even high-voltage supply. It is important to note that a system may consist of several interconnected subsystems, commonly referred to as an interconnected system. As is well known, the distribution system comprises two segments: primary distribution, which uses medium voltage, and secondary distribution, which uses low voltage (Lumbantobing, 2016).

2.2. Distribution Substation

A distribution substation is one of the key components of a distribution system, serving to connect the network to consumers and to supply or distribute electrical power to loads, whether medium-voltage or low-voltage consumers (Handoko, 2021). According to Ramadhani (2021), a distribution substation is generally understood as a facility that contains or consists of Medium-Voltage Switchgear (MV Switchgear), a Distribution Transformer (DT), and Low-Voltage Switchgear (LV Switchgear), all of which function to supply electrical power to customers operating at Medium Voltage (20 kV) or Low Voltage (220/380 V).

2.3. Transformer

A transformer is a simple, reliable, and efficient electromagnetic device used to convert alternating-current voltage from one level to another (Sianipar et al., 2025). In general, it consists of a laminated iron core and two windings: the primary winding and the secondary winding (Lumbantobing, 2016). The voltage transformation ratio depends on the ratio of the number of turns between the two windings. The windings are typically made of copper wire wound around the "legs" of the transformer core. In general, transformers can be classified into two types based on their construction: the core-type and the shell-type. In the core-type transformer, the core has two legs, each wound with one of the windings. In contrast, the shell-type transformer has three legs, with both windings placed on the central leg. These windings are not electrically connected but are magnetically coupled through the core. The flat portion of the core is referred to as the "yoke" (Lumbantobing, 2016).

2.4. Distribution Transformer

A distribution transformer is a component used to deliver electrical power from substations to load centers or consumers (Latupeirissa, 2017). In three-phase, four-wire distribution transformers, load imbalance frequently occurs. This imbalance is caused by differences in the load carried by each phase on the secondary side of the transformer-namely phase R, phase S, and phase T. Load imbalance among phases results in neutral current flowing through the transformer. The presence of neutral current can lead to power losses in the transformer (Setiadji et al., 2008).

2.5. Load Imbalance

Load imbalance refers to a condition in which the loads connected by customers or consumers on the secondary side of a transformer are not equal or balanced. When a load imbalance occurs in a three-phase system, the neutral conductor will carry current, and the phase angle differences will no longer be 120°. An unbalanced transformer load results in the appearance of neutral current (Siregar, 2013).

According to Setiadji et al. (2008), load imbalance in an electrical distribution system is a common occurrence, primarily caused by single-phase loads connected to the low-voltage distribution network. This imbalance leads to the flow of current in the transformer's neutral conductor. The presence of this neutral current contributes to power losses, including losses

due to current flowing through the transformer's neutral conductor and losses caused by neutral current that flows to ground.

2.6. Transformer Efficiency

In the industrial sector, transformers play a crucial role. They are used both as step-down devices to reduce voltage and as step-up devices to increase voltage. Transformers experience various types of losses, including copper losses caused by current flowing through the windings, and iron losses caused by alternating magnetic flux in the core, both of which reduce transformer efficiency. Transformer efficiency is defined as the ratio between output power and input power, and its value is influenced by the loading level. Efficiency is also affected by the internal losses present in the transformer (Pardamean, 2019).

2.7. Neutral Current

Neutral current in an electrical distribution system refers to the current flowing in the neutral conductor of a three-phase, four-wire low-voltage distribution network. This neutral current appears when certain conditions occur (Reza & Andi, 2021).

3. Methods

In conducting research, it is important to employ an appropriate method (Ilham et al., 2025; Patmasari, 2022; Patmasari et al., 2025). Research methods are scientific procedures used by researchers to collect data, analyze it, and draw conclusions to answer the research problems. Research methods also include the research approach, research design, data collection techniques, data analysis techniques, and research procedures (Sugiyono, 2019).

3.1. Type and Research Approach

To complete this research, a literature study approach was employed. This technique involves reviewing theories related to the research topic, obtained from various literature sources relevant to the study (Ilham, 2020; Ohoiwutun et al., 2024; Tebay & Ilham, 2023). The literature review also refers to the implementation of the transformer monitoring system application of PT PLN (Persero) Maluku and Papua regional edition 2, which stipulates that the maximum allowable load imbalance tolerance is 20%.

Furthermore, the analytical study uses two methods to analyze the measurement data, as follows: First, data analysis using Microsoft Excel to perform the initial calculations of technical data and load distribution of feeder distribution transformers. The data processed in Microsoft Excel will show the current values to be redistributed among phases to balance the load on each distribution transformer. However, Excel cannot present the overall results of load balancing specifically the technical impacts of the load balancing process. Therefore, simulation using the ETAP program is required. Second, simulation using ETAP allows only the entry of parameters that have been previously calculated and cannot provide recommendations on which current values should be adjusted. However, using ETAP 19 enables comprehensive visualization of results, from current to voltage, reflecting real field conditions. Consequently, we can analyze the technical impacts that arise after performing full load balancing.

3.2. Research Location and Time

The research location and data collection for this thesis are focused on the network system at ULP Merauke City (UP3 Merauke) of PT PLN (Persero). The research period, including data identification, data compilation, and the writing of this thesis, was carried out from June to October 2024.

3.3. Tools and Materials

The tools used in this research include writing instruments, a calculator, a laptop, a mobile phone, and a clamp meter. The research materials consist of secondary data, which include: technical data of distribution transformers on each feeder, load data of distribution transformers at ULP Merauke City, and transformer tagging position data for each feeder.

3.4. Research Flowchart

The entire research process was carried out starting from the literature review, data collection and processing, up to drawing conclusions. The analysis using ETAB is carried out through several systematic stages to ensure that the simulation results closely reflect actual field conditions. The process flow can be illustrated in the ETAB Analysis Stages Flow Chart (figure 1) below:
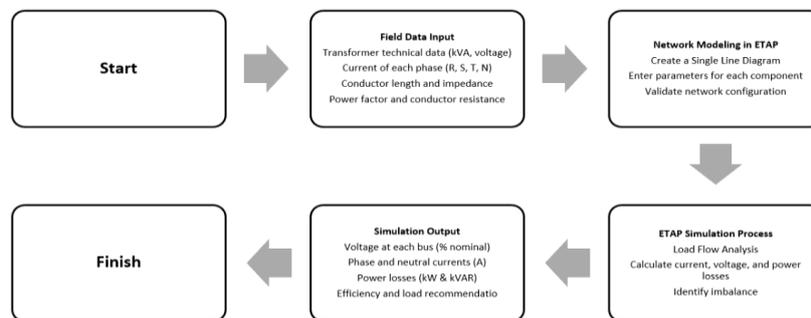

Figure 1. Flowchart of Analysis Stages Using ETAB

4. Results and Discussion

4.1. Angkasa

4.1.1. Load Analysis Before Balancing

Based on measurements and calculations in July 2024, transformer MRK262 recorded the maximum load of the Angkasa feeder with a peak current of 256 A, becoming the highest average load before balancing. Current measurements at various distribution substations show variations in current imbalance between substations, with some relatively balanced and others significant, as well as quite striking differences in average current, such as MRK262 which has a high average current of 213.67 A with imbalance still within reasonable limits, while MRK271 has an average current of only 14 A but its imbalance is greater. This condition indicates that current distribution between phases is not always even, which potentially affects power distribution efficiency and causes energy losses in the distribution network.

4.1.2. Power Losses Before Balancing

The data captures measurement points (MRK codes) with time-stamped readings of phase currents (R, S, T, N), power consumption (kW), and power losses. Load conditions vary widely, from low to high current values across the feeder. Power losses (0.68-10+ kW) result primarily from phase imbalance. Current imbalance between phases causes excessive neutral current, uneven voltage distribution, and significant power losses of up to 10 kW at several points.

4.1.3. Distribution Substation Load Balancing Plan

The data reveals significant load imbalances between phases R, S, and T at each measurement point. Recommendations in columns a, b, and c specify the necessary load shift positive values indicate where load should be increased, and negative values where it should

be decreased. For instance, at MRK018, phase T is overloaded and requires a reduction of 13 A. MRK033 shows a large disparity between phases S and T, requiring a 42 A correction on T. Imbalances vary widely by location: MRK262 has a major imbalance (e.g., +42.33 A on R, -24.67 A on S), while MRK137 is only slightly imbalanced, with corrections under 7 A.

Some points share identical patterns, like MRK043 and MRK048, where phase R needs +9.67 A and phase T needs -8.33 A. Others, such as MRK314, show substantial corrections (-15.67 A on R, +17.33 A on T). Overall, these variations underscore the need for precise load balancing to ensure system stability and prevent disruptions from current imbalance.

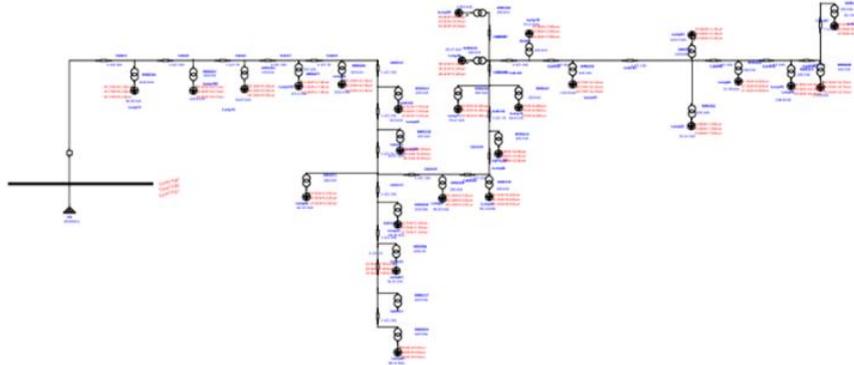### 4.1.4. Simulation Results After Load Balancing Using ETAB Software

Figure 2. Simulation Results After Load Balancing Using ETAB Software

The simulation in Figure 2 results of the distribution in the Angkasa area show power flow from the main feeder to several network branches, with bus voltage at each point averaging above 95% of the nominal voltage. Meanwhile, the displayed losses in kW and kVAR decrease compared to previous values at each conductor segment due to temporary neutral disconnection, with the magnitude of losses varying according to line length and the load served at each distribution point.

4.1.5. Power Losses After Substation Load Balancing Plan

The implementation of electrical load balancing on the Angkasa feeder successfully corrected significant phase imbalances and neutral currents, leading to a major reduction in system losses. Prior to balancing, substations exhibited highly uneven phase currents. For instance, MRK009 had readings of 10 A, 17 A, and 20 A across phases R, S, and T, with a neutral current of 18 A. A more severe case at MRK150 showed phases at 127 A, 195 A, and 172 A, with a neutral current reaching 89 A. This widespread imbalance resulted in cumulative power losses totaling 26.6 kW across the feeder.

After balancing, the results were markedly improved. All substations now show balanced phase currents, as seen at MRK009 where each phase carries 15.67 A. Consequently, the previously high neutral currents at every measurement point have been eliminated, dropping to 0 A. With the phases now evenly loaded, the neutral conductor no longer carries current. This correction directly caused a drastic decrease in power losses at each substation. The overall system efficiency has been enhanced, confirming that effective load balancing improves network stability and minimizes energy waste in the distribution system.

4.2. ERMASU

4.2.1. Load Analysis Before Balancing

Based on the data, measurements show current in three phases (R, S, T) and neutral (N) at various points of the Ermasu feeder, along with calculations of average current and load

imbalance factor. The recorded average current varies significantly, ranging from low loads such as MRK302 (11 A) to high loads such as MRK005 (191.67 A), reflecting differences in power usage according to demand patterns and energy distribution. Load imbalance is visible from the ratio of current in each phase to the average current; some points, such as MRK003 and MRK065, are relatively balanced, while other points, for example MRK228, show large imbalance with phase R much higher than phase S. This imbalance variation pattern is also seen in MRK200 and MRK300, where one phase dominates, potentially causing overload on that phase and underutilization on other phases. Conversely, points such as MRK223 and MRK232 show more proportional distribution, reflecting differences in load characteristics at each measurement location.

4.2.2. Power Losses Before Balancing

Several substations on the feeder show significant phase current imbalance, especially in large substations such as MRK005, MRK006, and MRK007, resulting in high neutral current and large power losses (9.14 kW, 6.92 kW, and 6.80 kW). This imbalance occurs because uneven phase current forces excess current to return through the neutral conductor, producing resistive heat and wasted energy. Although small substations experience low losses, accumulation in large substations reaches 71.5 kW. This data shows that phase imbalance is the main cause of inefficiency, so load balancing needs to be carried out to reduce energy losses and improve distribution reliability.

4.2.3. Substation Load Balancing Plan

Phase current imbalances are evident across multiple substations, leading to load distribution recommendations. For instance, MRK005 shows a significant disparity with currents of 265 A (R), 197 A (S), and 113 A (T), and a neutral current of 160 A. The calculated average here is 191.67 A, which results in a recommendation to shift loads: +73.33 A to phase R, +5.33 A to phase S, and -78.67 A from phase T.

Other points, like MRK006 and MRK200, also exhibit notable imbalances where one phase carries a dominant load. In contrast, locations such as MRK003 show relatively balanced conditions with minor deviations of only about ±6 A from their averages. Extreme cases like MRK228 further highlight uneven distribution, where one phase is significantly higher while others are very low. These varying levels of imbalance demonstrate that electrical loads are not uniformly distributed, and targeted load transfers are necessary to optimize the system by reducing neutral current and minimizing power losses.

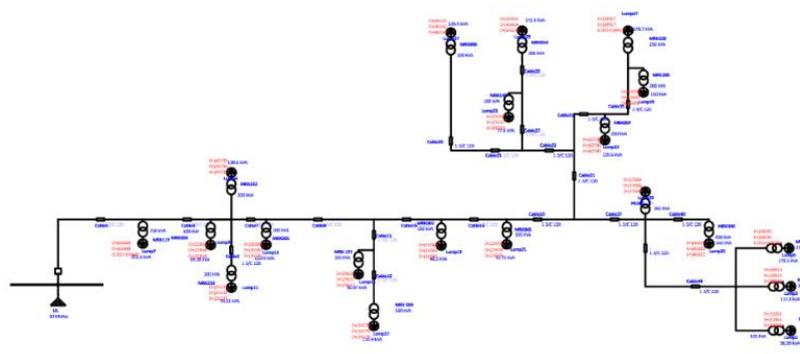### 4.2.4. Simulation Results After Load Balancing Using ETAB Software

Figure 3. Simulation Results After Load Balancing Using ETAB Software

The distribution simulation in the Ermasu in Figure 3 area illustrates power delivery from the main feeder to several network branches, with bus voltages at each point averaging above 95% of the nominal voltage. Meanwhile, the losses in kW and kVAR decreased compared to previous conditions due to neutral disconnection, with the magnitude of losses varying depending on line length and the load connected at each distribution point.

4.2.5. Power Losses After Substation Load Balancing Plan

Based on the data from substations in the Ermasu area, load balancing successfully corrected significant phase imbalances and eliminated energy losses. Before balancing, substations like MRK005 and MRK006 exhibited large current disparities between phases, which created high neutral currents reaching 160 A at MRK005 and resulted in total system losses of 71.5 kW.

After balancing, phase currents were equalized at each substation; for example, MRK005 achieved a balanced current of 191.67 A on all three phases. This allowed the neutral currents to drop to 0 A, as the load became evenly distributed and the neutral path was effectively disconnected. Consequently, power losses were drastically reduced, with total losses decreasing to 50.78 kW. In some cases, losses at individual substations were eliminated entirely, falling to 0 kW. This outcome confirms that systematic load balancing, followed by neutral disconnection, optimizes the distribution network by stabilizing phase currents and minimizing wasted energy, leading to a more efficient and reliable power system.

4.3. BAMPEL

4.3.1. Load Analysis Before Balancing

Calculations were performed on the average current at each measurement point (for example MRK015 to MRK322) based on the measured phase currents (R, S, T). Load imbalance factors (a, b, c) are derived as the ratio between the current of each phase to that average value, where a value of 1 indicates equality of phase current with the average, while deviation above or below 1 reflects imbalance. As an illustration, at MRK029 recorded factors R = 1.000, S = 1.049, and T = 0.951, showing that phase S exceeds the average while phase T is below the average. Significant imbalance was observed at panel MRK251, with current R = 16 A, S = 63 A, T = 40 A and load factors of 0.403, 1.589, and 1.008 respectively, indicating quite large current disparity between phases. Conversely, panel MRK322 shows relatively balanced phase current conditions with current R = 211 A, S = 208 A, T = 205 A and load factors of 1.014, 1.000, and 0.985, confirming uniformity of current distribution between phases.

4.3.2. Power Losses Before Balancing

The analysis of the Bampel feeder reveals a direct correlation between load magnitude, phase imbalance, and power losses. High-load substations like MRK125 (145.08 kW) and MRK322 (142.90 kW) are the primary contributors to overall consumption and also incur the highest losses exceeding 10 kW each. Medium-capacity points (above 100 kW) follow with losses of 7-8 kW. In contrast, small substations (under 20 kW) contribute minimally to both consumption and losses (below 1.2 kW). The root cause of these losses is phase current imbalance. Points with significant disparities, such as MRK125 (256-189-196 A) and MRK304 (197-122-215 A), experience high energy loss as heat in conductors and transformers. This occurs because the imbalance forces current through the neutral line and increases resistive losses. Even substations with relatively lower currents, like MRK015 (61-52-67 A), still incur measurable losses (2.84 kW) when phases are uneven. In summary, while total load

determines the scale of energy usage, it is the imbalance between phase currents that directly drives inefficiency and power loss across the feeder.

4.3.3. Substation Load Balancing Plan

A load balancing analysis of the Bampel feeder reveals significant phase current imbalances across its substations, quantified by comparing each phase to the calculated average current. The recommended adjustments, shown as positive or negative values, indicate whether a phase is overloaded (requiring a reduction) or underloaded (needing an increase).

For instance, at MRK075, the average current is 160.67 A. Phase T is overloaded by +39.33 A, while phases R and S are underloaded by -25.67 A and -13.67 A, respectively. MRK125 shows a similar need for correction, with phase R overloaded by +42.33 A against its 213.67 A average. More extreme imbalances are seen at points like MRK304, where phase S is underloaded by -56.00 A relative to its 178.00 A average.

In contrast, some substations like MRK322 are already relatively balanced, with only minor deviations of ±3 A from its 208 A average. Overall, this analysis provides a precise roadmap for corrective load transfers to equalize phase currents, which will reduce neutral current and minimize system-wide power losses on the feeder.

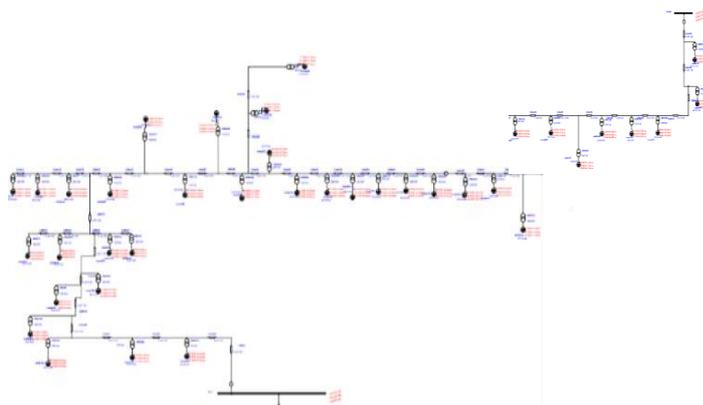### 4.3.4. Simulation Results After Load Balancing Using ETAB Software

Figure 4. Simulation Results After Load Balancing Using ETAB

Based on the distribution simulation in Figure 4 results in the Angkasa area, the power flow from the main feeder to the network branches indicates that the voltage at each bus remains, on average, above 95% of the nominal voltage. Meanwhile, the losses in kW and kVAR have decreased compared to the previous conditions across each feeder segment due to the neutral disconnection, with the magnitude of losses varying according to the line length and connected load capacity.

4.3.5. Power Losses After Substation Load Balancing Plan

The implementation of load balancing on the Bampel feeder successfully corrected severe phase imbalances and dramatically reduced system losses. Before balancing, substations like MRK125 and MRK304 exhibited significant current disparities between phases, resulting in high neutral currents for example, 107 A at MRK304. These imbalances caused total system losses of 146.89 kW.

After balancing, phase currents were equalized at each substation; for instance, MRK125 achieved a balanced current of 213.67 A on all three phases. Consequently, neutral currents were eliminated, dropping to 0 A, as the load became evenly distributed and the neutral path

was effectively disconnected. This intervention drastically cut total losses by 33.83 kW, reducing them to 113.06 kW. In many cases, losses at individual substations were eliminated entirely, falling to 0 kW. This outcome confirms that systematic load balancing, followed by neutral disconnection, is highly effective. It stabilizes phase currents, eliminates wasteful neutral flow, and significantly improves the efficiency and reliability of the power distribution network.

4.4. Kompi 1

4.4.1. Load Analysis Before Balancing

Load imbalance on the Kompi 1 feeder is assessed by comparing the current of each phase to the average current at each measurement point, where a ratio of 1.00 indicates perfect balance. The data shows varying conditions: points such as MRK034 and MRK203 are relatively balanced, while points such as MRK078, MRK099, MRK114, MRK263, and MRK273 experience significant imbalance, with some phases experiencing overload and other phases experiencing underload. This variation shows that although some areas operate within normal limits, extreme imbalance can cause power losses, excessive heating of equipment, and decreased electrical efficiency.

4.4.2. Power Losses Before Balancing

Feeder data shows that power losses are greatly influenced by phase current imbalance, not dependent on the total transformer load. Large-capacity transformers such as MRK063 (122.31 kW) and MRK020 (88.72 kW) recorded the highest losses, 8.56 kW and 6.21 kW respectively, along with significant phase imbalance. Small transformers with loads below 5 kW have minimal losses, but severe imbalance can still cause real losses, such as MRK078 (0.31 kW). Phase current imbalance forces compensating flow through the neutral conductor, converting energy into heat and increasing resistive and reactive losses, thus reducing distribution efficiency. Therefore, although total consumption determines the scale of energy use, phase current disparity becomes the main factor determining the magnitude of energy lost in the feeder.

4.4.3. Distribution Transformer Load Balancing Plan

The load balancing analysis for Kompi 1 quantifies the necessary phase adjustments to correct current imbalances. Recommendations specify the amount of current to add (+) or remove (-) from each phase relative to the calculated average. Transformers with the most severe imbalances require substantial corrections. For example, MRK020 (avg. 129.33 A) needs to shift 29.67 A to the underloaded phase T from overloaded phases R (-8.33 A) and S (-21.33 A). Similarly, MRK273 requires a significant redistribution, with an adjustment of up to +52 A to phase T. Other transformers like MRK158 also exhibit high deviations needing corrections exceeding ±30 A, indicating a dominant load on one or two phases. In contrast, smaller transformers such as MRK077 require only minor adjustments below ±5 A.

This systematic approach provides clear instructions: overloaded phases (negative values) should have load reduced and transferred to underloaded phases (positive values). For instance, at MRK049, the excess from overloaded phase T (-7.33 A) should be moved to underloaded phases R and S. Proper implementation of these recommendations is crucial to eliminate neutral current, reduce losses, prevent equipment overheating, and enhance the overall efficiency and longevity of the distribution system.

4.4.4. Simulation Results After Load Balancing Using ETAB Software
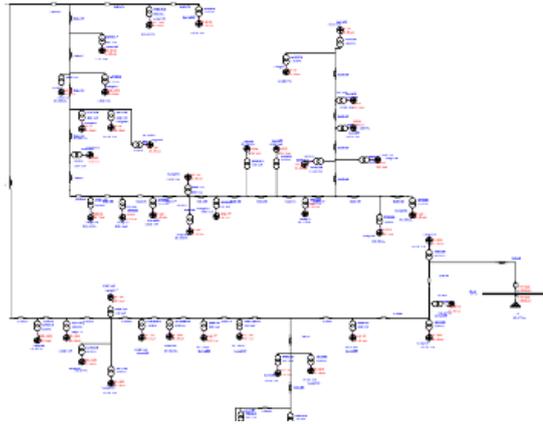

Figure 5. Simulation Results After Load Balancing Using ETAB Software

Based on the distribution simulation in Figure 5 results in the Angkasa area, the power flow from the main feeder to the network branches shows that the voltage at each bus remains on average above 95% of the nominal voltage. Meanwhile, the losses in kW and kVAR decreased compared to the previous condition at each feeder segment due to the removal of the neutral connection, with loss magnitudes varying according to the line length and the load capacity connected at each distribution point.

4.4.5. Power Losses After Transformer Load Balancing Plan

The implementation of load balancing on the KOMPI 1 feeder successfully corrected significant phase imbalances, eliminated neutral currents, and substantially reduced system losses. Before balancing, transformers exhibited severe current disparities, such as MRK020 (121-108-159 A) and MRK273 (71-107-167 A), leading to high neutral currents (e.g., 73 A and 99 A) and total system losses of 94.65 kW.

After balancing, phase currents were equalized at each transformer. For example, MRK020 achieved a uniform current of 129.33 A on all three phases. Consequently, neutral currents were eliminated, dropping to 0 A as the load was evenly distributed and the neutral path was disconnected. This intervention reduced total losses by 22.08 kW, bringing them down to 72.57 kW. This outcome confirms that systematic load balancing, followed by neutral disconnection, is highly effective. It stabilizes the network by equalizing phase currents, eliminating wasteful neutral flow, and significantly improving the efficiency of the power distribution system.

4.5. MULI Feeder

4.5.1. Load Analysis Before Balancing

This analysis identifies load imbalance between phases by comparing the current of each phase to the calculated average value. The imbalance is qualified using an index, where values significantly exceeding 1.00 indicate the phase is experiencing overload, while values below 1.00 indicate the phase is experiencing underload. Measurement results show significant imbalance in several transformers, for example MRK073, where phase R (291 A) has an index of 1.497 compared to phase T (119 A), resulting in a high neutral current of 178 A. Transformer MRK279 also shows dominance of phase R (254 A) with an index of 1.296, a condition that potentially reduces power quality and increases system losses. Conversely, several transformers show relatively balanced load distribution, such as MRK102 (43 A, 42 A, 41 A) and MRK285 (65 A, 69 A, 70 A) with indices close to 1.00. However, there are extreme cases,

such as MRK118, where phase T only carries 1 A, as well as MRK161 with one phase inactive (0 A), which shows very uneven load distribution, causing disproportionate stress on certain transformer windings and reducing the overall operational efficiency of the system.

4.5.2. Power Losses Before Load Balancing

The analysis of the Muli feeder confirms that phase current imbalance is the primary driver of power losses, regardless of the total load size. Transformers with the most severe imbalances incur the highest losses. For instance, MRK073, with highly uneven currents (291-173-119 A) and a neutral current of 178 A, results in a loss of 9.22 kW. Similarly, MRK279 experiences losses of 9.33 kW due to its imbalance. These large-capacity transformers are the main contributors to the feeder's total loss of 186.76 kW.

Crucially, the relationship between imbalance and loss holds even at lower power levels. A transformer like MRK045, with a load of only 12.79 kW, still suffers 0.90 kW in losses because of its uneven phase currents (30-12-14 A). This pattern demonstrates that energy is wasted as heat when phase loads are uneven, forcing current through the neutral conductor. Therefore, while total consumption sets the scale of energy use, it is the disparity between phase currents that critically determines the amount of loss, underscoring the necessity of load balancing to improve system efficiency.

4.5.3. Distribution Transformer Load Balancing Plan

The load balancing analysis for the MULI area reveals widespread phase current imbalances, with recommendations specifying the necessary corrective adjustments for each transformer. The principle is consistent: a negative value (−) indicates an overloaded phase requiring a load reduction, while a positive value (+) indicates an underloaded phase needing an increase. This facilitates a targeted shift of electrical load to achieve balance.

Transformers with severe imbalances require substantial corrections. For example, MRK073 (avg. 194.33 A) must reduce phase R by +96.67 A and increase phases T and S by -75.33 A and -21.33 A, respectively. Similarly, MRK011 needs to shift load from overloaded phase R to underloaded phases S and T.

In contrast, transformers like MRK102 show only minor adjustments (e.g., ±1.00 A), indicating they are already relatively balanced. Overall, the data underscores that the MULI distribution system faces significant balancing challenges. Implementing these phase-specific load transfers is crucial to correct imbalances, reduce associated power losses, and improve overall network efficiency.

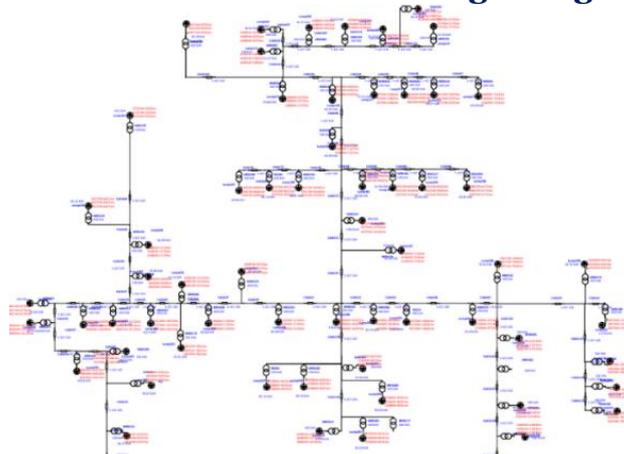### 4.5.4. Simulation Results After Load Balancing Using ETAB Software

Figure 6. Simulation Results After Load Balancing Using ETAB Software

Based on the distribution simulation in Figure 6 results in the Muli area, the power flow from the main feeder to the network branches shows that the voltage at each bus remains on average above 95% of the nominal voltage. Meanwhile, losses in kW and kVAR decreased compared to the previous condition at each feeder segment due to neutral disconnection, with loss magnitudes varying according to line length and the load capacity connected at each distribution point.

4.5.5. Power Losses After Transformer Load Balancing Plan

Load balancing on the MULI feeder successfully corrected major phase imbalances and significantly reduced system losses. Before balancing, transformers like MRK073 exhibited severe disparities, with phase R at 291 A and phase T at only 119 A. This uneven distribution, seen across many transformers, resulted in high neutral currents and total system losses of 186.76 kW.

After balancing, all transformers achieved uniform phase currents. This equalization allowed the neutral currents to drop to 0 A, as the load became evenly distributed and the neutral path was effectively disconnected. The intervention reduced total losses by 38.89 kW, bringing them down to 147.87 kW, with losses at individual transformers drastically minimized. This outcome confirms that systematic load balancing, followed by neutral disconnection, is a highly effective strategy. It stabilizes the network by eliminating phase imbalances and the associated wasteful energy loss, leading to a more efficient and reliable distribution system.

4.6. KOMPI 2

4.6.1. Load Analysis Before Balancing

Based on the data analysis results, the average current and load imbalance ratios (a, b, c) are calculated, which show the comparison of each phase current to the average. Values close to 1.00 indicate relatively balanced load, while values much higher or lower indicate phase imbalance. Several transformers show significant imbalance, for example MRK036 and MRK185, where current is concentrated in only one or two phases. Conversely, transformers such as MRK042 and MRK156 show relatively balanced phase loads. Overall, the data shows varying conditions: there are transformers with balanced phase loads, but there are also those that are highly imbalanced, potentially causing power losses, excessive heating, and stress on equipment.

4.6.2. Power Losses Before Load Balancing

Load measurements in the KOMPI 2 area reveal that phase current imbalance is the key factor driving power losses, independent of the total load on a transformer. Before balancing, the total system load was 102.21 kW, but losses varied dramatically from 0.11 kW at MRK259 to 8.83 kW at MRK156. This disparity is directly linked to the severity of phase imbalance. For instance, MRK036, with a load of only 36.83 kW, incurred 2.58 kW in losses due to its uneven currents (30-45-87 A) and a 53 A neutral current. Similarly, MRK109's significant imbalance resulted in 6.80 kW of losses.

Even at very low loads, imbalance causes measurable waste. MRK185, with a load of just 5.55 kW, still generated losses because one phase was inactive (0 A), forcing a 24 A neutral current. This data clearly shows that energy is lost as heat when phases are unbalanced, forcing current through the neutral conductor. Therefore, optimizing this distribution system requires correcting these phase imbalances to reduce losses and improve overall efficiency.

4.6.3. Distribution Transformer Load Balancing Plan

The load balancing recommendations quantify the necessary adjustment for each phase, where a positive value indicates an overloaded phase requiring a reduction, and a negative value indicates an underloaded phase needing an increase. The magnitude of the value reflects the severity of the imbalance.

Several transformers require significant corrections. For instance, at MRK109, phase S is underloaded by 43 A (-43), while phases R and T are overloaded by 28 A (+28) and 15 A (+15), respectively. An extreme case is MRK185, where load is heavily concentrated on phase R (+14), while phases S and T are significantly underloaded (-6 and -8).

Conversely, some points are already relatively balanced. Transformers like MRK042, MRK198, and MRK195 show only minor adjustment values (within ±9 A), indicating their phase currents are already close to the average. Overall, these recommendations provide a clear guideline for shifting load between phases to achieve a balanced system, with the required action ranging from minimal corrections to substantial redistributions.

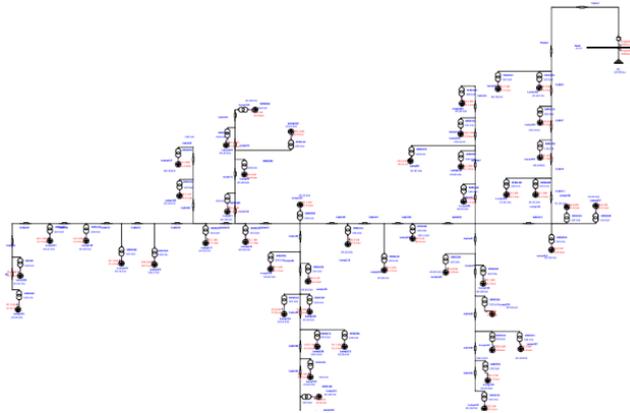### 4.6.4. Simulation Results After Load Balancing Using ETAB Software

Figure 7. Simulation Results After Load Balancing Using ETAB Software

The distribution simulation in the Kompi 2 area in Figure 7 shows that power flow from the main feeder to the network branches maintains an average bus voltage above 93% of the nominal voltage. In addition, power losses in kW and kVAR decreased compared to the initial condition at each feeder segment after neutral disconnection, with the magnitude of the reduction varying according to the feeder length and the connected load at each distribution point.

4.6.5. Power Losses After Distribution Transformer Load Balancing

Load balancing on the Kompi 2 feeder successfully corrected phase imbalances and significantly reduced system losses. Before balancing, uneven phase currents across transformers resulted in high neutral currents and total system losses of 101.21 kW. After balancing, phase currents were equalized at each location for example, MRK016 achieved 123 A on all three phases. This equalization eliminated neutral currents, reducing them to 0 A as the load became evenly distributed and the neutral path was disconnected.

As a direct result, total system losses were reduced by 25.81 kW, falling to 75.40 kW. This outcome confirms that systematic load balancing, followed by neutral disconnection, is an effective strategy. It stabilizes the network by eliminating phase deviations and the associated energy waste, leading to a more efficient and reliable distribution system.

4.7. PARAKO

4.7.1. Load Analysis Before Balancing

The calculation of average phase current (R, S, T) is used to evaluate load imbalance in transformers through factors (a, b, c), with a value of 1.00 indicating ideal balance. Analysis results show that transformers MRK028 and MRK322 experience significant imbalance in certain phases, while MRK061, MRK290, and MRK025 show relatively even load distribution. High neutral current in several transformers, such as MRK249 (41 A) and MRK247 (50 A), indicates the presence of residual imbalance that needs to be corrected to maintain system efficiency and reduce the risk of operational failure.

4.7.2. Power Losses Before Load Balancing

Phase current imbalance in this feeder is evident from the differences in loads among phases R, S, and T, which also causes an increase in neutral current (N). For example, in MRK025, the R phase current is higher than S and T, resulting in a neutral current of 40 A. This condition generates power losses (Losses) due to the additional current flowing through the neutral conductor and the more heavily loaded phases. Recorded Losses values, such as 6.46 kW in MRK025 and 8.04 kW in MRK247, reflect energy lost as conductor heating and increased distribution line impedance.

In general, the greater the imbalance, the higher the power losses. Data from MRK247 show that phase R current is much higher than S and T, with a neutral current reaching 50 A, resulting in the highest losses. Conversely, at measurement points with more balanced phase currents, such as MRK061, losses are relatively low (1.97 kW). This indicates that feeders with significant imbalance led to inefficient energy distribution and increased real power losses in the network.

4.7.3. Distribution Transformer Load Balancing Plan

The phase deviation values (a, b, c) indicate whether each phase is overloaded (positive) or underloaded (negative) relative to the average current. The objective is to reduce these deviations to near zero. Transformers with significant imbalances require targeted load redistribution. For example, MRK247 shows a clear need to shift load from the overloaded phase R (+22 A) to the underloaded phases S and T (-11 A each). Similarly, MRK322 must transfer load from the dominant phase S (+12.67 A) to phase R (-11.33 A). In contrast, other transformers are already operating with relative balance. MRK061 and MRK290 exhibit only minor deviations (within ±7 A), indicating that their phase currents are close to the average and no urgent corrective action is needed. This range of conditions highlights which transformers require priority attention for load balancing to improve system efficiency.

4.7.4. Simulation Results After Load Balancing Using ETAB Software
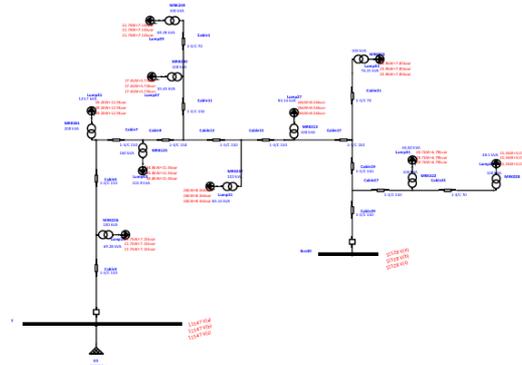

Figure 8. Simulation Results After Load Balancing Using ETAB Software

As shown in figure 8 about the distribution simulation in the Parako area shows that power flow from the main feeder to network branches maintains voltage profiles at each bus averaging above 93% of the nominal voltage. In addition, power losses in kW and kVAR decreased compared to the initial conditions across all feeder segments after neutral removal, with the magnitude of losses varying according to conductor length and the load connected at each distribution point.

4.7.5. Power Losses After Transformer Load Balancing

Load balancing on the feeder successfully eliminated phase imbalances and significantly reduced system losses. Before balancing, uneven phase currents resulted in total system losses of 38.64 kW. After balancing, phase currents were equalized at each transformer for example, MRK025 achieved a balanced 136.67 A on all three phases. This equalization eliminated neutral currents, reducing them to 0 A as the load became evenly distributed. As a direct result, total system losses were reduced by 11.04 kW, falling to 27.60 kW. This outcome confirms that systematic load balancing is highly effective. It stabilizes the network by correcting phase deviations, which eliminates wasteful energy loss and enhances the overall efficiency of the distribution system.

4.8. POLDER

4.8.1. Load Analysis Before Balancing

The average current for each phase R, S, and T in the transformer is calculated from the current measured in these three phases. Load imbalance is assessed with factors a, b, and c, which are the ratios of each phase current to the average current; values close to 1 indicate balanced load, while values that deviate significantly indicate imbalance. Several transformers, such as MRK174, MRK175, MRK134, and MRK100, remain in balanced condition, but several others, such as MRK121, MRK130, MRK153, MRK165, and MRK108, show significant imbalance. This imbalance is usually caused by one phase having a current much higher or lower than the other phases, for example in MRK130 and MRK165. This condition can cause higher power losses, excessive neutral current heating, and shorter equipment lifespan, so load redistribution needs to be carried out to maintain optimal transformer performance.

4.8.2. Power Losses Before Load Balancing

The analysis confirms that phase current imbalance is the primary driver of power losses on this feeder. The severity of the imbalance directly correlates with the magnitude of loss. Transformers with significant imbalances incur the highest losses. For instance, MRK125, with currents of 256 A, 189 A, and 196 A and a 99 A neutral current, results in a loss of 10.16 kW. Similarly, MRK130 experiences 9.33 kW in losses due to its uneven load. These conditions force high currents through the neutral conductor, converting energy into waste heat.

In contrast, more balanced transformers, such as MRK149, exhibit much lower neutral currents and consequently smaller losses (2.15 kW). This pattern demonstrates that energy waste is not solely a function of total load but is critically determined by the disparity between phases. The cumulative effect of these imbalances across the feeder results in total losses of 134.32 kW, underscoring the substantial energy wastage caused by unbalanced loads and highlighting the critical need for corrective load balancing to improve system efficiency.

4.8.3. Distribution Substation Load Balancing Plan

The load balancing analysis for the Polder area quantifies the necessary phase adjustments to correct current imbalances. The recommendations show the deviation of each

phase from the calculated average current, with positive values indicating an overloaded phase and negative values an underloaded one. The goal is to bring all values close to zero for a balanced system.

Several substations exhibit severe imbalances requiring substantial corrections. For instance, MRK130 (avg. 196 A) needs to reduce overloaded phase R by 58 A and increase underloaded phase T by 46 A. Similarly, MRK125 requires a major shift of 42.33 A from phase R to phase S. Other points like MRK098 and MRK118 also need significant adjustments in the range of 20-30 A.

In contrast, substations such as MRK117, MRK134, and MRK149 are already relatively balanced, with only minor recommended adjustments under 10 A. This data underscores that targeted load redistribution is essential, particularly at points with large deviations. Implementing these corrections will reduce high neutral currents, minimize power losses, prevent accelerated equipment wear, and ultimately create a more efficient and reliable distribution system in the area.

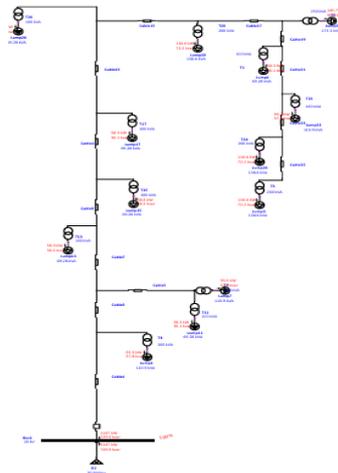### 4.8.4. Simulation Results After Load Balancing Using ETAB Software

Figure 9. Simulation Results After Load Balancing Using ETAB Software

The simulation results for the Polder in Figure 9 area indicate that power flow from the main feeder to the network branches maintains bus voltages averaging above 93% of nominal values. Additionally, active (kW) and reactive (kVAR) losses decreased compared to the initial condition at each feeder segment after neutral removal, with the magnitude of losses varying according to feeder length and the connected load at each distribution point.

4.8.5. Power Losses After Substation Load Balancing Plan

Load balancing on the Polder feeder successfully corrected significant phase imbalances and reduced system losses. Before balancing, substations like MRK130 exhibited severe current disparities (254-184-150 A), leading to high neutral currents (e.g., 92 A) and total system losses of 134.32 kW. After balancing, phase currents were equalized at each substation, which eliminated neutral currents by reducing them to 0 A. As a direct result, total system losses were reduced by 39.33 kW, falling to 94.99 kW. This outcome confirms that systematic load balancing is an effective strategy. It stabilizes the network by correcting phase deviations and eliminating the associated wasteful energy loss, leading to a more efficient and reliable distribution system.

4.8.6. Comparison of Losses Before and After Load Balancing Planning

Before load balancing in Merauke City, several feeders, such as Muli, Bampel, and Polder, exhibited high losses due to uneven current distribution across phases, while feeders with lower losses, such as Angkasa and Parako, still experienced load imbalance. After load balancing, all feeders showed a significant reduction in losses for example, Muli decreased from 186.76 kW to 147 kW, Bampel from 146.89 kW to 113.06 kW, and Kompi 1 and Kompi 2 also demonstrated notable improvements. These results indicate that load balancing effectively enhances distribution system efficiency while maintaining more stable power supply quality in Merauke City.

Based on the comparison of power loss values across eight feeders before and after load balancing, each feeder, including ANGKASA, ERMASU, BAMPEL, and POLDER, experienced reductions in losses of varying magnitudes. Generally, feeders with initially high losses, such as MULI (186.76 kW → 147 kW), BAMPEL (146.89 kW → 113.06 kW), and POLDER (134.32 kW → 94.99 kW), showed more significant reductions. Meanwhile, feeders with lower initial losses, such as PARAKO (38.64 kW → 27.60 kW) and ANGKASA (47.91 kW → 26.6 kW), also exhibited reductions, albeit less pronounced than those of the high-loss feeders. These results demonstrate that load balancing effectively reduces losses across all feeders.
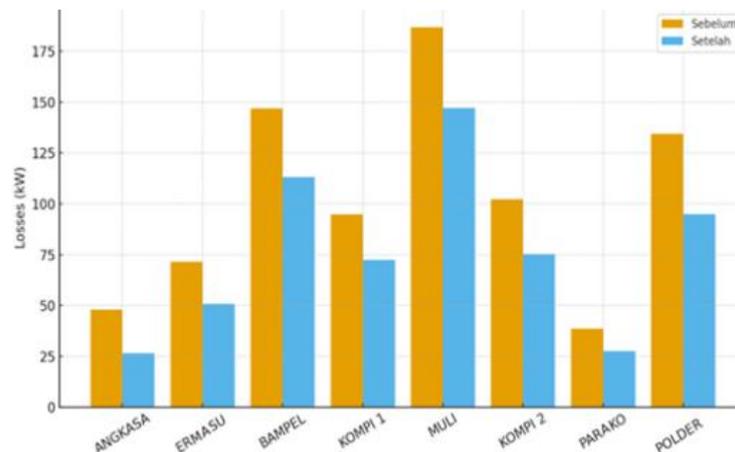
Note: Orange indicates values before load balancing, while blue indicates values after load balancing.
Figure 10. Comparison of Losses Before and After Load Balancing

The graph illustrates in Figure 10 the comparison of power losses across eight feeders before and after load balancing. Each orange bar represents the condition before balancing, while each blue bar represents the condition after balancing. In general, the heights of the bars after balancing are lower than those before, indicating a reduction in losses across all feeders. The most significant differences are observed in feeders with initially high losses, such as MULI, BAMPEL, and POLDER, where the reduction is quite substantial. Meanwhile, feeders with lower initial losses, such as PARAKO and ANGKASA, also show decreases, although the magnitude of reduction is smaller compared to the higher-capacity feeders.

5. Conclusion

Based on the calculations and analysis of load imbalance and power losses in distribution transformers at ULP Merauke City, this study concludes that significant load imbalance is prevalent across the network's feeders, directly leading to increased neutral currents and avoidable power losses. The core finding is that implementing targeted, data-driven phase balancing is highly effective. Simulations, such as with transformer MRK262,

demonstrate that balancing can reduce neutral currents by over 59% and lower power losses by more than 35%, thereby improving average transformer efficiency by 2-5%. This directly enhances network reliability, reduces operational costs, and extends asset lifespan.

Therefore, the primary recommendation for PT PLN UP3 Merauke is the systematic and regular implementation of a substation-specific load balancing program, prioritizing transformers with the highest imbalance indices. This program should integrate the phase-aware connection of new customers and include quarterly audits to prevent regression. For future research, it is recommended to develop a real-time monitoring and automated load switching system to dynamically maintain balance, and to conduct a longitudinal cost-benefit analysis of the balancing interventions described in this study to quantify their long-term economic impact on the utility.

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