IMPROVED POWER GRID STABILITY WITH REGULAR MAINTENANCE OF MEDIUM-VOLTAGE TRANSFORMER CONNECTIONS

Silvi Nur Rakhman Nisa'[1], Miftahur Rohman[2], Mochamad Faris Baihaqi[3]
[1,2]Department Electrical Engineering, Faculty Engineering, State University of Surabaya, Surabaya, 60231, Indonesia
[3]PT. PLN (Persero) ULP Ngagel, Gubeng, Surabaya, 60283, Indonesia
[1]silvinur.22013@mhs.unesa.ac.id
[2]miftahurrohman@unesa.ac.id
[3]m.faris@pln.co.id

Abstract

The power grid is a vital infrastructure that ensures the distribution of energy from the plant to the consumer. One of the important components in this network is the transformer, which regulates the voltage level as needed. In medium-voltage networks, transformer connections play a crucial role in maintaining system stability. Unmaintained connection conditions can cause disturbances in the form of decreased voltage quality, blackouts, and equipment damage. Unfortunately, connection maintenance is often done reactively, only when a fault occurs. This study aims to analyze the impact of routine maintenance of transformer connections on the stability of the power grid at PT PLN (Persero) UP3 South Surabaya – ULP Ngagel. The methods used include field observation, documentation of maintenance activities, and analysis of disturbance data before and after maintenance. The results of the study show that routine maintenance is able to reduce the frequency of connection failures, improve voltage stability, and extend the life of network components.

Keyword: *Transformer connection, Power grid stability, Routine maintenance, Voltage quality.*

I. INTRODUCTION

Electricity is one of the primary needs that sustain modern life. The sustainable and stable availability of electrical energy is highly dependent on reliable distribution network infrastructure (Zahra *et al.*, 2025). In the electrical system, the medium-voltage distribution network plays a crucial role as a link between substations and end consumers. In this network, the transformer is a core component that functions to adjust the voltage level, ensuring that electrical energy can be distributed efficiently and safely. Voltage stability and equipment quality, including transformers, are the main determinants of grid reliability (Lee and Kim, 2025).

One aspect that often goes unnoticed but has a big impact on network performance is transformer connections. This connection serves as a vital line for the flow of electricity. However, over time, various disturbances such as corrosion, sagging, or wear can degrade the quality of the connection (Feng *et al.*, 2025). Disruptions to these connections not only have the potential to cause voltage quality degradation and power outages, but they can also trigger serious damage to other network equipment. Unfortunately, the maintenance approach that is still widely applied is reactive, i.e. repairs are only made after the outage occurs (Hu *et al.*, 2023).

In fact, from various studies and field experience, preventive or routine maintenance approaches have been shown to significantly improve network reliability and extend the economic life of equipment. Regular maintenance, which includes periodic inspections and repairs to transformer connections, allows for early detection of potential problems before they develop into larger disruptions (Qiao *et al.*, 2025). Thus, the risk of power outages and large repair costs can be minimized.

Given this importance, this study focuses on the analysis of the effect of routine maintenance of transformer connections on the stability of the power grid in the medium voltage network at PT PLN (Persero) ULP Ngagel. This specific focus is crucial because, while much research has focused on transformers as an overall unit, they explicitly highlight and analyze connections (as critical points of weakness that are often missed) in the context of medium-voltage distribution networks, particularly those caused by corrosion, sagging, and wear. The main objective of this study is to analyze and empirically evaluate the effect of the implementation of routine maintenance of transformer connections on the voltage stability and reliability of the medium-voltage distribution network. Through this approach, we not only analyze theoretically, but also participate directly in field maintenance activities to explore and apply working principles and procedures for effective maintenance of transformer connections (Wang *et al.*, 2025).

By combining in-depth technical analysis and practical involvement in the field, it is hoped that this research can make a real contribution and solutions that can be implemented to improve preventive maintenance practices at PT PLN (Persero). In the end, the results of this study are expected to support the improvement of the quality of electrical energy services to the community, ensuring the availability of a more stable and reliable electricity supply.

II. THEORY

Transformers are indispensable static apparatuses within electrical power systems, engineered to modulate voltage levels between circuits while maintaining constant frequency (Li *et al.*, 2026). Within medium-voltage (MV) distribution networks, typically operating between 1 kV and 35 kV, their function is particularly critical (Prasojo *et al.*, 2025). These transformers serve as the primary interface for stepping down high-voltage from the transmission grid to levels suitable for industrial, commercial, and residential consumers (Zhang *et al.*, 2025). The strategic deployment of these devices is fundamental to ensuring the efficiency, safety, and stability of power distribution, especially in urban centers and industrial zones characterized by high load densities. Their performance directly dictates the viability of the entire downstream electrical infrastructure.

While the transformer core and windings are robustly designed, the integrity of the overall system often hinges on its external connections(Alabdullh *et al.*, 2024). These electromechanical joints, which link the transformer to network elements such as subterranean cables, overhead lines, busbars, and protective devices like circuit breakers, represent the most vulnerable points in the assembly. These interfaces are perpetually susceptible to degradation mechanisms, including galvanic corrosion, mechanical fretting, and loss of clamping force due to thermal cycling and vibration (Vatsa and Hati, 2024). Such deterioration inevitably leads to an increase in contact resistance, a precursor to more severe operational failures.

The consequences of a compromised transformer connection extend far beyond the localized component (Zuñiga *et al.*, 2024). An elevated contact resistance precipitates thermal runaway due to Joule heating, governed by the principle $P=I^2R$, where P is power loss, I is current, and R is resistance. This localized overheating can degrade and ultimately puncture insulation materials, creating a high-risk scenario for phase-to-ground or phase-to-phase faults, equipment fires, and extended power outages. From a systemic perspective, such a fault perturbs the stability of the grid, manifesting as significant voltage sags, perceptible voltage flicker, or even abrupt load shedding. This instability compromises the system's capacity to maintain nominal operating parameters and distribute power uniformly, threatening the reliability of service to all connected consumers (Zhang *et al.*, 2022).

To counteract the inherent risks associated with connection degradation, a proactive and data-driven preventive maintenance strategy is imperative. This regimen transcends rudimentary visual checks and encompasses a suite of sophisticated diagnostic and corrective actions. Key activities include the verification of connection torque to ensure optimal clamping force, the meticulous cleaning of terminals to remove oxides and contaminants, and the deployment of non-destructive testing methods. Infrared thermography, in particular, has proven to be an exceptionally effective tool for identifying incipient faults by detecting anomalous thermal signatures long before they escalate to catastrophic failure (Zhang *et al.*, 2021). The timely replacement of components exhibiting wear or corrosion is also a critical element of this proactive asset management approach (Islam *et al.*, 2023).

Ultimately, a rigorously implemented preventive maintenance program for transformer connections is a cornerstone of modern power grid management. By systematically identifying and rectifying potential failure points before they can impact operations, this strategy significantly mitigates the risk of unplanned outages, extends the operational lifespan of critical assets, and bolsters the overall reliability of the distribution network. The direct outcome is a more stable and efficient power delivery system, which translates to enhanced quality of service for end-users and a marked reduction in system disruption indices. Consistent maintenance is not merely a procedural requirement but a fundamental investment in the resilience and integrity of our electrical infrastructure (Abaza *et al.*, 2025).

III. METHOD

Before maintenance, there is a preliminary procedure that must be carried out, which is specifically a series of testing and administrative steps for the transformer system and its connections. The procedure can be seen in Figure 1.

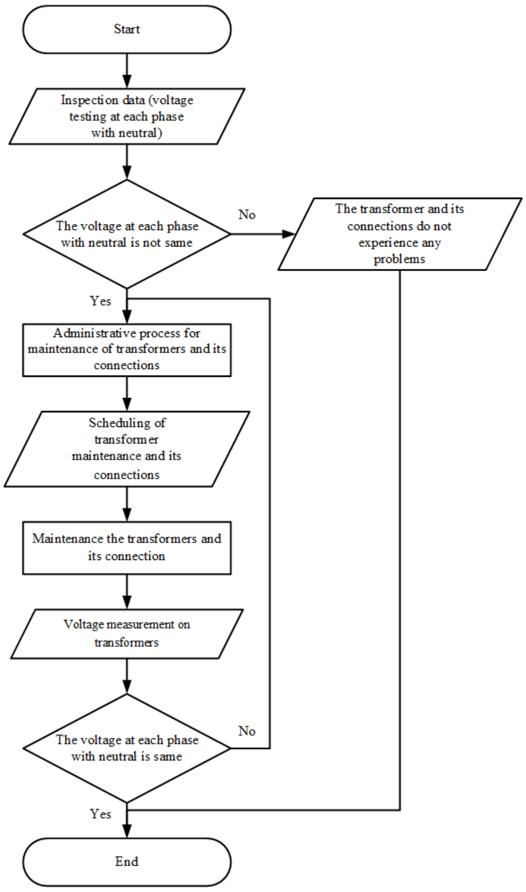

Figure 1. Maintenance Procedures

The first step of this procedure is Data Inspection by performing voltage testing at each phase against neutral. The results of these tests are then evaluated:

1. If the voltage at each phase against the neutral is the same (ideal condition), then it is concluded that the transformer and its connections are not troubled and the procedure is terminated.
2. If the voltage at each phase is not the same (indicating an imbalance), then the maintenance process must be continued.

The continued maintenance process includes:

1. Administrative process for the maintenance of transformers and their connections.
2. Scheduling of the maintenance of transformers and their connections.
3. Implementation of maintenance of transformers and their connections.

After the maintenance is completed, the voltage remeasurement is carried out on the transformer. This measurement serves as a verification: If the voltage at each phase against neutral is now the same, the procedure is considered successful and terminated. If the voltage at each phase is still not the same, then it must be repeated, restarting from the administrative process until the voltage is verified balanced.

Maintenance of transformer connections is essential to ensure optimal performance and prevent damage that can disrupt the electrical system. In the implementation of transformer connection maintenance, several steps are carried out, including:

A. Measuring voltage and current on the Split Connect Panel connected to the transformer

Before starting the maintenance of the transformer connection, it is necessary to measure the voltage and current on the connection panel for the low-voltage network. To measure how effective the maintenance is. The documentation when voltage and current measurements before starting maintenance can be seen in Figure 2.


Figure 2. Voltage and Current Measurement Before Starting Maintenance

B. Removing the Neozed Hochsicherung (NH Fuse) attached to the Low Voltage Split Contact Panel

The Neozed Hochsicherung (NH Fuse) serves as the first low-voltage safety at the transformer output. This device is designed to protect electrical installations from the impact of overcurrent. Its working principle is based on temperature-sensitive melting elements. When an overcurrent condition occurs, the elements inside the fuse will melt, physically breaking the circuit. This mechanism effectively prevents damage to connected electrical equipment, such as motors or transformers, and ensures the operational stability of the electrical system .

The main function of the NH Fuse is as a passive protection device that operates automatically in the event of a disturbance. Its high breaking capacity allows it to interrupt large short circuit currents quickly and reliably. This is crucial in electricity distribution systems to minimize downtime and repair costs. Additionally, its compact and modular design allows for easy integration into distribution panels, making it a standard choice in a wide range of industrial and commercial applications.

For operational safety and worker safety reasons, the NH Fuse removal procedure should always be prioritized before performing any work on the circuit. This fuse release ensures that the load is completely disconnected from the power source, so there is no potential danger of electric shock or arc fire. These procedures are essential for technicians and maintenance personnel to adhere to to ensure a safe working environment and prevent unwanted accidents.

C. Performing a fuse cut out (FCO)

Fuse Cut Out (FCO) is a protective device used in electrical distribution networks. Its function is to isolate the electrical circuit by limiting the voltage and excess current flowing through the system, and diverting it to the ground. The FCO operates in a simple yet effective manner, making it one of the most basic safety devices in the distribution network. Nonetheless, its main limitation is its limited use at relatively small power levels.

The FCO is known for several significant advantages. These devices are relatively economical compared to more complex protection devices, as they do not require additional equipment such as relays or instrument transformers. The FCO also has a reputation for high reliability in breaking circuits in the event of a fault. This makes it a popular choice in many distribution systems, especially in areas with limited budgets.

One of the main advantages of the FCO is its flexibility. The device is available in a variety of designs, from "disposable" to reusable versions with replaceable melt elements (links). This flexibility allows the FCO to adapt to a wide range of operational and budgetary needs. The simple, easy-to-replace design also speeds up the maintenance process in the event of a breakdown.

Figure 3. Fuse Cut Out (FCO) Termination

Nonetheless, the FCO has some significant operational weaknesses. This device is not suitable for remote control, which means the operator must be in a physical location to operate it. This is an obstacle in a system that requires quick and automated recovery. In addition, FCO is also not ideal for dual-switch operations that may be required in some more advanced network configurations.

Safety procedures in electrical work are very strict, and the order of removal of protective devices is crucial. In systems that use a combination of NH Fuse and FCO, the NH Fuse must be removed first. This ensures that the entire load is disconnected from the power source before personnel undertake further work.

After the NH Fuse is removed, only then can the FCO connected to the transformer be isolated. This sequence ensures that the entire transformer circuit is in a no-voltage state before maintenance work begins. Compliance with these procedures is essential to ensure worker safety and prevent serious electrical accidents from occurring. The documentation when removing fuse cut out can be seen in Figure 3.

D. Visual and connection checks

Figure 4. Transformer Connection Inspection

Visual examination includes physical condition and hygiene checks. Physical conditions are performed to detect signs of damage such as corrosion, oil leaks, or cracks. Hygiene checks are performed to ensure that the joints are free from dust, dirt, and moisture that may interfere with conductivity.

In connection inspections, the tightness of the connection and the condition of the cable are the main focus in maintenance. The tightness of the connections is ensured to ensure that all connections and terminals are properly installed, there are no signs of wear, or excessive expansion of the terminals. Cable condition checks are carried out to ensure that the condition of the cables and conductors at the terminals is not damaged or worn. The documentation when visual and connection checks can be seen in Figure 4.

After doing these stages, the next thing to do is to conduct an analysis. In this case, the equation used includes:

1. Average voltage using equation (1)
$$V_{Average} = \frac{V_{Phase\,R}+V_{Phase\,S}+V_{Phase\,T}}{3} \quad (1)$$
2. Margin tolerance using equation (2)
$$Margin\ Tolerance = V_{Average} \times 2\% (2)$$
3. Phase voltage percentage - inter-phase neutral using equation (3)
$$Percentage\ (\%) = \frac{V_{Max}-V_{Min}}{V_{Min}} \times 100\% (3)$$

IV. RESULTS AND DISCUSSION

When carrying out routine maintenance activities, the following transformer voltage measurement results are obtained in table 1:

Based on the results of observations before and after network maintenance, the data exposed in Table 1 was obtained. This can be interpreted as maintenance activities can be carried out because the tolerance limit of the voltage balance between phases is 2% of the average voltage, in accordance with the terms and conditions of proper operation from PT. PLN (Persero). This can be proven by the following calculations:

TABLE 1
Transformer Voltage Measurement Results

Type	Point	Before			After		
		R	S	T	R	S	T
V	P-N	232	236	242	232	234	234
V	P-P	392	396	403	392	395	395

Known phase voltage – neutral before maintenance:
Phase R = 232 Volt
Phase S = 236 Volt
Phase T = 242 Volt

From the three voltage data, it was obtained using equation (1). The average voltage obtained is as follows:

$$V_{Average} = \frac{V_{Phase\,R} + V_{Phase\,S} + V_{Phase\,T}}{3}$$
$$V_{Average} = \frac{232 + 236 + 242}{3}$$
$$V_{Average} = \frac{710}{3}$$
$$V_{Average} = 236\ Volt$$

From the average voltage data, using equation (2), a margin of 2% is obtained for a tolerance of:

$$Margin\ Tolerance = V_{Average} \times 2\%$$
$$Margin\ Tolerance = 236 \times 2\%$$
$$Margin\ Tolerance = 4{,}72\ Volt$$

With a tolerance margin of 4.72 Volts, maintenance needs to be carried out because the ratio of phase-neutral voltage between phases does not meet the requirements of the calculation. The calculation in question uses equation (3), the following results are obtained:

1. Phase R compared to Phase T (P-N)
$$Percentage = \frac{V_{Max} - V_{Min}}{V_{Min}} \times 100\%$$
$$Percentage = \frac{242 - 232}{232} \times 100\%$$
$$Percentage = \frac{10}{232} \times 100\%$$
$$Percentage = 4{,}31\%$$
2. Phase R compared to Phase S (P-N)
$$Percentage = \frac{V_{Max} - V_{Min}}{V_{Min}} \times 100\%$$
$$Percentage = \frac{236 - 232}{232} \times 100\%$$
$$Percentage = \frac{4}{232} \times 100\%$$
$$Percentage = 1{,}72\%$$
3. Phase S compared to Phase T (P-N)
$$Percentage = \frac{V_{Max} - V_{Min}}{V_{Min}} \times 100\%$$
$$Percentage = \frac{242 - 236}{236} \times 100\%$$
$$Percentage = \frac{6}{236} \times 100\%$$
$$Percentage = 2{,}54\%$$

Once the unqualified margin is known, maintenance is carried out. The results after maintenance are measured according to Table 1, and the calculations obtained are as follows:

It is known that the phase voltage – neutral after maintenance:

Phase R = 232 Volt
Phase S = 234 Volt
Phase T = 234 Volt

From the three voltage data, it was obtained using the formula (1). The average voltage obtained is as follows:

$$V_{Average} = \frac{V_{Phase\,R} + V_{Phase\,S} + V_{Phase\,T}}{3}$$

$$V_{Average} = \frac{232 + 234 + 234}{3}$$

$$V_{Average} = \frac{700}{3}$$

$$V_{Average} = 233\,Volt$$

From the average voltage data, using formula (2), a margin of 2% is obtained for a tolerance of:

$$Margin\,Tolerance = V_{Average} \times 2\%$$

$$Margin\,Tolerance = 233 \times 2\%$$

$$Margin\,Tolerance = 4{,}67\,Volt$$

With a tolerance margin of 4.67 Volts, maintenance needs to be carried out because the ratio of phase–neutral voltage between phases does not meet the requirements of the calculation. The calculation in question uses equation (3), the following results are obtained:

1. Phase R compared to Phase T (P-N)

$$Percentage = \frac{V_{Max} - V_{Min}}{V_{Min}} \times 100\%$$

$$Percentage = \frac{234 - 232}{232} \times 100\%$$

$$Percentage = \frac{2}{232} \times 100\%$$

$$Percentage = 0{,}86\%$$

2. Phase R compared to Phase S (P-N)

$$Percentage = \frac{V_{Max} - V_{Min}}{V_{Min}} \times 100\%$$

$$Percentage = \frac{234 - 232}{232} \times 100\%$$

$$Percentage = \frac{2}{232} \times 100\%$$

$$Percentage = 0{,}86\%$$

3. Phase S compared to Phase T (P-N)

$$Percentage = \frac{V_{Max} - V_{Min}}{V_{Min}} \times 100\%$$

$$Percentage = \frac{234 - 234}{234} \times 100\%$$

$$Percentage = \frac{0}{234} \times 100\%$$

$$Percentage = 0\%$$

To make it easier to visualize, the graph of the voltage for each phase with neutral, can be seen in Figure 5.

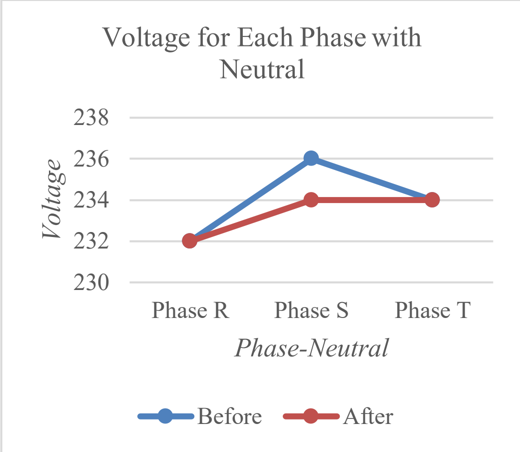

Figure 5. The Graph of The Voltage for Each Phase with Neutral

The analysis of the results of the voltage measurement of this transformer is based on the operational standards set by PT. PLN (Persero), namely: The balance tolerance limit of phase-neutral voltage is a maximum of 2% of the average voltage of the system. Maintaining voltage balance is a crucial aspect in transformer maintenance to ensure even load distribution and prevent equipment damage due to overheating in high-load phases.

1. Pre-Maintenance Conditions

The calculation shows that the average voltage (V_{avg}) before maintenance is 236.67 Volts. With a tolerance of 2%, a margin limit of 4.73 Volts is obtained as in Table 2.

The calculation results show that the imbalance between phases R and T (difference of 10 Volt) and phases S and T (difference of 6 Volt) significantly exceeds the tolerance limit of 4.73 Volt (2%). This large difference indicates a load balancture on the secondary side of the transformer. This imbalance has the potential to cause one of the phases to carry a much larger current load, which in turn can increase the overall operating temperature of the transformer and accelerate insulation degradation, which can ultimately trigger unplanned failures.

TABLE 2
Pre-Maintenance Conditions

Phase Comparison	Voltage Difference (Volts)	Status (Eligible?)
Phase R versus Phase T	232 - 242	No
Phase R versus Phase S	232 - 236	Yes
Phase S versus	236 - 242	No

Phase T		

2. Post-Maintenance Condition

TABLE 3
Post-Maintenance Condition

Phase Comparison	Voltage Difference (Volts)	Status (Eligible?)
Phase R versus Phase T	232 - 234	Yes
Phase R versus Phase S	232 - 234	Yes
Phase S versus Phase T	234 - 234	Yes

Once maintenance is performed (which likely involves phase load balancing), the average voltage (V_{avg}) changes to 233.33 Volts, resulting in a tolerance margin limit of 4.67 Volts obtained as in Table 3.

All phase-neutral comparisons after maintenance result in a voltage difference (maximum of 2 Volts) that is well below the tolerance limit of 4.67 Volts. These results show that the maintenance actions carried out (such as re-balancing the load on the network or connection repairs) have been completely successful in addressing the problem of voltage imbalance. The impact on the system is:

a. Transformer Efficiency Increased. The load is distributed more evenly, reducing power losses in the transformer.
b. Longer Equipment Life. Transformer components operate under more optimal temperature and stress conditions, extending transformer life.
c. Customer Power Quality. The customer receives a stable and balanced voltage, which is important for the operation of sensitive equipment.

In maintaining the reliability of electricity distribution, PT. PLN (Persero) has parameters that are used as a benchmark for reliability. These parameters include:

A. SAIDI (*System Average Interruption Duration Index*) is the average duration of power outages felt by customers per year. SAIDI is formulated as follows:

$$SAIDI = \frac{\Sigma U_i n_i}{\Sigma N} \quad (4)$$

With:

U_i is the duration of the outage
n_i the number of customers is extinguished
N is the number of customers served

B. SAIFI (*System Average Interruption Frequency Index*) is the average frequency of outages felt by customers per year. SAIFI is formulated as follows:

$$SAIFI = \frac{\Sigma n_i}{\Sigma N} \quad (5)$$

With:

n_i the number of customers is extinguished
N is the number of customers served

The parameters SAIDI (average duration of outages) and SAIFI (average frequency of outages) are the key metrics used by PT. PLN to measure the level of reliability of electricity services. Although U_i, n_i, and N data for actual calculations are not available, the analysis should elucidate the relationship between voltage correction and these two indices.

Voltage imbalances that occur before maintenance (10 V balance) are high-risk factors that may indirectly worsen the value of SAIDI and SAIFI in the future.

1. Increased risk of outages. Severe overbalancing can cause chronic overloading in one of the transformer phases, leading to internal damage (such as hotspots or coil failure). This damage will result in an unplanned forced outage.
2. Impact on the Index. Each such forced blackout will:
   a. Improve SAIDI. Because the duration of the outage (U_i) will be high, considering that repairing the transformer takes a long time.
   b. Increase SAIFI. As the frequency of blackout events (n_i) increases.

The results of maintenance that successfully balance the voltage (as shown by the data after maintenance) have an immediate impact i.e. Outage Risk Mitigation. With a balanced voltage, the transformer operates under safer conditions, reducing the probability of unplanned outages caused by phase overload.

To support these findings, we can compare hypothetical reliability data (based on operational experience) assumed before and after this corrective maintenance in Table 2:

TABLE 2
Reliability Index Yield Forecast

Indicator	Conditions if There is No Maintenance (High Risk)	Conditions After Successful Maintenance (Low Risk)
SAIDI (Minutes/ Subscribers/ Years)	Higher (e.g., > 300)	Lower (e.g., < 150)
SAIFI (Time/ Customer/ Year)	Higher (e.g., > 5)	Lower (e.g., < 3)

The maintenance carried out not only improves the quality of power at the time of observation, but is also a vital preventive measure to maintain the performance targets of SAIDI and SAIFI PT. PLN (Persero). By reducing the risk of transformer failure due to voltage balancing, the reliability of the electricity distribution system has been fundamentally improved.

V. CONCLUSION

Inadequate maintenance of the transformer can lead to a progressive decrease in performance, characterized by an unnatural increase in operating temperature, insulation degradation, as well as the potential failure of other critical components. This impact directly affects the stability and quality of electricity services, as well as causing financial losses due to emergency repairs and loss of revenue. Therefore, an effective maintenance strategy—including routine inspections, diagnostic testing, and timely corrective interventions—is a strategic investment to maintain the reliability of the power distribution system and the health of transformer assets. Based on the results of measurements in the field, maintenance proved absolutely necessary because before the intervention there was a significant voltage imbalance with a difference of 10 Volts, exceeding the tolerance limit of 4.73 Volts (2% of the average voltage of 236.67 Volts), which had the potential to trigger transformer failure. After maintenance, the average voltage is 233.33 Volts with a difference between phases of only 2 Volts, below the tolerance limit of 4.67 Volts. These results show that actions such as load balancing and connection repair have succeeded in normalizing voltage, reducing the risk of forced outage, and increasing the reliability of the electricity distribution system according to the target index of SAIDI and SAIFI PT. PLN.

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