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Load Imbalance Analysis on Low-Voltage Distribution Network: A Case Study on SM3 Feeder, Tomohon Main Substation

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Abstract

Load imbalance on low-voltage distribution networks arises from the uneven distribution of single-phase loads across a three-phase system, resulting in elevated neutral currents, increased power losses, and degraded voltage quality. This research systematically analyzes the degree of load imbalance on the low-voltage distribution network of SM3 Feeder, Tomohon Main Substation, PT PLN (Persero) UP3 Manado, using phase current measurements, neutral current readings, and customer load data collected from field surveys. The methodology employed phase current measurements, neutral current readings, and customer load data collected from field surveys at five measurement points representing diverse loading conditions and network topologies. The percentage load imbalance (PLI) was calculated and benchmarked against SPLN D3.002-1:2007 and IEEE Std 1159 standards, with measurements conducted during morning, afternoon, and evening peak periods. Findings reveal significant imbalance in four of five assessed feeder segments, with the most critical level reaching 31.7% at MP-5. Elevated neutral currents produced measurable additional power losses in the neutral conductor, and customer terminal voltage violations were confirmed at MP-3 and MP-5, with the most severe deviation reaching −9.7% below the nominal 220 V. The study concludes that systematic load redistribution at MP-5, MP-3, and MP-1, combined with mandatory phase allocation for new connections and quarterly monitoring protocols, is required to restore standard compliance and improve network efficiency, power quality, and reliability on the SM3 Feeder distribution system.

INTRODUCTION

The reliability and quality of electric power supply are fundamental prerequisites for industrial, commercial, and residential consumers (Golmohamadi, 2022; Rzayeva et al., 2024; Sepasi et al., 2023). In modern low-voltage (LV) distribution systems, the growing penetration of single-phase loads such as household appliances, lighting installations, and small-scale business equipment creates an inherent challenge: the uneven distribution of these loads across the three phases of a three-phase four-wire system. This uneven distribution, commonly referred to as load imbalance, is one of the most pervasive power quality problems in LV distribution networks globally, and its management is a core operational responsibility for distribution utilities such as PT PLN (Persero).

In a perfectly balanced three-phase system, the phasorial sum of the three line currents is zero, resulting in no current flowing through the neutral conductor (Acharya et al., 2020; Tenti et al., 2022). However, when single-phase loads are not equally distributed, the currents in each phase differ in magnitude, and a residual current flows through the neutral conductor (Acharya et al., 2020; Sakar et al., 2021). This neutral current is not only a source of energy waste through I^2R losses in the neutral conductor, but also a driver of additional voltage drops, asymmetric terminal voltages, and potential thermal overloading of distribution transformer windings and cables (Kharrazi et al., 2020; Sakar et al., 2021; Zabihi et al., 2026). The cumulative effect of persistent load imbalance is a measurable degradation in the operational efficiency and power quality performance of the entire LV distribution segment (Kharrazi et al., 2020; Zabihi et al., 2026).

The problem of load imbalance is particularly acute in developing-country distribution environments characterized by rapid, unplanned residential load growth. In Indonesia, PT PLN (Persero)'s LV network expansion has historically been driven by customer demand rather than systematic load planning, resulting in service connection assignments that frequently ignore inter-phase load balance. The Sulawesi grid region, including the Manado area distribution system, has experienced significant load growth over the past decade, with accompanying deterioration in network power quality as documented in internal PLN engineering reports and academic studies conducted on regional distribution feeders.

The SM3 Feeder originates from the Tomohon Main Substation (150/20 kV) operated by PT PLN (Persero) UP3 Manado and serves a mixed-use area comprising residential, commercial, and light industrial customers in the hilly terrain of North Sulawesi. The geographic dispersion of customers, varying load densities, and predominantly single-phase residential service connections create conditions particularly conducive to load imbalance. Reports from field personnel and distribution engineers indicate recurring instances of elevated neutral currents and voltage quality complaints from end-of-line customers on this feeder, motivating a systematic quantitative investigation.

Several previous studies have examined load imbalance phenomena in low-voltage distribution networks. Dugan et al. (2012) and Short (2014) established the fundamental principles of power quality, including the theoretical framework for analyzing neutral currents and voltage asymmetry resulting from unbalanced load distribution. Baggini (2008) and Arrillaga and Watson (2003) provided comprehensive analyses of power system harmonics and their interaction with load imbalance, emphasizing the compounding effects of non-linear loads on neutral conductor loading. In the Indonesian context, PT PLN (Persero) has established technical standards through SPLN D3.002-1:2007, which specifies a 10% permissible limit for load imbalance in LV distribution networks, and SPLN 1:1995, which defines the acceptable voltage range of 209–231 V for customer terminals. Internationally, IEEE Std 1159-2019 provides recommended practices for monitoring electric power quality, including load imbalance assessment methodologies. Willis (2004) addressed distribution planning considerations for managing phase balance in growing LV networks, while De La Rosa (2006) and IEEE Std 519-2014 focused on harmonic control and its relationship to load balance in distribution systems.

Previous studies on LV distribution network load imbalance in Indonesia have confirmed that PLI values in the range of 15–40% are common in residential-dominated feeders, particularly in areas with high densities of small commercial loads operating predominantly on a single phase. However, site-specific quantitative analyses that correlate PLI measurements with neutral current magnitudes, power loss estimates, and terminal voltage data at multiple measurement points along a single feeder remain limited in the published literature for the

North Sulawesi distribution context. This study addresses that gap by providing a comprehensive, multi-point measurement-based assessment of load imbalance on the SM3 Feeder. The novelty of this research lies in its integrated approach that combines multi-point phase current measurements, temporal load variation analysis, standard compliance benchmarking against both PLN and IEEE standards, and the development of a prioritized corrective action hierarchy (from emergency redistribution to quarterly monitoring protocols) specifically applied to the SM3 Feeder a feeder characterized by hilly terrain, dispersed load clusters, and significant residential single-phase customer density thereby providing a replicable assessment framework applicable to similar LV networks across PT PLN's eastern Indonesia distribution portfolio.

The specific objectives of this study are: (1) to measure and quantify load imbalance across phases in selected segments of the SM3 Feeder LV network; (2) to evaluate the impact of load imbalance on neutral current magnitude, power losses, and voltage quality; (3) to compare measured imbalance levels against PLN and international standards; and (4) to propose practical, prioritized corrective measures for reducing load imbalance and improving distribution system efficiency on the SM3 Feeder. This research is expected to provide practical benefits for PT PLN (Persero) UP3 Manado by offering actionable recommendations for load redistribution, mandatory phase allocation policies, and monitoring protocols, thereby improving network efficiency, power quality, and customer satisfaction. Additionally, this study contributes to the broader body of knowledge on LV distribution load imbalance assessment in tropical, hilly, developing-country contexts and demonstrates a replicable methodology applicable to similar distribution feeders across Indonesia.

METHOD

Study Area and Network Description

The SM3 Feeder is a 20 kV medium-voltage feeder originating from the Tomohon Main Substation (150/20 kV), operated by PT PLN (Persero) UP3 Manado in North Sulawesi Province, Indonesia. The feeder supplies power to multiple distribution transformers (DTR) of ratings ranging from 100 kVA to 200 kVA, each serving a localized LV distribution network at 380/220 V. The LV network connected to this feeder serves a customer base comprising predominantly single-phase residential connections (R-1 tariff class), supplemented by three-phase commercial (B-2) and small industrial loads. The area traversed by the SM3 Feeder is characterized by hilly terrain, resulting in extended feeder routing, longer-than-optimal LV feeder spans, and dispersed load clusters that are inherently more susceptible to end-of-line voltage drops than flat-terrain distribution configurations.

Five measurement points (MP-1 through MP-5) were selected along the SM3 Feeder LV network to represent the diversity of loading conditions and network topologies present in the feeder. MP-1 and MP-2 are located in near-substation segments with relatively high load densities and shorter feeder runs; MP-3 and MP-4 represent mid-feeder segments with mixed residential-commercial loads; and MP-5 is located at an end-of-line segment serving a dense residential cluster at the greatest electrical distance from the distribution transformer. Selection criteria prioritized measurement points where voltage quality complaints and elevated neutral currents had been previously reported by PLN UP3 Manado distribution engineering staff, ensuring that the most operationally significant segments were captured in the analysis.

Measurement Equipment and Procedure

Phase current and neutral current measurements were performed using calibrated digital clamp meters (Fluke 376 FC) with a measurement accuracy of ±1.5% of reading for AC current. Voltage measurements were performed using calibrated digital multimeters (Fluke 117) with an accuracy of ±0.5% of reading. All instruments were within their valid calibration periods at the time of measurement. Measurements were taken at the main LV distribution board at each measurement point, with the clamp meter applied to each phase conductor and the neutral conductor in sequence. Three readings were taken per conductor at each time interval and averaged to reduce the influence of short-duration load fluctuations.

Measurements were conducted at three time intervals representing distinct loading regimes: morning (07:00–09:00), corresponding to residential wake-up load and commercial opening loads; afternoon (13:00–15:00), representing moderate residential load with commercial activity; and evening peak (18:00–20:00), corresponding to maximum simultaneous residential load coinciding with commercial evening activity. The evening peak period was identified as the maximum loading condition based on preliminary current measurements and is used as the basis for all primary analyses and standard compliance evaluations in this study.

Load Imbalance and Power Loss Calculation

For each measurement point and time interval, the arithmetic mean of the three measured phase currents was computed and the PLI was calculated using the standard expression given in Section II.A. Results are reported for the evening peak period as the worst-case condition. Neutral conductor power losses were estimated using the measured I_N values and the neutral conductor resistance specification of 0.524 Ω/100 m for a standard 35 mm² aluminium LVTC (Low Voltage Twisted Conductor) cable, consistent with PLN's standard LV feeder construction specification. The loss value represents the estimated additional power dissipated in the neutral conductor per 100 m of feeder length at the measured neutral current, and serves as an indicative lower bound on the total imbalance-attributable losses in each segment.

Standard compliance assessment was performed by comparing the measured PLI against the 10% threshold specified in SPLN D3.002-1:2007, and by comparing measured customer terminal voltages against the permissible range of 209–231 V specified in SPLN 1:1995. Segments where either criterion was violated are classified as non-compliant and are designated as priority targets for corrective intervention.

RESUTS AND DISCUSSION

Phase Current Measurements and Load Imbalance Quantification

Table 1 presents the measured phase currents, neutral currents, and calculated PLI at the five measurement points during the evening peak load period (18:00–20:00), which represents the maximum loading condition and serves as the primary basis for standard compliance evaluation.

Table 1. Measured Phase Currents and Load Imbalance SM3 Feeder LV Network (Peak Load Period)

Meas. Point	I_R (A)	I_S (A)	I_T (A)	I_avg (A)	I_N (A)	PLI (%)
MP-1	48.2	35.6	52.4	45.4	12.8	15.4
MP-2	62.5	71.3	58.9	64.2	10.1	11.1
MP-3	33.1	21.7	38.5	31.1	14.3	23.8
MP-4	55.0	53.8	56.4	55.1	2.3	2.4
MP-5	27.3	44.6	19.8	30.6	22.1	31.7

Source: Field measurement results, PT PLN (Persero) UP3 Manado, 2026

The results demonstrate a wide variation in load imbalance across the five measurement points. Four of the five segments (MP-1, MP-2, MP-3, and MP-5) exhibit PLI values exceeding the 10% standard threshold. MP-3 and MP-5 show substantially elevated imbalance levels of 23.8% and 31.7% respectively, indicating severely unbalanced load distribution. The neutral current at MP-5 (22.1 A) represents approximately 72% of the average phase current symptomatic of extreme single-phase loading concentration on phase S. Only MP-4, with a PLI of 2.4%, demonstrates compliant balance, reflecting a well-distributed customer connection arrangement in that segment.

Table 2 presents a comparison of PLI values across the three measurement time intervals (morning, afternoon, evening peak) for all five measurement points, enabling assessment of how load imbalance varies throughout the daily load cycle.

Table 2. PLI (%) Comparison Across Three Measurement Periods SM3 Feeder LV Network

Meas. Point	Morning 07:00–09:00	Afternoon 13:00–15:00	Evening Peak 18:00–20:00	Max PLI (%)	Standard Compliance
MP-1	9.2	11.8	15.4	15.4	Non-Compliant
MP-2	7.4	8.9	11.1	11.1	Non-Compliant
MP-3	16.3	19.1	23.8	23.8	Non-Compliant
MP-4	1.8	2.1	2.4	2.4	Compliant
MP-5	22.5	26.8	31.7	31.7	Non-Compliant

Source: Field measurement results (three measurement periods), PT PLN (Persero) UP3 Manado, 2026

Table 2 reveals that load imbalance at all non-compliant measurement points worsens progressively from morning to evening peak. MP-1 transitions from a compliant 9.2% PLI in the morning to a non-compliant 15.4% at evening peak, highlighting the dynamic nature of the imbalance condition and the inadequacy of single-point measurements for comprehensive network assessment. MP-5 exhibits non-compliant PLI at all three measurement periods (22.5%, 26.8%, and 31.7%), indicating that the structural maldistribution of customer connections in this segment produces significant imbalance even during off-peak loading conditions. This finding has important implications for corrective measure design: load redistribution at MP-5 must be sufficient to achieve compliance under all load conditions, not merely at morning off-peak.

Neutral Current and Power Loss Analysis

Table 3 presents the neutral current, computed neutral conductor power loss per 100 m of feeder length, PLI, and standard compliance status for each measurement point during the evening peak period.

Table 3. Neutral Current and Estimated Power Loss SM3 Feeder LV Network (Peak Load Period)

Meas. Point	I_N (A)	R_N (Ω/100 m)	P_N (W/100 m)	PLI (%)	Standard Compliance
MP-1	12.8	0.524	85.8	15.4	Non-Compliant
MP-2	10.1	0.524	53.4	11.1	Non-Compliant
MP-3	14.3	0.524	107.1	23.8	Non-Compliant
MP-4	2.3	0.524	2.8	2.4	Compliant
MP-5	22.1	0.524	256.3	31.7	Non-Compliant

Source: Field measurement results (I_N) and author's calculation (P_N), PT PLN (Persero) UP3 Manado, 2026

The power loss data underscore the economic significance of load imbalance. At MP-5, neutral conductor loss of 256.3 W per 100 m is directly attributable to the 31.7% imbalance and the resulting 22.1 A neutral current. At MP-3, losses of 107.1 W per 100 m result from the 23.8% imbalance. Collectively, the four non-compliant segments (MP-1, MP-2, MP-3, MP-5) contribute an estimated combined neutral conductor loss of approximately 500 W per 100 m of total feeder length during peak demand a figure that compounds significantly over the extended feeder lengths characteristic of the SM3 Feeder topology. Assuming an average LV span of 150 m between distribution boards and an annual peak demand duration of approximately 1,500 hours (estimated from load profile data), the annual energy loss in neutral conductors attributable to load imbalance in the non-compliant segments is on the order of 112 kWh per segment per year, representing a meaningful and recoverable energy efficiency loss.

MP-4, with its 2.4% PLI and negligible neutral conductor loss (2.8 W per 100 m), serves as a practical benchmark demonstrating the distribution system performance achievable when customer connections are well-balanced across phases. The contrast between MP-4 and MP-5 where neutral conductor losses are approximately 90 times higher clearly illustrates the magnitude of efficiency improvement available through systematic load redistribution.

Voltage Quality Assessment

Table 4 presents line-to-neutral voltages measured at customer terminal boards at each measurement point, with percentage deviation from the nominal 220 V for the most deviating phases.

Table 4. Measured Customer Terminal Voltages SM3 Feeder LV Network (Peak Load Period)

Meas. Point	V_R (V)	V_S (V)	V_T (V)	Dev. R (%)	Dev. T (%)	Status
MP-1	215.4	221.3	213.8	−2.1	−2.8	Acceptable
MP-2	218.7	219.5	217.9	−0.6	−0.9	Acceptable
MP-3	207.2	220.8	204.5	−5.8	−7.0	Violation
MP-4	219.8	220.2	220.1	−0.1	+0.05	Acceptable
MP-5	202.1	219.3	198.7	−8.1	−9.7	Violation

Source: Field measurement results, PT PLN (Persero) UP3 Manado, 2026

Voltage quality results confirm the adverse impact of severe load imbalance on customer supply voltage. At MP-3, phases R and T fall to 207.2 V and 204.5 V respectively, with deviations of −5.8% and −7.0% both exceeding the permissible ±5% limit. The most critical condition is at MP-5, where phase T drops to 198.7 V (−9.7% deviation) and phase R to 202.1 V (−8.1% deviation), constituting severe under-voltage conditions directly attributable to the high neutral current in those segments. At MP-5, the phase S voltage (219.3 V) remains near nominal, consistent with the fact that phase S carries the highest current and therefore the lowest impedance-related voltage rise from the neutral point displacement. MP-2 and MP-4 remain within the permissible voltage range at all phases.

The voltage data at MP-5 and MP-3 indicate that affected customers are experiencing supply voltages below the statutory minimum. For a customer located at MP-5 whose equipment is designed to operate at 220 V, the actual supply voltage of 198.7 V represents an 11.6% under-supply relative to rated voltage a condition that will measurably reduce the output of incandescent lamps, significantly reduce the starting torque of single-phase induction motors (which is proportional to the square of voltage), and may cause malfunction of sensitive electronic equipment with narrow input voltage tolerance. The cumulative duration of these under-voltage conditions across the peak loading period (approximately 2 hours per day during the 18:00–20:00 period) translates to a significant accumulated degradation of customer service quality over time.

Severity and Distribution of Load Imbalance

The measurement results reveal that four of five assessed segments exhibit PLI values exceeding the 10% standard threshold, indicating that non-compliance is a systemic characteristic of the SM3 Feeder LV network rather than an isolated occurrence. This finding is significant because it implies that the corrective measures required are not merely targeted local interventions at one or two problematic connection points, but rather a comprehensive, feeder-wide load management programme. The imbalance pattern at MP-5 (31.7%) and MP-3 (23.8%) is consistent with the organic, customer-driven growth of LV networks in residential areas, where new service connections are commonly assigned to the nearest accessible phase at the distribution board without systematic consideration of existing phase loading or inter-phase balance targets.

The temporal analysis (Table 4) reveals that load imbalance worsens consistently from morning to evening peak at all non-compliant segments. This pattern reflects the evening coincidence of residential loads cooking, lighting, entertainment electronics, and cooling which are predominantly connected to a concentrated subset of phases in each residential cluster. The fact that MP-5 exhibits non-compliant PLI even at morning off-peak conditions (22.5%) underscores that the imbalance in this segment is structural rather than demand-driven, meaning that even a significant general reduction in overall demand would not bring this segment into compliance without physical load redistribution.

The strong and consistent correlation between PLI and neutral current magnitude across all measurement points validates PLI as a reliable leading indicator of neutral conductor stress and associated power losses in LV distribution networks. The highest neutral current (22.1 A at MP-5, PLI 31.7%) and second highest (14.3 A at MP-3, PLI 23.8%) demonstrate a clear monotonic relationship between the degree of maldistribution and the resulting neutral current loading. MP-4, as the only compliant segment (PLI 2.4%), serves as a natural control point that confirms this relationship: its negligible neutral current (2.3 A) and minimal power loss (2.8 W/100 m) represent the network performance achievable when connection assignments are managed systematically.

Impact on Voltage Quality and Customer Experience

The under-voltage conditions confirmed at MP-3 and MP-5 during peak load have direct and quantifiable adverse consequences for customers served by those segments. At MP-5 phase T, the measured terminal voltage of 198.7 V represents a departure of 21.3 V from the nominal supply voltage a deficit that is neither marginal nor tolerable within the regulatory framework. For fluorescent lamp ballasts designed for 220 V operation, a supply voltage of 198.7 V (90.3% of nominal) can reduce lumen output by approximately 12–15% and increase lamp current by a comparable proportion as the ballast attempts to maintain arc voltage. For single-phase induction motor loads (fans, pumps, compressors), starting torque which is proportional to V^2 is reduced to approximately 81.6% of its nominal value at this voltage, potentially causing difficulty in starting under load.

A further consequence noted at MP-5 is the pronounced asymmetry in terminal voltages across the three phases. With phase T at 198.7 V, phase S at 219.3 V, and phase R at 202.1 V, three-phase equipment served from this distribution board experiences a three-phase voltage imbalance in addition to the under-voltage condition. For three-phase equipment such as small industrial motors, the presence of negative-sequence voltage components caused by three-phase imbalance produces circulating currents in the motor windings that increase heating, reduce efficiency, and accelerate insulation degradation. Even a 2–3% voltage imbalance which is substantially exceeded at MP-5 is sufficient to cause measurable derating of three-phase induction motors according to NEMA MG-1 guidelines.

The self-reinforcing nature of the under-voltage condition at overloaded phases has already been noted in the theoretical framework. In the case of MP-5, the high proportion of switching power supply loads (common in modern residential environments computers, LED drivers, phone chargers, and television power supplies) means that constant-power behavior is pervasive. As supply voltage drops during the evening peak, these loads draw progressively higher current to maintain their output power, further increasing the imbalance between phases and deepening the voltage drop in a positive feedback loop. This dynamic explains why the PLI at MP-5 increases disproportionately from afternoon (26.8%) to evening peak (31.7%) compared to the increase at MP-3, which has a lower proportion of constant-power load types.

Corrective Measures and Recommendations

Based on the comprehensive analysis of measurement data, the following prioritized and operationally detailed corrective measures are recommended for restoring compliance and improving power quality on the SM3 Feeder LV network:

Priority 1 Emergency inter-phase load redistribution at MP-5: This is the most urgent intervention required given the severity of both the PLI violation (31.7%) and the voltage quality violations (up to −9.7%). The redistribution programme should begin with a customer connection audit at the MP-5 distribution board, mapping the current phase assignment and estimated peak load (in amperes) of each connected customer. Customers currently on phase S (44.6 A) whose service cables are physically accessible at the distribution board should be identified as candidates for transfer to phase T (19.8 A). The target is to achieve approximate phase balance, bringing all phases within approximately 5% of the board average. Based on the current data, transferring approximately 12–15 A equivalent of phase S load to phase T would bring the segment into compliance. This redistribution requires no network infrastructure changes only rewiring of service cable terminations at the distribution board.

Priority 2 Load redistribution at MP-3: Following the MP-5 intervention, MP-3 (PLI 23.8%) should be addressed. The same audit and redistribution methodology applies: identify the heaviest phase (T at 38.5 A) and the lightest phase (S at 21.7 A), and transfer customer connections to reduce the differential. Approximately 8–10 A of load should be transferred from phase T to phase S to achieve compliance. This action should also substantially improve the terminal voltage quality at MP-3, where the current violation of −7.0% on phase T is the second most severe voltage deficiency in the network.

Priority 3 Secondary intervention at MP-1: Although MP-1 (PLI 15.4%) is less severely non-compliant than MP-3 and MP-5, and its terminal voltages remain within the permissible range, the 15.4% imbalance exceeds the standard threshold and warrants attention after the higher-priority interventions are completed. The current profile at MP-1 (I_R 48.2 A, I_S 35.6 A, I_T 52.4 A) indicates that phase T is the most heavily loaded, and approximately 6 A of load should be transferred from phase T to phase S to bring the PLI below 10%.

Priority 4 Mandatory phase allocation policy for new connections: To prevent future imbalance accumulation on the SM3 Feeder, PT PLN UP3 Manado technical staff should implement a mandatory phase allocation review for all new single-phase customer connection requests. Prior to assigning a service connection phase, the connection officer must verify the current phase loading at the relevant distribution board (using either the most recent measurement records or the customer database load data) and assign the new connection to the most lightly loaded available phase. This policy requires no capital investment and prevents the progressive deterioration of balance that has led to the current non-compliant conditions.

Priority 5 Establishment of quarterly monitoring protocols: A sustainable load balance management programme requires a regular measurement cadence to detect emerging imbalance conditions before they reach violation levels. Quarterly measurement of phase currents and neutral currents at all LV distribution boards on the SM3 Feeder using calibrated clamp meters by distribution engineering field crews should be established as a routine maintenance activity. Measurement records should be entered into a tracking system (even a simple spreadsheet database) to enable trend analysis and early intervention. Distribution boards where PLI exceeds 7% (i.e., approaching the 10% threshold) should be flagged for monitoring at the next quarterly cycle and for pre-emptive load redistribution review.

Practical Implementation Considerations

The corrective measures proposed above are operationally feasible within PLN UP3 Manado's existing technical capabilities and do not require procurement of specialized equipment or engagement of external contractors. Termination rewiring at LV distribution boards is a routine task within the competency of PLN's distribution maintenance crews. The principal resource requirements are crew time for the field audits and rewiring work, and management commitment to enforce the mandatory phase allocation policy for new connections. Based on typical PLN distribution maintenance productivity data, the physical redistribution work at MP-5 and MP-3 is estimated to require approximately 1–2 man-days per segment, representing a modest investment relative to the energy savings and regulatory compliance benefits achieved.

It is also recommended that the redistributed segments (MP-5, MP-3, and MP-1) be re-measured within two weeks of the redistribution work to verify that the target PLI reduction has been achieved and that no unintended consequences (such as transformer overloading on a previously underloaded phase) have resulted from the connection changes. Post-redistribution measurement data should be retained as the baseline record for subsequent quarterly monitoring cycles.

CONCLUSION

This study has presented a comprehensive field-based analysis of load imbalance on the SM3 Feeder low-voltage distribution network at the Tomohon Main Substation, PT PLN (Persero) UP3 Manado. Measurements conducted at five representative segments across three daily load periods have provided a multi-dimensional characterization of the imbalance conditions, their temporal variation, and their impact on neutral current loading, power losses, and customer terminal voltage quality. The following principal conclusions are drawn: Load imbalance levels exceeding the 10% standard threshold (SPLN D3.002-1:2007) were identified in four of five assessed segments during the evening peak period. The most severe imbalance reached 31.7% at MP-5, far exceeding the permissible limit. Only MP-4 demonstrated consistent standard-compliant balance (PLI 2.4%) across all measurement periods, confirming that non-compliance is a systemic condition on the SM3 Feeder. Temporal analysis revealed that load imbalance worsens consistently from morning to evening peak at all non-compliant segments. MP-5 exhibited non-compliant PLI across all three measurement periods (22.5%, 26.8%, 31.7%), confirming that the imbalance is structural in nature and cannot be resolved through demand-side management alone only physical load redistribution will achieve compliance. Elevated neutral currents reaching 22.1 A at MP-5 and 14.3 A at MP-3 produced measurable additional power losses, with estimated neutral conductor losses of 256.3 W and 107.1 W per 100 m respectively. The compliant MP-4 segment (2.8 W per 100 m) confirms that the approximately 90-fold loss difference between MP-5 and MP-4 is fully attributable to the maldistribution of customer connections. Customer terminal voltage violations below the statutory minimum (209 V) were confirmed at MP-3 and MP-5, with the most severe deviation reaching −9.7% at MP-5 phase T (198.7 V). These conditions represent regulatory non-compliance under SPLN 1:1995, with measurable consequences including reduced motor starting torque, degraded lighting output, and increased risk of malfunction in voltage-sensitive electronics. Priority corrective actions are: (a) emergency inter-phase load redistribution at MP-5 and MP-3; (b) secondary redistribution at MP-1; (c) mandatory phase allocation policy for all new customer connections; and (d) establishment of quarterly current monitoring protocols at all LV distribution boards. All measures are operationally achievable within PLN UP3 Manado's existing technical capabilities, estimated at 1–2 man-days of field work per segment, and are expected to restore standard compliance across all non-compliant segments of the SM3 Feeder. The measurement methodology, analysis framework, and corrective measure hierarchy developed in this study provide a replicable approach applicable to similar residential LV distribution networks across PT PLN's North Sulawesi and eastern Indonesia distribution portfolio, and can serve as a reference for regional engineering planning and maintenance programme development.

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