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Analysis of Load Balancing in Low-Voltage Distribution Substations

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ABSTRACT
This study investigates the impact of load imbalance in low-voltage distribution systems on energy efficiency and operational reliability, focusing on the PHMB substation managed by PT PLN ULP Cirebon Kota. Through a field-based quantitative case study, the research identifies a significant phase current imbalance—exceeding 20%—resulting in a high neutral current (90 A) and monthly energy losses of 358.20 kWh. A load redistribution strategy, shifting 13 A from Phase R and 43 A from Phase T to Phase S, successfully reduced the imbalance to 11.27% and lowered neutral current to 64 A. This intervention achieved a 49.5% reduction in monthly energy losses (saving 177.12 kWh) and halved power losses in the neutral conductor. The study highlights the practical benefits of structured load balancing in improving power quality and energy efficiency in Indonesian distribution networks. Findings contribute empirical evidence for utility-level decision-making and policy design in developing countries, especially where advanced automation is not yet widely implemented.

INTRODUCTION

The electric power distribution system is a critical component in the energy supply chain from generation to end users. Globally, the demand for efficient and reliable power distribution continues to rise in tandem with population growth and urban-rural industrialization. In Indonesia, low-voltage distribution systems (380/220V) play a vital role in serving residential and small business customers. However, one of the primary challenges in these systems is phase load imbalance, which results in increased neutral current, energy losses, degraded power quality, and potential damage to distribution equipment (Gawrylczyk & Trela, 2019). This problem is exacerbated by limitations in real-time monitoring and static load allocation strategies.

The urgency to address load imbalance in low-voltage distribution networks is not only technical but also directly affects operational efficiency and energy costs. Phase imbalance can cause power losses of over 60%, depending on the current deviation between phases (Makhadmeh et al., 2019a), and it also shortens the lifespan of transformers and protective devices. In practice, Indonesia's state-owned utility, PLN, faces challenges in managing load distribution at substations, particularly in areas with fluctuating load densities. This situation underscores the need for accurate load measurements and systematic load balancing strategies (Zhang et al., 2019).

Theoretically, an ideal power distribution system requires balanced load distribution across all three phases to minimize neutral current and active power loss. Within this framework, the concept of load balancing has evolved as a strategic approach using optimization algorithms such as genetic algorithms, swarm intelligence, and heuristic methods supported by smart meter data (Snodgrass & Xie, 2020). Previous studies also show that phase imbalance often stems from uneven customer allocation and dynamic consumption patterns without flexible phase configurations (Wu et al., 2018). Accordingly, the conceptual framework of this study refers to optimal load redistribution strategies supported by field measurement and imbalance evaluation.

This study aims to: (1) determine the method of load redistribution at the PHMB distribution substation operated by PT PLN ULP Cirebon Kota; (2) quantify power losses caused by load imbalance; and (3) identify the technical benefits of such load redistribution. The core research questions include how to calculate the effect of phase imbalance on neutral current, and how to estimate energy losses in the substation. A case study approach was applied using field measurements and a quantitative thematic analysis based on the collected data.

The scientific contribution of this article lies in its empirical elaboration of phase imbalance assessment at low-voltage substations within an Indonesian local context, which remains underrepresented in the academic literature. Furthermore, the study contributes practical insights from a utility perspective to improve distribution efficiency using replicable and policy-aligned methods (Darabi et al., 2010; Wu et al., 2018). By integrating technical, conceptual, and local case perspectives, this article aims to inform more efficient and sustainable energy distribution policy development.

Low-voltage electricity distribution is a key element in electrical power systems responsible for delivering energy from substations to end users. In this context, phase load imbalance is a major issue impeding efficiency and power quality. Theoretically, phase imbalance refers to discrepancies in current or load distribution across the three phases of a three-phase network, which may result in elevated neutral current, power loss, and voltage distortion. To mitigate this, load balancing theory has been developed to dynamically redistribute load across phases for system stability and network efficiency (Mulenga et al., 2021).

Numerous prior studies have examined techniques for managing phase imbalance in low-voltage networks. A common conventional method is phase swapping, which involves reassigning customer connections between phases based on current and voltage measurements (Setlhaolo & Xia, 2016). This method can reduce power losses significantly when applied selectively. In contrast, automated technologies such as Automatic Phase Balancing Devices (APBD) have proven effective in maintaining current imbalance below 15% amid fluctuating loads. Other studies highlight that smart meter-based optimization using metaheuristic algorithms such as Genetic Algorithms can balance loads and reduce daily energy losses substantially (Makhadmeh et al., 2019b).

Despite these developments, several research gaps remain. First, there is limited application of direct observational load balancing methods in Indonesia's distribution networks, which feature unique topologies and load characteristics. Secondly, there is a lack of systematic field-based studies evaluating the quantitative impact of imbalance on neutral current. Additionally, integration between load monitoring systems and automated control devices at the substation level remains limited—particularly in urban substations like PHMB with high load variability.

This study addresses these gaps through a case study at the PHMB substation under PT PLN ULP Cirebon Kota using field-based quantitative measurements. It empirically analyzes phase imbalance and energy loss, while evaluating the impact of conventional but structured load redistribution. The study enriches the currently simulation-heavy literature by offering local data to support evidence-based utility decision-making (Wang et al., 2019).

From a methodological perspective, previous studies have increasingly applied heuristic optimization techniques such as the Whale Optimization Algorithm and Particle Swarm Optimization, particularly in smart grid and V2G (Vehicle-to-Grid) systems. However, these methods are not yet feasible in conventional networks lacking smart meters. Therefore, manual monitoring and direct field measurements remain highly relevant in developing countries. A hybrid approach combining on-site observation and thematic computation of neutral current, phase imbalance, and power loss has proven more practical in such context. Thus, the conceptual synthesis in this study is grounded in the integration of power distribution theory, technical understanding of phase imbalance, and field-based quantitative assessment of load parameters at substations. By uniting theory and practice, the study provides empirical contributions that may guide strategies for balanced low-voltage distribution and inform technical policy development for sustainable operations.

RESEARCH METHODS

This research adopts a quantitative case study approach focused on the PHMB substation managed by PT PLN ULP Cirebon Kota. The case study strategy enables in-depth observation and direct measurement of load imbalance under real-world operating conditions. The quantitative approach facilitates numerical analysis of technical parameters including neutral current, phase imbalance, and active power losses—allowing systematic and objective interpretation.

Primary data were collected through direct field measurements. These include current values for each phase (R, S, T), neutral current, load voltage, and active power at the substation. Measurements were taken over a period of time to capture daily load variations. Secondary data such as technical documentation, distribution maps, and PLN standards were also used to validate the findings (Z. Huang et al., 2023).

Data collection involved technical observation using standard electrical instruments such as clamp meters, digital multimeters, and power quality analyzers. All instruments provided real-time and accurate readings. Measurements were conducted by trained field technicians following safety protocols and PLN operational procedures. Each reading was taken three times, and the average value was used to ensure reliability.

Inclusion criteria required substations with a minimum load of 5 kW per phase and valid historical data for the past week. Substations undergoing maintenance or with malfunctioning meters were excluded. This ensured that the analyzed data accurately reflected normal operations and provided a reliable basis for evaluating load balancing (Matus et al., 2015).

The unit of analysis was the PHMB substation as part of PLN's low-voltage distribution system serving both residential and commercial loads. The unit of observation included outgoing feeder terminals where phase currents were individually measured. Key technical parameters included current, voltage, power, energy loss, and imbalance metrics. Measurement points were determined based on network structure and existing load mapping by PLN's technical team (Naumov, 2024).

The data analysis used quantitative thematic methods focusing on phase imbalance percentage and energy loss estimation due to neutral current. Calculations were based on standard phase imbalance equations and active power loss formulas involving current and conductor impedance. Microsoft Excel and MATLAB were used for data processing and trend visualization. Results were validated by comparing them with PLN's maximum permissible imbalance thresholds. This technique follows widely adopted quantitative methods for evaluating power distribution performance (J. Huang et al., 2021).

RESULTS AND DISCUSSION

4.1. Results

This study investigates the effects of load imbalance on the operational efficiency and energy losses of a 250 kVA distribution transformer (PHMB) at PT PLN (Persero) ULP Cirebon Kota. The transformer, with a nominal full-load current of 360.85 A (calculated from 250 kVA, 400 V, 3-phase system), was analyzed under peak load conditions (WBP) at 19:20.

4.1.1. Transformer Load Analysis

Based on field measurements, the recorded phase currents were: (a) Phase R: 197 A, (b) Phase S: 128 A, (c) Phase T: 227 A. Where the average phase current is 184 A. This yields a transformer load of 51% of its full capacity, which complies with the national utility standard (SK ED PLN No.0017.E/DIR/2014) specifying <60% as optimal for equipment longevity.

Table 1. Phase Current and Load Calculation

Phase	Current (A)	Deviation from Average (A)
R	197	+13
S	128	-56
T	227	+43

4.1.2 Voltage and Current Imbalance Assessment

The voltage across phases R-N, S-N, and T-N were 226 V, 226 V, and 227 V respectively, producing a voltage imbalance of only 0.15% (well within NEMA MG1-1998 threshold of 1%). However, current imbalance was more significant. Using the IEEE recommended formula:

$$I_{unbalance} = \left| \frac{(a-1)+(b-1)+(c-1)}{3} \right| \times 100\%$$

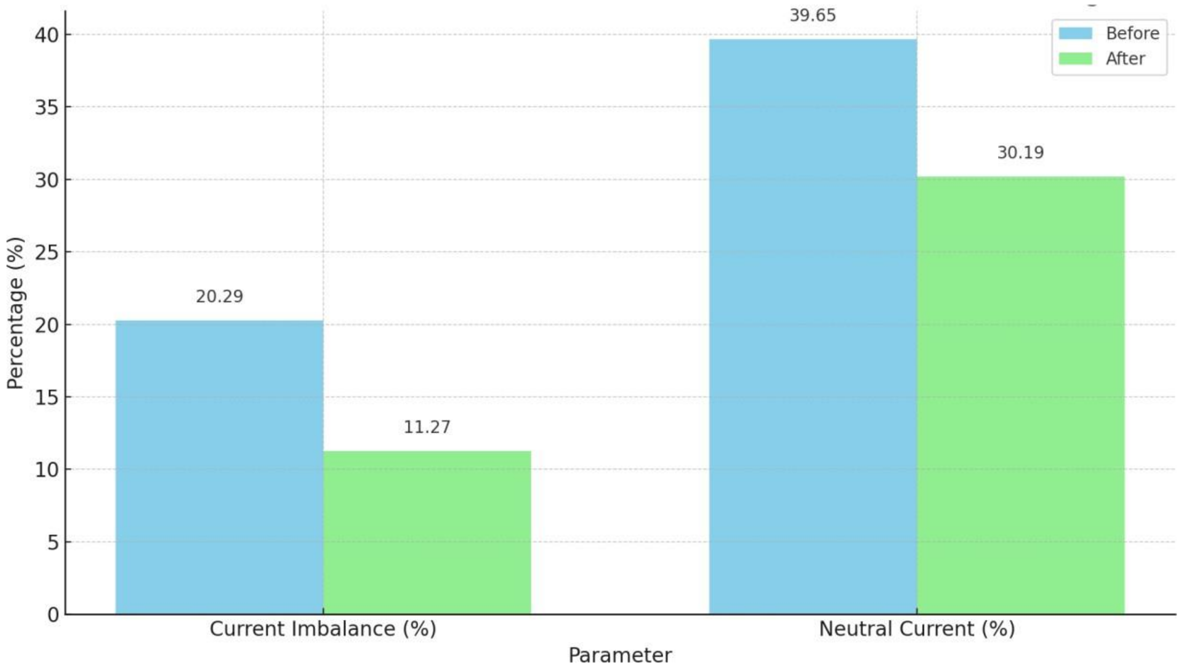
where: $a = \frac{I_R}{I_{Avg}} = 1.07$, $b = \frac{I_S}{I_{Avg}} = 0.69$, and $c = \frac{I_T}{I_{Avg}} = 1.23$. Yields an imbalance of 20.29%, exceeding the PLN recommended threshold (<20%), indicating poor load distribution. Neutral current was 90 A, which is 39.65% of the maximum phase current—an undesirable condition that introduces additional I^2R losses and heating in the neutral conductor.

4.1.3 Load Redistribution and Reassessment

A load reallocation was proposed. Transfer 13 A from Phase R and 43 A from Phase T to Phase S (deficient by 56 A) that post-redistribution measurements showed: Phase R: 176 A, Phase S: 156 A, Phase T: 212 A, Neutral current: 64 A. This improved current balance, with the new imbalance value reducing to 11.27%, and neutral current falling to 30.19% of max current. The imbalance comparison before and after redistribution shown in Tabel 2 and Picture 1.

Table 2. Imbalance Comparison Before and After Redistribution

Condition	Current Imbalance (%)	Category	Neutral Current (%)	Category
Before	20.29	Poor	39.65	Poor
After	11.27	Fair	30.19	Poor

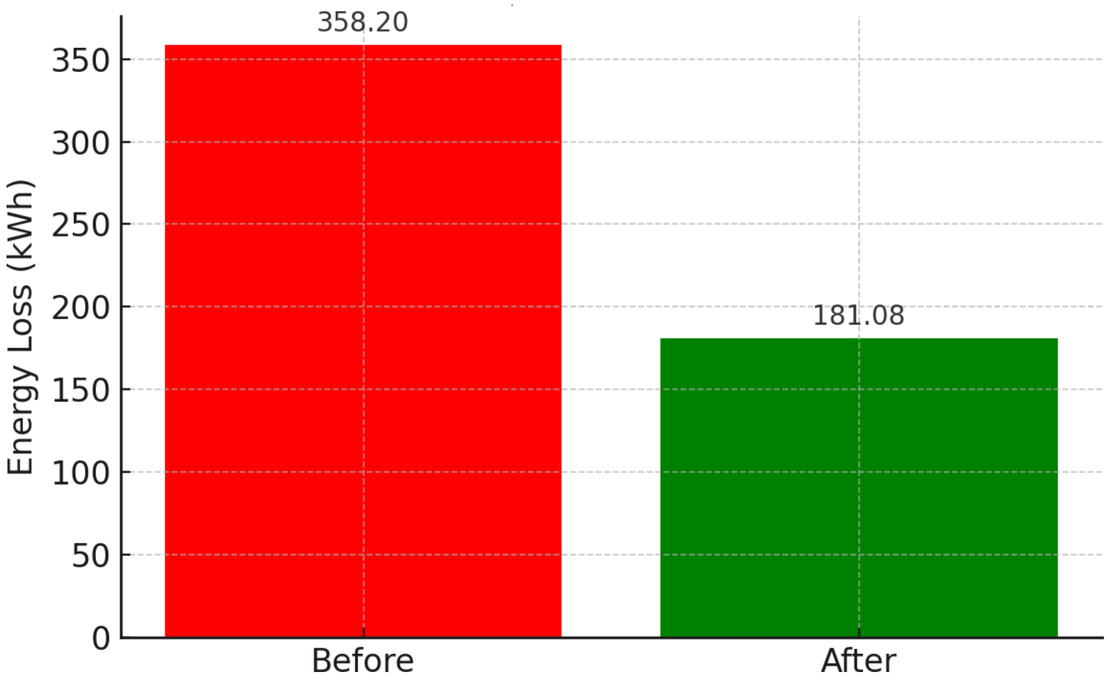


Picture 1. Current Imbalance and Neutral Current Before vs. After

The data support that the rebalancing phase loads reduces unbalanced current, thereby improving system reliability and efficiency.

4.1.4 Power and Energy Loss Analysis

With a neutral conductor resistance (R_N) of 0.2457 Ω (70 mm² copper, 1 km), power losses were calculated using the formula $P_N = I_N^2 \times R_N$. The result show that before: $P=90^2 \times 0.2457=1.99$ kW and after: $P=64^2 \times 0.2457=1.006$ kW. Assuming 6 hours/day of peak load, energy loss before: 1.99×6×30=358.20 kWh/month and energy loss after: 1.006×6×30=181.08 kWh/month, therefore total energy savings is 177.12 kWh/month (≈49.5% reduction). Monthly Energy Loss Comparison before versus after shown in picture 2.



Picture 2. Monthly Energy Loss Comparison

4.2. Discussion

The research result highlighting a significant current imbalance among phases in the PHMB distribution substation, leading to a high neutral current and increased energy losses, underscores several critical issues in power distribution systems. This scenario depicts a common challenge in managing phase imbalances, which can cause inefficiencies and potential operational problems. Phase imbalance often results from uneven load distribution, which decreases the available capacity of main feeders and low-voltage transformers. Specifically, the phase with the least spare capacity limits the total usable capacity of the system, creating inefficiencies and higher operational costs (Ma et al., 2016). Consequently, this imbalance can lead to an increased reinforcement cost (ARC), which grows exponentially as assets approach their capacity limits. While the voltage imbalance in the context remains within acceptable limits, the phase current asymmetry contributes substantially to system inefficiencies.

Addressing phase imbalance involves distinguishing between systemic and random imbalances. Systemic imbalances, caused by uneven load allocations, are often correctable through low-cost interventions like phase swapping. Random imbalances, on the other hand, require more complex and costly demand-side management (Kong et al., 2018). Therefore, accurately distinguishing and addressing these imbalance components can significantly enhance the system's operational efficiency. Moreover, phase imbalances affect the line losses in distribution systems. For instance, loop distribution systems can see minimized line losses through control schemes like those involving the Unified Power Flow Controller (UPFC), which compensates for reactance voltage drops and can eliminate loop currents, effectively reducing total line loss (Sayed & Takeshita, 2014).

The high neutral current (90 A in this case) is an indication of the imbalance, as excess current returns along the neutral line, leading to energy wastage quantified as elevated energy losses (358.20 kWh per month here). These losses not only represent a financial cost but also demand capacity that could otherwise serve additional loads or facilitate system reliability and expansion (Ciontea & Iov, 2021).

The load balancing strategy discussed focuses on redistributing phase loads to achieve a reduction in current imbalance, neutral current, and energy losses, while enhancing power efficiency. The results you mentioned are indicative of improvements attributed to effective load balancing. The specific strategy involved redistributing 13 A and 43 A from phases R and T, respectively, to phase S, leading to a decrease in current imbalance to 11.27%. Such redistribution efforts are intended to align the phases more closely, thus reducing the imbalance which helps in lowering the reactive power losses and enhancing the stability of the system (Hooshmand & Soltani, 2012). Reducing the neutral current from 64 A is a key outcome, as high neutral currents can signify an unbalanced system and lead to unnecessary losses in the neutral conductor. Achieving this reduction can also mitigate the risk of excessive heating in the neutral paths, which could otherwise cause unnecessary wear and fire hazards. This is often addressed through algorithms or models focusing on optimizing phase arrangements and can involve heuristic approaches to rephase laterals and transformers in the network for enhanced balance (Lin et al., 2008).

The strategy reduced monthly energy losses by 181.08 kWh, resulting in net energy savings of 177.12 kWh. This highlights the effectiveness of phase balancing in reducing system energy wastage, which translates to greater efficiency and cost savings for the utility company. The reduction in energy losses can be attributed to the decrease in both ohmic losses in the lines and reduced reactive power flow, as balanced systems tend to operate more efficiently (Grigoraș et al., 2020).

Furthermore, the reported decrease in neutral line losses from 1.990 kW to 1.006 kW during peak load hours is significant as it underscores the impact of load balancing on power loss reduction. The optimization of phase loads, typically done using methods like genetic algorithms or particle swarm optimization, aims to minimize the power loss across the system by ensuring that each phase shares the load more equally, thus reducing the operating costs and extending the lifespan of the system components (Atteya et al., 2017; Chen & Cherng, 2000). Overall, the outcomes demonstrate the substantial benefits load balancing can bring, not just in terms of economic savings but also in enhancing the reliability and efficiency of power distribution systems.

CONCLUSION

This study concludes that load imbalance in low-voltage distribution transformers significantly affects system performance, energy losses, and overall efficiency. Measurements on the PHMB distribution substation revealed a considerable current imbalance among phases—exceeding 20%—which resulted in a high neutral current (90 A) and elevated energy losses of 358.20 kWh per month. Although the voltage imbalance remained within acceptable limits (<1%), the asymmetry in phase currents caused non-negligible inefficiencies in the system.

Following a load balancing strategy—redistributing 13 A and 43 A from phases R and T to phase S—the current imbalance decreased to 11.27%, and the neutral current dropped to 64 A. This redistribution reduced monthly energy losses to 181.08 kWh, indicating a net energy saving of 177.12 kWh. In terms of power loss, the system's neutral line losses decreased from 1.990 kW to 1.006 kW during peak load hours.

The results affirm that implementing load balancing on distribution transformers not only improves power quality and reduces neutral current but also enhances the thermal and operational efficiency of the system. These improvements contribute to lowering operational costs, extending equipment life, and supporting energy conservation goals in the distribution network. Therefore, routine monitoring and load rebalancing are recommended as preventive and corrective measures in electrical distribution systems, particularly in areas with fluctuating or asymmetric load demands.

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