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Analysis of Inserted Transformer Installation to Reduce Distribution Transformer Overload at PT PLN (Persero) ULP Abepura, Koya Barat

Dultudes Mangopo[1], Ekawati Margaretha Ohee[2], Idham Khaliq[3]

[1,2,3] Department of Electrical Engineering, Faculty of Engineering, Universitas Cenderawasih, Jayapura, Indonesia.
Email: elektro_doel@yahoo.com[1], ekawati_ohee@ftuncen.ac.id[2], idham@ftuncen.ac.id[3]

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ABSTRACT
The continuous increase in electrical energy demand, particularly in semi-urban areas, has created significant challenges for the reliability and operational performance of power distribution systems. One critical problem is the occurrence of overload conditions on distribution transformers, which may accelerate insulation degradation, increase thermal stress, and reduce equipment lifespan. This study aims to evaluate the effectiveness of installing an inserted transformer as a technical solution to mitigate overload in the medium-voltage distribution network of PT PLN (Persero) ULP Abepura, Koya Barat. A descriptive quantitative case study approach was employed using field measurement data from the ABE-262 distribution transformer before and after the installation of a 160 kVA inserted transformer. The measured parameters included phase current, voltage profile, transformer loading percentage, phase imbalance, and neutral current during peak load time (WBP) and off-peak load time (LWBP). The results show that the loading of the main transformer decreased from 92.40% to 63.12% during WBP and from 78.94% to 26.56% during LWBP. Meanwhile, the inserted transformer absorbed only 13.32% of the total load during WBP and 9.47% during LWBP, indicating the availability of reserve capacity for future demand growth. The installation also improved phase balance, as shown by the reduction in phase imbalance from 12.4% to 5.6%, and reduced neutral current from 69.7 A to 49.3 A during LWBP. These findings confirm that the inserted transformer is an effective, economical, and practical solution for reducing transformer overload, improving load distribution, and enhancing distribution system reliability. In addition, this strategy provides operational redundancy and reserve capacity, thereby supporting the long-term resilience of distribution networks in areas with limited infrastructure.

Keywords: Distribution Transformer, Inserted Transformer, Overload Mitigation, Load Redistribution, Phase Balance.

I. Introduction

The growth in electricity demand in Indonesia continues to increase in line with the development of urban and semi-urban areas. This growth is not only related to household consumption but also to the expansion of public services, commercial activities, and small-scale economic sectors that depend on reliable electricity supply. Therefore, the reliability of distribution transformers becomes an important factor in supporting local economic activities and public service continuity. This increase places pressure on power distribution systems, particularly on distribution transformers operating beyond their nominal capacity. Such overload conditions accelerate insulation aging and reduce system reliability (IEEE, 2011). In this study, overload refers to a condition in which the operating load of a distribution transformer approaches or exceeds the recommended loading limit. A distribution transformer is an electrical device used to step down medium-voltage electricity to low-voltage electricity for end users, while an inserted transformer refers to an additional transformer installed near an overloaded service area to redistribute part of the load from the main transformer. According to the IEEE C57.91-2011 guideline, distribution transformers should not be operated beyond safe loading limits to prevent excessive temperature rise and degradation of insulating oil (IEEE, 2011). In line with this, Zhang et al. (2025) emphasize that transformers operating beyond optimal capacity exhibit significant thermal performance degradation, shortening equipment lifespan by up to 25% of its original design. Therefore, transformer load management becomes a key aspect in maintaining distribution system reliability.

The main problem examined in this study occurred in the Koya Barat area under PT PLN (Persero) ULP Abepura, where the ABE-262 distribution transformer experienced high loading during operational measurement. Field data showed that before the intervention, the loading of transformer ABE-262 reached 92.40% during peak load time (WBP) and 78.94% during off-peak load time (LWBP). These values indicate that the transformer was operating near or above the recommended operational limit, especially during peak demand. If this condition is not addressed, the transformer may experience higher thermal stress, reduced operating lifespan, increased technical losses, and a greater probability of service interruption. Various prediction-based methods have been developed to anticipate overload conditions. Rahmawati et al. (2024) show that transformer load forecasting using the Holt-Winters method can assist operators in estimating power consumption trends more accurately. Zhang et al. (2025) further add that the utilization of Large Language Model (LLM)-based approaches can improve short-term load estimation accuracy. However, as noted by Mehmood and Hussain (2025), such intelligent approaches require advanced digital management systems and communication infrastructure, which are not always available in areas with limited electrical networks.

Furthermore, several studies focus on overload mitigation through anomaly detection and transformer condition monitoring. Min et al. (2025) highlight that prediction systems based on deep temporal modeling are effective in detecting dissolved gases caused by thermal stress in on-load tap changers, which play an important role in preventive transformer protection. Although this technology performs well in advanced systems, Odongo et al. (2022) demonstrate that in rural distribution networks, simpler IoT solutions based on LoRa can still enhance fault detection and improve system reliability. Meanwhile, approaches based on electric vehicles (EVs) and energy storage have also become a research focus. Hussain, Bui, and Kim (2023) report that dynamic pricing models can support distributed EV load management, while Zhang et al. (2025) point out that uncontrolled EV penetration can cause voltage fluctuations and accelerate transformer wear. Roy et al. (2023) reinforce this view through a case study in the United States, showing increased thermal stress on transformers due to EV charging during peak hours. Therefore, physical interventions such as inserted transformers become highly relevant in environments with limited infrastructure, where software-based load management cannot yet be fully implemented.

As a local example, Muhammad et al. (2022) demonstrate that the installation of an inserted transformer at ULP Langsa Kota successfully reduced transformer loading by up to 25% without requiring primary network reconstruction. Similarly, Anjas and Ilham (2022) show that the addition of inserted substations in South Sulawesi can improve phase balance and reduce power losses. These studies confirm that the inserted transformer approach is not only relevant in the international context but has also been proven effective in Indonesian distribution networks. In addition, studies published in Golden Ratio also emphasize the importance of infrastructure and technological support in strengthening regional development and institutional performance. Elpisah et al. (2021) explain that regional economic performance is closely related to development capacity, while Nurhidayah et al. (2024) show that local economic sectors require supporting systems to improve productivity. Furthermore, Addae and Brown (2025) indicate that artificial intelligence and digital analytical approaches can support future decision-making, which is relevant for the future integration of digital monitoring in power distribution systems.

Based on this background, this study aims to analyze the effectiveness of installing a 160 kVA inserted transformer to reduce overload on the ABE-262 distribution transformer at PT PLN (Persero) ULP Abepura, Koya Barat. The analysis is based on a case study using field measurement data before and after the installation of the inserted transformer. The measured parameters include phase current, transformer loading percentage, phase imbalance, and neutral current during WBP and LWBP conditions. The key findings show that the loading of the main transformer decreased from 92.40% to 63.12% during WBP and from 78.94% to 26.56% during LWBP. The inserted transformer absorbed 13.32% of the total load during WBP and 9.47% during LWBP, indicating the availability of reserve capacity for future demand growth. In addition, phase imbalance decreased from 12.4% to 5.6%, showing that the intervention improved load distribution across phases. The contribution of this study lies in providing empirical evidence from a PLN distribution network case supported by quantitative measurement results and comparative analysis before and after intervention. The findings are expected to provide practical recommendations for PLN and other utility operators in implementing load redistribution strategies, improving transformer reliability, reducing technical risk, and preparing future integration with digital monitoring systems.

II. Literature Review and Hypothesis Development

2.1. Transformer Overload, Thermal Risk, and Distribution Reliability

Distribution transformers are essential components in electrical distribution systems because they convert medium-voltage electricity into low-voltage electricity for end users. In semi-urban distribution networks, increasing residential, commercial, and public-service electricity demand often causes distribution transformers to operate close to or beyond their recommended capacity. This condition creates transformer overload, which refers to an operating condition in which the transformer load approaches or exceeds the safe operating limit. Transformer overload is not only a loading issue but also a thermal and asset-risk problem. When the load increases, the winding temperature and hot-spot temperature also increase. This condition accelerates insulation aging, reduces oil quality, and shortens the technical lifespan of the transformer. Staszewski et al. (2025) explain that transformer aging is strongly influenced by hot-spot temperature, which is directly related to load intensity and loading duration. Similarly, Azeem et al. (2026) show that modern load patterns caused by urbanization and increasing residential demand intensify transformer stress and increase the probability of failure.

These studies collectively indicate that transformer overload must be treated as part of distribution asset risk management. From a utility perspective, an overloaded transformer increases the probability of unplanned outage, maintenance cost, energy loss, and customer service disruption. Therefore, overload mitigation should be designed not only to reduce the loading percentage but also to improve the long-term reliability of the distribution system. In the context of PT PLN (Persero) ULP Abepura, Koya Barat, the overload condition of transformer ABE-262 represents a practical problem in semi-urban distribution networks. The transformer load reached 92.40% during peak load time before the installation of the inserted transformer. This condition indicates that the transformer operated close to a critical loading level and required a practical intervention to reduce thermal stress and maintain service reliability.

2.2. Load Redistribution and Inserted Transformer as a Capacity Optimization Strategy

Load redistribution is a practical strategy used to manage transformer overload by shifting part of the electrical load from an overloaded transformer to another transformer or by reallocating loads among phases. This approach is often more feasible than large-scale network reconstruction, especially in semi-urban areas where budget, space, and infrastructure limitations restrict rapid distribution network expansion. Krstivojević et al. (2025) argue that targeted investment in distribution equipment can improve network performance without requiring extensive reconstruction. In line with this view, the addition of an auxiliary or inserted transformer can improve transformer capacity utilization by sharing part of the load from the main transformer. Muhammad et al. (2022) also found that the use of an inserted transformer in a PLN distribution network successfully reduced transformer loading without major primary network reconstruction. Anjas and Ilham (2022) further showed that the addition of an inserted substation improved phase balance and reduced distribution losses.

The synthesis of these studies shows that an inserted transformer works through three main mechanisms. First, it reduces the load of the main transformer by transferring part of the load to an additional transformer. Second, it improves capacity optimization because the load is distributed across more than one transformer. Third, it creates reserve capacity that can be used to support future demand growth or operational flexibility during disturbance and maintenance activities. For utility companies, load redistribution through an inserted transformer can be implemented through several practical steps. First, utilities should identify transformers with loading levels approaching or exceeding the operational safety limit during peak load time. Second, utilities should map customer distribution, phase-current conditions, cable distance, voltage profile, and load density. Third, the inserted transformer should be placed at a strategic load center to minimize technical losses and improve voltage quality. Fourth, part of the low-voltage customer load should be transferred from the overloaded transformer to the inserted transformer while maintaining balanced phase allocation. Fifth, post-installation monitoring should be conducted to evaluate transformer loading, phase imbalance, neutral current, voltage profile, and reserve capacity. Therefore, inserted transformer installation is not merely an additional equipment investment. It is a targeted load-management strategy that supports asset protection, capacity optimization, and operational reliability.

2.3. Phase Balance, Neutral Current, and Technical Loss Reduction

Phase imbalance is a common problem in low-voltage distribution networks, particularly in systems dominated by single-phase customers. Unequal distribution of load among R, S, and T phases produces unbalanced phase currents. This imbalance generates neutral current, increases conductor heating, and contributes to additional technical losses. Rizal et al. (2025) explain that phase imbalance causes unequal current distribution, resulting in higher neutral current and power losses. Sinurat (2026) also found that improving three-phase load balance can reduce neutral current and increase transformer efficiency. These findings confirm that transformer performance should not only be evaluated from total loading percentage but also from the balance of phase currents and neutral current.

In this study, phase balance and neutral current are important indicators because the inserted transformer changes the allocation of customer loads in the low-voltage network. If the transferred loads are selected by considering the R, S, and T phase-current conditions, the current distribution becomes more proportional. A more proportional current distribution reduces neutral current and technical losses, which in turn improves the efficiency and reliability of the distribution system. The relationship between transformer loading, phase balance, and neutral current forms the technical logic of this study. Reducing the loading of the main transformer may decrease thermal stress, while improving phase balance may reduce neutral current and additional losses. Thus, inserted transformer implementation should be assessed through an integrated approach involving loading percentage, phase imbalance, neutral current, and reserve capacity.

2.4. Risk Management, Resilience, and Digital Monitoring in Distribution Systems

Modern distribution systems are required to be reliable and resilient. Reliability refers to the ability of the system to provide continuous electricity service under normal operating conditions, while resilience refers to the ability of the system to withstand, adapt to, and recover from disturbances. Rouholamini et al. (2025)

emphasize that increasing demand, aging infrastructure, and operational uncertainty make resilience an important issue in distribution system planning. Redundancy is one of the key strategies for improving resilience. Razzaghi et al. (2026) explain that distribution systems with flexible configurations and backup capacity are more capable of maintaining service continuity during disturbances. In this context, the inserted transformer provides operational redundancy because part of the load can be shifted or supported by an additional transformer. This condition improves operational flexibility and reduces dependence on a single overloaded transformer.

From a risk management perspective, the inserted transformer reduces the exposure of the main transformer to peak loading. Lower loading reduces thermal stress, decreases failure probability, and extends the available response time for maintenance planning. From a resilience perspective, the inserted transformer provides additional capacity and operational flexibility that can support the system during load growth, disturbance, or maintenance conditions. In addition to physical intervention, digital monitoring and data analytics are increasingly relevant in distribution system management. Digital monitoring allows utilities to collect real-time data on current, voltage, temperature, loading percentage, phase imbalance, and neutral current. Big data analytics can help identify load patterns, detect overload trends, and support preventive maintenance decisions. Although artificial intelligence and analytical models have been discussed in various research contexts, their relevance in power distribution lies in their ability to support data-driven decision-making and reduce the complexity of operational analysis (Addae & Brown, 2025). Therefore, inserted transformer implementation can be strengthened in the future by integrating field intervention with digital monitoring and predictive analytics.

The need for reliable electricity infrastructure also has broader socio-economic relevance. Elpisah et al. (2021) emphasize that regional economic structure is important in understanding development performance, while Nurhidayah et al. (2024) show that local economic sectors require supporting systems to improve productivity. In this context, reliable electricity distribution is one of the supporting infrastructures needed for households, public services, and productive economic activities. Therefore, improving distribution transformer reliability through load redistribution has both technical and developmental significance.

2.5. Literature Synthesis and Research Gap

Previous studies have examined transformer thermal aging, load forecasting, transformer overload mitigation, phase imbalance, neutral current, and distribution system resilience. However, many of these studies discuss the issues separately. Thermal studies tend to focus on hot-spot temperature and insulation aging, while phase-balance studies focus on current imbalance and losses. Meanwhile, reliability and resilience studies often focus on system planning and redundancy. The research gap lies in the limited empirical evidence that integrates transformer loading reduction, phase balance improvement, neutral current reduction, reserve capacity, and resilience implications within one practical case of inserted transformer implementation. This study addresses that gap by analyzing field measurement data before and after the installation of a 160 kVA inserted transformer on transformer ABE-262 at PT PLN (Persero) ULP Abepura, Koya Barat. The novelty of this study lies in its integrated technical analysis. The study does not only report the reduction in main transformer loading, but also examines how load redistribution affects phase imbalance, neutral current, reserve capacity, and distribution system reliability. Therefore, this study contributes practical evidence for utilities in designing cost-effective load redistribution strategies in semi-urban distribution networks.

2.6. Hypothesis Development

a. Effect of Inserted Transformer on Transformer Loading

Transformer overload occurs when the supplied load approaches or exceeds the recommended operating capacity. Overloaded transformers experience higher thermal stress, which accelerates insulation aging and increases the risk of failure. Previous studies show that additional distribution equipment and targeted load redistribution can reduce transformer loading and improve asset utilization (Krstivojević et al., 2025; Muhammad et al., 2022). The installation of an inserted transformer functions as a load-sharing mechanism. When part of the customer load is transferred from the main transformer to the inserted transformer, the apparent power supplied by the main transformer decreases. As a result, the loading percentage of the main transformer is expected to decrease. In this study, the effect is evaluated by comparing the loading percentage of transformer ABE-262 before and after the installation of the inserted transformer. The theoretical expectation is that the inserted transformer will reduce the burden of the main transformer and move its operating condition into a safer loading range.

H1: The installation of an inserted transformer has a significant effect on reducing the loading of the main distribution transformer.

b. Effect of Inserted Transformer on Phase Balance

Phase imbalance occurs when the current distribution among R, S, and T phases is unequal. This condition is common in low-voltage networks dominated by single-phase customers. High phase imbalance can cause voltage fluctuation, additional heating, power losses, and lower service quality. Rizal et al. (2025) and Sinurat (2026) show that improving phase balance can reduce technical losses and improve transformer efficiency. The installation of an inserted transformer allows part of the load to be reallocated. If the load transfer is conducted by considering phase-current distribution, the imbalance among phases can be reduced. Therefore, the inserted transformer is expected to improve phase balance in the distribution system. This hypothesis is supported by the logic that load redistribution affects not only the total load but also the proportional distribution of current among phases. In this study, phase balance is evaluated by comparing the phase-current conditions before and after the intervention.

H2: The installation of an inserted transformer has a significant effect on improving phase balance in the distribution system.

c. Effect of Inserted Transformer on Neutral Current

Neutral current is mainly caused by unbalanced phase currents in a three-phase distribution system. When phase currents are unequal, the difference generates current flow in the neutral conductor. This neutral current contributes to conductor heating and additional technical losses. The relationship between phase imbalance and neutral current has been confirmed in previous studies. Rizal et al. (2025) found that higher phase imbalance increases neutral current and power losses, while Sinurat (2026) showed that phase balancing can reduce neutral current and improve transformer efficiency. The inserted transformer is expected to reduce neutral current because load redistribution can decrease the difference among phase currents. Therefore, neutral current is used in this study as a measurable indicator of improved load distribution and reduced technical losses.

H3: The installation of an inserted transformer has a significant effect on reducing neutral current in the distribution transformer.

d. Effect of Inserted Transformer on System Reliability

System reliability depends on the ability of distribution components to operate within safe technical limits. A transformer that operates under excessive loading is more vulnerable to overheating, insulation degradation, and unplanned failure. Reducing transformer loading and improving phase balance are therefore important for maintaining reliable electricity supply. The inserted transformer reduces the load burden of the main transformer and improves the operating condition of the distribution network. Lower loading decreases the risk of thermal stress, while better phase balance and lower neutral current contribute to more stable operation. The theoretical justification for this hypothesis is based on the relationship between operating stress and failure probability. When the main transformer operates under lower loading and better phase-current conditions, the probability of disturbance decreases. Therefore, inserted transformer installation is expected to improve distribution system reliability.

H4: The installation of an inserted transformer has a significant effect on improving the reliability of the distribution system.

e. Effect of Inserted Transformer on System Resilience

System resilience refers to the ability of the distribution network to withstand and recover from disturbances. One of the main strategies to improve resilience is redundancy. Redundancy provides alternative capacity or operational flexibility when part of the system experiences disturbance or maintenance. The inserted transformer creates additional capacity in the distribution network. This additional capacity allows part of the load to be supported by another transformer and provides flexibility for future load growth. Razzaghi et al. (2026) emphasize that flexible and redundant configurations are important for improving distribution system resilience. In this study, the inserted transformer absorbed only part of the total load after installation, indicating that reserve capacity remained available. This reserve capacity is important because it gives the utility more flexibility to manage future demand increases, emergency conditions, and maintenance activities. Therefore, the inserted transformer is expected to strengthen the resilience of the distribution network.

H5: The installation of an inserted transformer has a significant effect on increasing the resilience of the distribution network.

III. Research Method

This study employs a descriptive quantitative case study approach based on field measurement data to evaluate the effectiveness of installing an inserted transformer in reducing overload in a medium-voltage distribution network. The case study approach is appropriate because the research focuses on a specific technical problem in one distribution network and compares measurable operating conditions before and after the intervention. The research was conducted in the Koya Barat area, managed by PT PLN (Persero) ULP Abepura, with the focus on the ABE-262 distribution transformer. Transformer overload is widely recognized as a major factor that accelerates insulation degradation, increases thermal stress, and reduces transformer service life (IEEE, 2011; Widagdo, 2023; Dong et al., 2018). The methodological design was developed to evaluate whether the installation of a 160 kVA inserted transformer could reduce transformer loading, improve phase balance, reduce neutral current, and provide reserve capacity. These indicators were selected because transformer loading is closely related to thermal performance, while phase imbalance and neutral current are associated with additional losses and operational reliability in distribution systems (IEEE, 2011; Andika et al., 2018).

3.1. Research Design and Location

Koya Barat was selected as the research location because it has a consistently high peak-load profile and relatively dense customer distribution. These characteristics make the area suitable for evaluating the implementation of an inserted transformer as a load redistribution strategy. The object of this study was the ABE-262 distribution transformer in the 20 kV medium-voltage distribution system supplying residential and commercial customers. The unit of analysis in this study is the operating condition of the ABE-262 distribution transformer before and after the installation of the inserted transformer. The comparison was conducted during two operating periods, namely peak load time or Waktu Beban Puncak (WBP) and off-peak load time or Luar Waktu Beban Puncak (LWBP). WBP was observed at 19:00 WIT, while LWBP was observed at 10:00 WIT. These two time points were selected because transformer loading generally varies between peak and off-peak periods, and such variation needs to be considered when evaluating distribution transformer performance (Rahmawati et al., 2024).

The selection of ABE-262 as the research sample was based on purposive technical criteria. The criteria include: (1) the transformer experienced loading close to or above the recommended operational limit during WBP; (2) the transformer supplied an area with relatively dense customer load; (3) the location allowed the installation of an inserted transformer without primary network reconstruction; and (4) before-and-after measurement data were available for analysis. Purposive selection is appropriate in technical case studies when the selected object directly represents the operational problem being investigated (Muhammad et al., 2022; Anjas & Ilham, 2022).

3.2. Data Sources and Data Collection Procedure

This study uses field measurement data consisting of transformer operating conditions before and after the installation of the inserted transformer. The data include phase currents, line-to-line voltage, apparent power, transformer loading percentage, phase imbalance, and neutral current. The data were obtained from operational measurements conducted in the Koya Barat distribution network managed by PT PLN (Persero) ULP Abepura. To improve the validity and reliability of the data, the secondary operational data were verified through three procedures. First, the data were checked for completeness by ensuring that each measurement included phase current, voltage, loading percentage, and neutral current. Second, the data were checked for consistency by comparing the values recorded during WBP and LWBP with the known operating characteristics of the transformer. Third, the data were validated through cross-checking with PLN field measurement records and technical calculation results. Data validation is necessary because accurate monitoring and evaluation of transformer parameters are essential for preventing equipment failure and ensuring system reliability (Dhingra et al., 2008).

The data collection procedure was conducted in five stages. First, the pre-intervention operating condition of transformer ABE-262 was recorded during WBP and LWBP. Second, the inserted transformer was installed at the selected load point. Third, a portion of the low-voltage customer load was transferred from the main transformer to the inserted transformer. Fourth, post-intervention measurements were conducted during the same operating periods, namely WBP and LWBP. Fifth, the pre-intervention and post-intervention data were compared to evaluate the technical effect of the inserted transformer. This before-and-after comparison is relevant for evaluating load redistribution because inserted transformer implementation is expected to reduce the burden of the main transformer and improve distribution network performance (Muhammad et al., 2022; Anjas & Ilham, 2022).

3.3. Equipment and Measurement Parameters

Data collection was carried out using calibrated digital measuring instruments with an accuracy level of approximately ±1%. The measuring instruments were used to record electrical parameters on the low-voltage side of the distribution transformer. The measured parameters include phase currents in R, S, and T phases, line-to-line voltage, apparent power in kVA, transformer loading percentage relative to nominal capacity, and neutral current. Instrument calibration and measurement accuracy were considered to reduce potential measurement errors. Before the measurement results were used for analysis, the instruments were checked to ensure that the readings were stable and suitable for field measurement. The same types of parameters were recorded before and after the installation of the inserted transformer to ensure comparability. Measurement consistency is important because transformer performance evaluation depends on reliable current, voltage, and loading data (Dhingra et al., 2008; IEEE, 2011).

The measurement parameters were selected because each parameter is directly related to the research objectives. Phase current and voltage were used to calculate apparent power. Apparent power was used to determine the transformer loading percentage. Phase-current differences were used to evaluate phase imbalance. Neutral current was used as an additional indicator of load imbalance and technical losses. Phase imbalance and excessive loading are known contributors to transformer overheating, power losses, and reduced service life (Andika et al., 2018; Rizal et al., 2025; Sinurat, 2026). In addition, environmental conditions such as ambient temperature and humidity were considered during measurement because environmental and thermal conditions can influence transformer performance. Temperature rise directly affects insulation aging and operational reliability; therefore, transformer loading was used as a major indicator of thermal stress and long-term equipment reliability (Naiborhu, 2026; Staszewski et al., 2025).

3.4. Inserted Transformer Installation Procedure

The inserted transformer was installed at a medium-load point located approximately ±180 meters from the main transformer. This location was selected to enable load redistribution without requiring reconstruction of the primary medium-voltage network. The inserted transformer used in this study has a capacity of 160 kVA, a voltage ratio of 20 kV/400 V, and ONAN cooling type. The installation process was performed by connecting the inserted transformer to support the existing low-voltage distribution network. Load redistribution was carried out by transferring a portion of customer load from the main transformer to the inserted transformer through reconnection of low-voltage cable connections at the distribution panel.

The technical logic of the installation was based on load-sharing between the main transformer and the inserted transformer. By transferring part of the customer load to the inserted transformer, the apparent power supplied by the main transformer was expected to decrease. This reduction would lower the loading percentage of the main transformer and provide additional reserve capacity in the distribution network. Similar load redistribution through inserted transformers has been reported as an effective approach for reducing transformer overload in PLN distribution networks (Muhammad et al., 2022; Anjas & Ilham, 2022). This study does not introduce a completely new measurement method. However, the methodological contribution lies in the integrated before-and-after evaluation of inserted transformer implementation using several technical indicators at the same time, namely transformer loading percentage, phase imbalance, neutral current, and reserve capacity. This integrated evaluation provides a more comprehensive assessment than simply comparing transformer loading before and after installation.

3.5. Load Calculation and Analysis

Current and voltage data from the three phases (R, S, T) were measured under WBP and LWBP conditions, then used to calculate apparent power (S) and loading percentage. The formulas used are as follows:

$$S = \sqrt{3} \times V \times I (1)$$

$$\text{Loading Percentage} = \frac{S}{S_{\text{nominal}}} \times 100\% (2)$$

These formulas are commonly used in three-phase distribution transformer analysis because apparent power, voltage, and current are the main parameters for evaluating transformer loading. The calculated loading percentage was then compared with the recommended operating limit for transformer loading to assess whether the transformer operated under safe or overloaded conditions (IEEE, 2011). The calculation results were used to compare four main operating conditions: (1) the loading of the main transformer before insertion during WBP; (2) the loading of the main transformer before insertion during LWBP; (3) the loading of the main transformer after insertion during WBP; and (4) the loading of the main transformer after insertion during LWBP. In addition, the loading absorbed by the inserted transformer was also calculated to identify reserve capacity and the effectiveness of load redistribution. The analysis was conducted using a descriptive quantitative approach. Numerical results were examined to assess changes in transformer loading, phase-current distribution, phase imbalance, and neutral current before and after the installation of the inserted transformer.

3.6. Phase Balance and Neutral Current Analysis

Phase balance was evaluated based on the difference in current between phases. The imbalance was calculated using the following formula:

$$\text{Phase Imbalance (\%)} = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{avg}}} \times 100\% (3)$$

An imbalance value below 10% was used as the reference criterion for interpreting phase stability in the distribution system. This criterion was used because excessive phase imbalance can increase neutral current, conductor heating, technical losses, and transformer stress (IEEE, 2019; Andika et al., 2018). Neutral current was analyzed as an indicator of load imbalance in the three-phase low-voltage distribution system. When the current distribution among R, S, and T phases is not proportional, neutral current increases. Therefore, a reduction in neutral current after the installation of the inserted transformer is interpreted as an improvement in phase balance and a reduction in technical losses. Previous studies also confirm that better phase balance can reduce neutral current and improve transformer efficiency (Rizal et al., 2025; Sinurat, 2026).

3.7. Data Validation and Measurement Reliability

The analysis in this study was conducted by integrating all measured parameters into one evaluation framework. Transformer loading percentage was used to determine whether overload was reduced. Phase imbalance was used to evaluate whether current distribution across R, S, and T phases became more proportional. Neutral current was used to assess whether load imbalance and potential technical losses decreased. The loading percentage of the inserted transformer was used to determine whether reserve capacity remained available for future load growth. The interpretation of results was linked directly to the research objectives and conclusions. If the loading percentage of the main transformer decreased after installation, the inserted transformer was considered effective in reducing overload. If phase imbalance and neutral current decreased, the inserted transformer was considered effective in improving load distribution and operational efficiency. If the inserted transformer still had unused capacity, the system was considered to have additional reserve capacity that could support future demand growth and system resilience. This integrated analysis ensures that the conclusion is not based only on one parameter, but on a combination of technical indicators that represent transformer loading, load balance, efficiency, reliability, and resilience. This approach is consistent with the view that distribution system reliability is influenced by load management, equipment condition, phase balance, and operational flexibility (Rouholamini et al., 2025; Razzaghi et al., 2026).

IV. Result and Discussion

4.1. Research Findings

a. Transformer Loading Before the Installation of the Inserted Transformer

The measurement results show that the ABE-262 distribution transformer experienced high loading before the installation of the inserted transformer. During peak load time or Waktu Beban Puncak (WBP), the transformer loading reached 92.40%. During off-peak load time or Luar Waktu Beban Puncak (LWBP), the loading decreased to 78.94%. These values indicate that the transformer operated close to or above the commonly recommended operational loading limit, particularly during WBP. The loading condition before the intervention confirms that ABE-262 was exposed to a high thermal-risk operating condition. A loading level above 90% during WBP indicates a limited operating margin and increases the possibility of thermal stress, insulation degradation, and service reliability problems. Although the LWBP loading was lower, the value of 78.94% still approached the operational warning limit. Therefore, the transformer required a load redistribution strategy to reduce the burden during peak and off-peak conditions.

Table 1. Loading of Transformer ABE-262 Before the Installation of the Inserted Transformer

Condition	Peak Load Time (WBP)	Off-Peak Load Time (LWBP)
Before Insertion	92.40%	78.94%

Table 1 shows the loading condition of transformer ABE-262 before the installation of the inserted transformer. During peak load time (WBP), the main transformer operated at 92.40% of its capacity, indicating an overload condition. Although the loading slightly decreased to 78.94% during LWBP, this condition still approached the recommended operational capacity limit of 80%. Excessive loading can lead to thermal stress and insulation degradation, as reported by Muhammad et al. (2022), who found that transformer overloading accelerates insulation degradation and reduces the operational lifespan of the transformer. This finding is also consistent with Roy et al. (2023), who highlight that increased load stress—especially during peak demand—can significantly impact transformer thermal conditions and overall performance.

b. Transformer Loading After the Installation of the Inserted Transformer

After the installation of the inserted transformer, the loading of the main transformer ABE-262 decreased significantly. During WBP, the loading decreased from 92.40% to 63.12%. During LWBP, the loading decreased from 78.94% to 26.56%. Meanwhile, the inserted transformer absorbed 13.32% of the total load during WBP and 9.47% during LWBP. These results indicate that the inserted transformer successfully redistributed part of the load from the main transformer to the additional transformer. The decrease from 92.40% to 63.12% during WBP represents a reduction of 29.28 percentage points. Meanwhile, the decrease from 78.94% to 26.56% during LWBP represents a reduction of 52.38 percentage points. This reduction shows that the main transformer operated within a safer loading range after the intervention.

Table 2. Calculation Results of Transformer ABE-262 Loading After Installation of the Inserted Transformer

Condition	Peak Load Time (WBP)	Off-Peak Load Time (LWBP)
After Insertion	63.12%	26.56%
Inserted Transformer	13.32%	9.47%

Table 2 indicates that the inserted transformer did not operate near its maximum capacity after installation. The loading absorbed by the inserted transformer was only 13.32% during WBP and 9.47% during LWBP. This condition is technically important because it shows the availability of reserve capacity for future load growth. In other words, the inserted transformer does not only reduce the immediate overload problem but also provides operational flexibility for the distribution network.

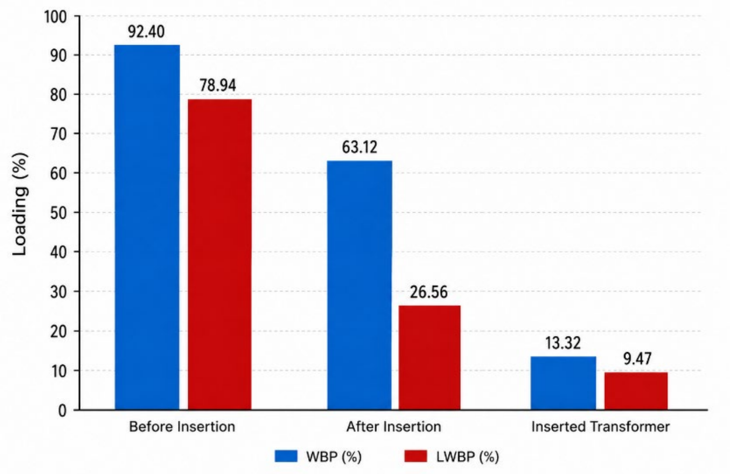


Figure 1. Comparison of Transformer ABE-262 Loading Before and After Installation of the Inserted Transformer

Figure 1 presents the comparison of transformer loading before installation, after installation, and on the inserted transformer. The figure shows that the main transformer loading decreased substantially after the intervention, while the inserted transformer still had a large unused capacity. The visual comparison supports the quantitative finding that load redistribution through an inserted transformer is effective in reducing the loading burden of the main transformer.

c. Phase Balance and Neutral Current During LWBP

The measurement results during LWBP show that the installation of the inserted transformer improved the phase-current distribution of the main transformer. Before installation, the phase currents were 113.6 A for phase R, 133.2 A for phase S, and 153.3 A for phase T. The neutral current reached 69.7 A, while the phase imbalance was 12.4%. After the installation of the inserted transformer, the phase currents of the main transformer decreased to 42.93 A for phase R, 60.5 A for phase S, and 87.9 A for phase T. The neutral current decreased to 49.3 A, and the phase imbalance decreased to 5.6%. The reduction in phase imbalance from 12.4% to 5.6% indicates an improvement in phase balance after load redistribution. This reduction is equivalent to a decrease of 6.8 percentage points. The neutral current also decreased from 69.7 A to 49.3 A, or by 20.4 A. These changes indicate that the load transfer was not only effective in reducing the main transformer loading but also improved the proportional distribution of current among phases.

Table 3. Comparison of Transformer Loading Before, After, and Inserted Transformer at ABE-262 Substation, Koya Barat Area During LWBP

Measurement Time	Phase Current R (A)	Phase Current S (A)	Phase Current T (A)	Neutral Current (A)	Phase Imbalance (%)
Before Insertion	113.6	133.2	153.3	69.7	12.4%
After Insertion	42.93	60.5	87.9	49.3	5.6%
Inserted Transformer	16.35	18.4	6.35	18.37	9.49%

Table 3 shows that the current values of the main transformer decreased after the installation of the inserted transformer. The reduction in neutral current confirms that phase-current distribution became more balanced. This result is consistent with the theoretical relationship between phase imbalance and neutral current, where a more balanced current distribution reduces current flow in the neutral conductor. Lower neutral current can contribute to lower conductor heating, lower technical losses, and better distribution efficiency.

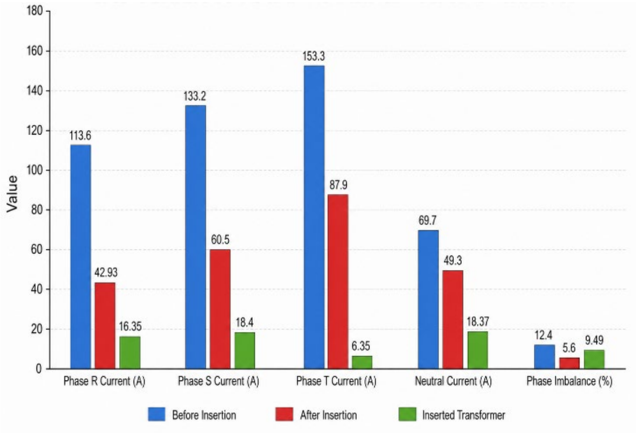


Figure 2. Comparison of Transformer Loading Before, After, and Inserted Transformer During LWBP

Figure 2 illustrates the reduction in phase currents, neutral current, and phase imbalance during LWBP. The figure should be presented in an editable chart format rather than as a screenshot, and the same color scheme and axis style should be used consistently with the other figures.

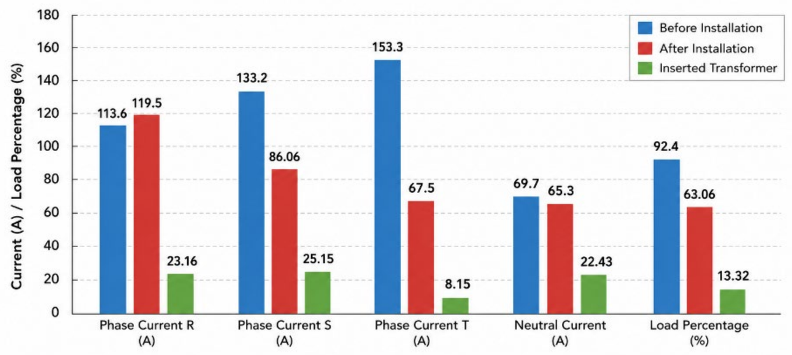
d. Phase Balance, Neutral Current, and Loading During WBP

During WBP, electricity demand reached its highest operating condition. Before the installation of the inserted transformer, the main transformer recorded phase currents of 113.6 A for phase R, 133.2 A for phase S, and 153.3 A for phase T. The neutral current was 69.7 A, and the loading percentage reached 92.40%. After the installation of the inserted transformer, the phase currents of the main transformer changed to 119.5 A for phase R, 86.06 A for phase S, and 67.5 A for phase T. The neutral current decreased to 65.3 A, while the loading percentage decreased to 63.12%. The inserted transformer absorbed part of the load, with phase currents of 23.16 A for phase R, 25.15 A for phase S, and 8.15 A for phase T. The neutral current of the inserted transformer was 22.43 A, and its loading percentage was 13.32%. Although phase R of the main transformer increased slightly after the intervention, the total loading percentage decreased substantially from 92.40% to 63.12%. This condition indicates that the intervention reduced the overall loading burden of the main transformer, even though phase-current redistribution still requires further balancing. Therefore, the finding does not contradict load redistribution theory; rather, it shows that inserted transformer installation should be followed by more detailed phase allocation adjustment to achieve optimal phase balance.

Table 4. Comparison of Transformer Loading Before, After, and Inserted Transformer at ABE-262 Substation, Koya Barat Area During WBP

Measurement Time	Phase Current R (A)	Phase Current S (A)	Phase Current T (A)	Neutral Current (A)	Loading Percentage (%)
Before Insertion	113.6	133.2	153.3	69.7	92.40%
After Insertion	119.5	86.06	67.5	65.3	63.06%
Inserted Transformer	23.16	25.15	8.15	22.43	13.32%

Table 4 shows that the inserted transformer reduced the main transformer loading during peak load conditions. The reduction in neutral current from 69.7 A to 65.3 A also indicates an improvement, although the decrease was smaller than that observed during LWBP. This result suggests that peak-load conditions are more dynamic and may require additional load-balancing adjustments after the installation of the inserted transformer.



Condition	Phase Current R (A)	Phase Current S (A)	Phase Current T (A)	Neutral Current (A)	Load Percentage (%)
🟦 Before Installation	113.6	133.2	153.3	69.7	92.4
🟥 After Installation	119.5	86.06	67.5	65.3	63.06
🟩 Inserted Transformer	23.16	25.15	8.15	22.43	13.32

Figure 3. Comparison of Transformer Loading Before and After Installation of the Inserted Transformer During WBP

Figure 3 illustrates the comparison of transformer loading during peak load time (WBP) before and after the installation of the inserted transformer. Prior to installation, the main transformer ABE-262 operated at 92.40% of its capacity during WBP. After installation, the loading of the main transformer decreased to 63.06%. The inserted transformer absorbed 13.32% of the total load during WBP, helping to reduce the load on the main transformer and distribute it more evenly, thereby improving power distribution efficiency. The implementation of an inserted transformer not only reduces the main load but also creates redundancy within the distribution system. In the event of a disturbance in one transformer, part of the load can be transferred to another transformer, although not entirely. This condition enhances system resilience and extends the technical response time in handling disturbances, as discussed by Diahovchenko et al. (2022). These findings indicate that the implementation of an inserted transformer can function as a secondary protection solution, strengthening the operational reliability of distribution networks, particularly in semi-urban areas.

4.2. Discussion

The findings of this study confirm that the installation of an inserted transformer is effective in reducing overload on the ABE-262 distribution transformer. The main transformer loading decreased from 92.40% to 63.12% during WBP and from 78.94% to 26.56% during LWBP. This reduction indicates that the inserted transformer successfully transferred part of the electrical load from the main transformer to an additional transformer. The reduction in loading has practical implications for transformer thermal management. A transformer that operates at a lower loading percentage has a lower probability of excessive temperature rise, insulation aging, and premature equipment failure. Therefore, the installation of the inserted transformer can be interpreted as a preventive asset-management strategy. This finding supports IEEE (2011), which emphasizes the importance of controlling transformer loading to reduce thermal stress and maintain transformer service life.

The results are also consistent with Muhammad et al. (2022), who found that inserted transformer installation in a PLN distribution network reduced transformer loading without requiring extensive primary network reconstruction. Similar findings were reported by Anjas and Ilham (2022), who showed that the addition of an inserted substation improved network efficiency and reduced loading problems. The consistency between this study and previous Indonesian studies indicates that the inserted transformer approach is suitable for local distribution networks where demand growth occurs faster than network reinforcement. Compared with international studies, this research provides a more local and practical perspective. Roy et al. (2023) and Zhang et al. (2025) discuss transformer loading problems in relation to modern load growth, electric vehicle penetration, and thermal stress. Those studies emphasize the need for advanced monitoring and demand-side management. However, the local condition in Koya Barat differs from many international contexts because the distribution network still requires practical and infrastructure-based solutions that can be implemented without complex digital control systems. Therefore, the inserted transformer is more appropriate for semi-urban areas with limited infrastructure readiness.

The improvement in phase balance also supports the effectiveness of load redistribution. During LWBP, phase imbalance decreased from 12.4% to 5.6%, while neutral current decreased from 69.7 A to 49.3 A. This result is consistent with Jain and Karimi-Ghartemani (2022), who state that phase symmetry plays an important role in reducing energy losses and improving transformer operating conditions. The decrease in neutral current indicates that the intervention improved current distribution across the phases and reduced potential technical losses in the neutral conductor. However, the WBP data show an important operational finding. Although the overall transformer loading decreased significantly, phase R current increased from 113.6 A to 119.5 A after installation. This result is not a contradiction to the theory of load redistribution. Instead, it indicates that the total load was successfully reduced, but phase-level load transfer was not yet fully optimized. This finding highlights the need for post-installation phase balancing to ensure that the benefits of inserted transformer installation are distributed evenly across all phases.

The long-term impact of the inserted transformer can be explained through three aspects: maintenance cost, energy loss, and system resilience. First, lower loading reduces thermal stress, which can reduce the frequency of maintenance and delay premature transformer replacement. Second, lower neutral current and improved phase balance can reduce technical losses, particularly losses caused by unbalanced current flow. Third, the reserve capacity available in the inserted transformer provides operational flexibility for future demand growth and emergency load transfer. From a cost perspective, the inserted transformer approach may be more economical than large-scale network reconstruction. The installation can reduce overload by redistributing existing low-voltage loads, while avoiding major changes in the primary network. For PLN and similar utility operators, this strategy can be implemented as a staged investment: first by identifying overloaded transformers, then installing inserted transformers at strategic load centers, and finally integrating the system with digital monitoring for long-term optimization.

The findings also support the concept of resilience in distribution systems. Diahovchenko et al. (2022) emphasize the importance of reducing transformer loss of life under high loading conditions. In this study, the inserted transformer created additional capacity and reduced dependence on a single overloaded transformer. This redundancy strengthens operational resilience because the system has more flexibility during load growth, disturbance, or maintenance activities. Overall, the findings align with existing theories on transformer loading, phase balance, and distribution reliability. The results do not contradict previous theories; instead, they refine the practical understanding of inserted transformer implementation. The main contribution of this study is the empirical evidence that inserted transformer installation can reduce overload, improve phase balance, reduce neutral current, provide reserve capacity, and support distribution system resilience in a semi-urban Indonesian distribution network.

V. Conclusion

This study concludes that the installation of a 160 kVA inserted transformer is an effective technical solution for reducing overload on the ABE-262 distribution transformer at PT PLN (Persero) ULP Abepura, Koya Barat. The loading of the main transformer decreased from 92.40% to 63.12% during WBP and from 78.94% to 26.56% during LWBP. The inserted transformer absorbed 13.32% of the total load during WBP and 9.47% during LWBP, indicating that reserve capacity remains available for future load growth. The installation of the inserted transformer also improved load distribution. During LWBP, phase imbalance decreased from 12.4% to 5.6%, and neutral current decreased from 69.7 A to 49.3 A. During WBP, the neutral current also decreased from 69.7 A to 65.3 A. These results indicate that the inserted transformer contributed to better phase distribution and reduced the burden on the main transformer.

The practical implication of this study is that inserted transformers can be used by utility operators as a cost-effective load redistribution strategy in areas with limited infrastructure capacity. PLN can apply this strategy by identifying overloaded transformers, mapping customer load distribution, selecting strategic insertion points, transferring low-voltage loads based on phase-current conditions, and conducting post-installation monitoring. This study also shows that inserted transformer installation should not stop at load transfer. Additional phase balancing is needed after installation, especially during WBP, because phase-level current distribution may still be uneven even when total transformer loading decreases. Therefore, post-installation evaluation of phase currents, neutral current, voltage profile, and loading percentage is necessary to ensure optimal performance.

For future research, further studies should integrate digital monitoring technologies, such as real-time current sensors, voltage monitoring, transformer temperature monitoring, and intelligent load analytics. These technologies can help utilities identify overload trends, predict future load growth, evaluate phase imbalance, and optimize load transfer decisions. Future research may also estimate the economic impact of inserted transformer installation, including maintenance cost reduction, technical loss reduction, payback period, and long-term transformer lifespan extension. In conclusion, the inserted transformer approach provides both immediate and long-term benefits. In the short term, it reduces overload and improves transformer operating conditions. In the long term, it supports distribution capacity optimization, reduces operational risk, and strengthens the resilience of semi-urban distribution networks.

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