

Analysis of voltage drop causes at SMK Ponpes Manba'ul 'Ulum Cirebon

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ABSTRACT

This study aimed to identify the causes, evaluate, and quantify the magnitude of voltage drop at SMK Ponpes Manba'ul'Ulum Cirebon. A descriptive quantitative approach using a single case study strategy was applied. Data were collected from PT PLN ULP Sumber, Cirebon, and through direct field measurements using a Digital Earth Tester, Digital Insulation Tester, and monitoring of a three-phase kWh meter. The findings revealed that the main cause of voltage drop was transformer overload at Distribution Substation CKPB, with a loading level of 91.20%, exceeding the 80% limit specified by the Indonesian Electricity Supply Standard (SPLN). Additional contributing factors included a 710-meter conductor length with a 70 mm² cross-sectional area, inter-phase load imbalance ($I_1 = 105$ A, $I_2 = 149$ A, $I_3 = 141$ A), and insulation resistance anomalies detected at several test points (0 M Ω at N-T, T-G, and N-G). Before transformer uprating, the voltage drop reached 28.49 V (14.92%), exceeding the SPLN 72:1987 tolerance range of 5–10%. After uprating the transformer capacity from 100 kVA to 160 kVA combined with load splitting, the voltage drop decreased to 13.57 V (6.33%) and transformer loading declined to 57.10%.



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INTRODUCTION

The availability of high-quality electrical energy is a fundamental prerequisite for the sustained operational activities of educational institutions, industrial facilities, and households alike. The electrical distribution system functions as the primary medium for delivering energy from generation sources to end users through a complex and hierarchical network infrastructure. Globally, voltage quality issues in low-voltage distribution networks have become a serious concern, given their significant impact on the reliability of electrical equipment and overall system efficiency. Voltage drop and power losses in electrical power distribution systems are attributed to several factors, including the considerable distance from source to load, load imbalance, equipment aging, and inadequate conductor cross-sections, all of which, if left unaddressed, can degrade the reliability of the power system and the quality of energy distribution, potentially damaging customer equipment (Asmaul et al., 2024). In

Indonesia, PT PLN (Persero), as the primary provider and distributor of electrical power, faces similar challenges in maintaining voltage quality at the end of the network, particularly in the low-voltage network (JTR) segment, which constitutes the terminal link of the distribution chain. The service drop, as the most downstream point of the distribution system, is the most vulnerable link to voltage quality anomalies due to the cumulative line impedance that increases with conductor length.

Although voltage drop problems in distribution networks have been extensively studied in electrical engineering literature, a notable academic gap exists concerning research focused on voltage drop analysis in Islamic boarding school-based educational facilities (*pesantren*), which exhibit unique load characteristics and energy consumption patterns distinct from conventional study objects such as office buildings or residential complexes. From a practical standpoint, the voltage drop phenomenon occurring at SMK Ponpes Manba'ul'Ulum Cirebon indicates the presence of technical problems that have not yet been systematically and quantitatively identified. Voltage variation is fundamentally caused by the relationship between voltage and reactive power, wherein the voltage drop across a conductor is directly proportional to the reactive power flowing through it, and the significant addition of load over time at a distribution substation further aggravates this condition (Nadia et al., 2024). This situation underscores the academic urgency of investigating the causes of voltage drop quantitatively and on the basis of primary data, in order to generate technically actionable recommendations as a foundation for network improvement.

Conceptually, voltage drop is an inevitable phenomenon in electrical power distribution systems; however, its magnitude must be controlled so as not to exceed the tolerance limits prescribed by national electrical standards. Within the theoretical framework of distribution systems, the radial network configuration most commonly employed by PLN is an inherent factor influencing voltage distribution along the line, in that the farther the load point from the distribution transformer, the greater the voltage drop that occurs. Overloading a distribution transformer reduces its conversion efficiency, and as an essential component in power systems, a transformer must operate under safe conditions to ensure the reliability and economic efficiency of electrical power supply to customers (Wang et al., 2023). Accordingly, voltage drop analysis cannot be conducted in a piecemeal fashion; rather, it must integrate all technical network parameters comprehensively, from conductor specifications and line length to transformer condition and the load characteristics installed on the customer side.

Based on the foregoing context, this study is formulated around three primary research questions: first, what causes voltage drop at SMK Ponpes Manba'ul'Ulum Cirebon; second, how can the magnitude of the voltage drop be evaluated; and third, what is the measured value of the voltage drop at the study location. The primary objective of this research is to systematically identify the causal factors of the voltage drop phenomenon, to evaluate its severity based on primary data obtained from PT PLN (Persero) ULP Sumber, Cirebon Regency, and to use these findings as a technical basis for network improvement planning. Voltage drop analysis must be performed to ensure that the magnitude of the voltage drop along the distribution line from the source to the end of the network complies with the applicable SPLN standard (Prastia et al., 2024). A descriptive quantitative approach with a case study strategy was adopted to ensure that all findings are empirically grounded and scientifically accountable.

The novelty of this research rests on three fundamental aspects. First, this study investigates the voltage drop phenomenon in a specific and previously unstudied object, namely an Islamic boarding school-based vocational secondary school (SMK) in Cirebon Regency, which has unique load characteristics and energy usage patterns. Second, this research integrates primary data from the official authority of PT PLN (Persero) ULP Sumber, thereby ensuring superior data validity and accuracy of technical calculations. Transformers are essential and costly components in secondary electrical distribution networks, and transformer faults directly affect the reliability of power supply in the network (Mbembati & Bakiri, 2023). Third, from a practical contribution perspective, the findings of this study are expected to provide concrete technical recommendations for both PT PLN (Persero) and educational institution administrators. In the PT PLN (Persero) distribution system, voltage drop approaching the applicable standard threshold requires preventive action to prevent further deterioration (Turahma et al., 2025).

The conceptual foundation of this research rests on the theory of electrical power distribution systems, which has developed systematically within the discipline of electrical engineering. A distribution system is a subsystem of the electrical power system that functions to deliver energy from the substation to end customers through medium-voltage (MV) and low-voltage (LV) networks. In its theoretical context, voltage drop is defined as the difference between the voltage at the sending end and the voltage at the receiving end, caused by the line impedance consisting of resistance (R) and reactance (X) components. Voltage drop and power losses in distribution systems are caused by several factors, including the distance from source to load, load imbalance, equipment aging, conductor cross-sectional area, and connection joints, all of which, if unaddressed, will reduce the reliability of the power system and the quality of energy distribution (Bachari et al., 2024). The radial distribution network configuration most commonly used by PT PLN (Persero) in Indonesia inherently places the load points farthest from the distribution transformer in the most vulnerable position with respect to cumulative voltage drop. Radial topology offers the advantage of construction simplicity and ease of maintenance; however, it suffers from single points of failure and progressively greater voltage drop at the end of the network (Eftimie et al., 2023).

A mapping of prior studies reveals that research on voltage drop in Indonesian distribution networks has been conducted with a variety of approaches and study objects. At the low-voltage distribution network of the Ambon State Polytechnic, conductor length and cross-sectional area were proven to significantly influence the magnitude of voltage drop percentage; longer conductors with smaller cross-sections produce greater resistance, ultimately causing voltage regulation to exceed the permissible limit (Tahalele & Yesaya, 2024). Another study conducted on Feeder CPK of PT PLN (Persero) UP3 Bandung found that conductor type, transformer load conditions, and cable joint integrity are the three main causes of voltage drop. The type of conductor affects the impedance value of the line, wherein the resistance of the conductor is influenced by its resistivity, length, and cross-sectional area; the greater the resistivity, the greater the voltage drop along the feeder (Medina et al., 2022). Meanwhile, in the Nangka Village low-voltage network study, the measured voltage at peak load was only 170 V for a single-phase nominal source of 220 V, indicating a severity requiring immediate technical intervention. Voltage drop is one of the recurring problems in electrical power distribution systems attributable to conductor length along the distribution line, and when voltage drop exceeds the standard threshold it is detrimental to both the public and PT PLN (Persero) (Sunaryo & Faisal, 2022).

From the mapping of prior studies, several relevant and significant research gaps can be identified. First, the majority of voltage drop studies in Indonesia focus on residential areas, industrial buildings, or technical university campuses, while studies placing pesantren-based educational facilities as the study object have not been found in the available literature. Second, most prior studies employ software simulation approaches such as ETAP to analyze voltage drop, thereby limiting field validation based on official PLN primary data. Voltage drop along power lines is generally directly proportional to line length and load, and inversely proportional to conductor cross-section; improvement of the voltage profile in distribution networks can be achieved through the installation of a new or supplementary transformer (Sunaryo & Faisal, 2022). Third, no study was found that explicitly integrates grounding system analysis as a variable jointly examined in relation to the voltage drop phenomenon in non-urban educational facilities in the West Java region. Grounding systems in low-voltage electrical installations are an essential component for protection against lightning-induced currents and abnormal voltage disturbances; however, many electrical systems exhibit structural deficiencies in their grounding, arising from lack of technical knowledge, design negligence, or cost considerations, which increases the vulnerability of the installation to electric shock, voltage surges, and lightning damage (Freire et al., 2025).

This research is positioned to fill these gaps by directly investigating the voltage drop phenomenon in the field at a specific and previously unstudied study object, namely SMK Ponpes Manba'ul'Ulum Cirebon, using primary data from PT PLN (Persero) ULP Sumber, Cirebon Regency. Power quality is an increasingly critical global issue, particularly with the growing use of electronic devices that underpin the modern economy, and research evaluating and improving power quality in

campus or educational institution distribution networks demonstrates that the electrical equipment used in such institutions contributes to power quality challenges that must be systematically addressed (Samuel et al., 2024). The primary contribution of this research in closing the identified literature gap lies in the specificity of the study object, the validity of the primary data used, and the analytical approach that comprehensively integrates all technical network parameters.

Methodological trends in voltage drop studies in distribution networks demonstrate a significant evolution from manual analytical calculation approaches, to software-based simulation, and then to field data-driven analysis supported by digital monitoring systems. Load data, including information on load imbalance, can have a significant influence on the accurate estimation of power quality indicators, and the use of inaccurate consumption profiles will produce inaccurate estimates of various power quality indicators, including voltage regulation in low-voltage distribution networks (Costanzo et al., 2021). Another trend in international voltage drop research is the growing attention to the impact of load imbalance on the voltage profile of low-voltage networks. Low-voltage distribution networks represent the final stage in the delivery of electrical energy from generation to the consumer, and their operational condition has a major impact on the comfort of many electricity users; load imbalance problems in low-voltage networks often still rely on the planner's experience, resulting in significant management limitations (Lu et al., 2024).

A conceptual synthesis of the overall literature reviewed yields an analytical framework that will serve as the methodological foundation of this research. Voltage drop in a low-voltage network is a function of three primary interacting variables: (1) the impedance characteristics of the line, comprising the resistance and reactance of the conductor as a function of cable type, cross-sectional area, and length; (2) the load current flowing through the line as a representation of the total power consumed by customers at any given time; and (3) the power factor, which determines the reactive component of the load current contributing to voltage losses in the line. Maintaining adequate supply voltage magnitude is essential for ensuring the efficiency and effectiveness of the operations of both the electricity supply network and consumer equipment, as the theoretical impact of supply voltage magnitude on consumer equipment performance, including additional energy consumption and reduced equipment lifespan due to voltage fluctuations, constitutes a directly measurable economic burden on end users (Elphick et al., 2024). In addition to these three technical variables, the condition of the grounding system at the receiving installation warrants examination given its role in stabilizing the voltage reference and preventing overvoltage on undisturbed phases in a three-phase system. Grounding systems optimized with consideration of soil resistivity, electrode material, and grounding configuration have been proven to significantly influence grounding efficiency (Tatarenko et al., 2024).

RESEARCH METHODS

This study employs a descriptive quantitative approach with a single case study strategy as the selected research type. The descriptive quantitative approach was chosen because this research aims to systematically identify, measure, and describe the voltage drop phenomenon occurring in the low-voltage distribution network of SMK Ponpes Manba'ul'Ulum Cirebon, based on numerical and measurable data. Descriptive quantitative research is an approach that helps to describe, demonstrate, or summarize data objectively; although quantitative data are used, the objective of this research is to describe results descriptively rather than to test relationships or differences between variables (Aziza, 2023). The case study strategy was chosen because the research object constitutes a contemporary phenomenon occurring in a real and specific context—namely, the condition of the low-voltage distribution network at a particular location—which cannot be separated from its technical environment (Yin, 2018).

The data sources in this study are primary in nature, obtained directly from the field through technical observation and measurement at the research location. Primary data were sourced from two main entities: (1) PT PLN (Persero) ULP Sumber, Cirebon Regency, as the distribution network manager serving the study area, from whom technical network data were obtained comprising distribution transformer specifications, low-voltage network topology, and installed load data; and (2) direct field measurements conducted by the research team at critical points along the distribution line

from the secondary terminal of the distribution transformer to the main panel at the SMK Ponpes Manba'ul'Ulum building. Descriptive quantitative case studies collect, synthesize, and present data from multiple sources including documents, observations, and measurable quantitative data, in order to produce a holistic picture of the condition under investigation (Harrison et al., 2017).

The data collection techniques used in this study are field observation and direct measurement using calibrated electrical measuring instruments. Field observation was conducted to obtain a comprehensive physical picture of the distribution network condition. The measurement instruments used include: (1) a Digital Earth Tester, Kyoritsu KEW 4105A model, to measure grounding resistance; (2) a Digital Insulation Tester, Kyoritsu 3007A model, to measure conductor insulation resistance at the 1000 V scale; and (3) three-phase kWh meter monitoring using built-in measurement codes (code 41 for Phase R, code 42 for Phase S, code 43 for Phase T). Voltage measurements were conducted over seven consecutive days at three measurement times per day (07:00, 12:00, and 17:00 local time) to obtain a representative voltage profile under morning, daytime, and afternoon loading conditions.

The data inclusion criteria established for this study are as follows: (a) measurement data taken under normal load and peak load conditions, representative of the actual operational condition of the network; (b) technical network data originating from official documents of PT PLN (Persero) ULP Sumber, Cirebon Regency; (c) measurements conducted under normal weather conditions without significant atmospheric disturbances; and (d) data obtained from the distribution line that directly supplies SMK Ponpes Manba'ul'Ulum Cirebon from the designated distribution transformer. Exclusion criteria include: (a) data taken during network faults or planned outages; (b) measurements conducted with uncalibrated instruments; and (c) data from networks having no direct connection to the distribution line supplying the study location. The methodology of direct load current and voltage measurement at several distribution stations, analysis of daily and weekly load data, and comparison against applicable SPLN tolerance limits constitute a valid and reliable approach for evaluating the operational performance of distribution networks (Wardoyo et al., 2025).

The unit of analysis in this study is the low-voltage distribution line segment connecting the CKPB Distribution Substation of PT PLN (Persero) ULP Sumber to the main electrical panel at SMK Ponpes Manba'ul'Ulum Cirebon. The study subjects encompass four main components: (1) the CKPB distribution transformer with a capacity of 100 kVA and a primary/secondary voltage of 20 kV/400 V; (2) the 710-meter conductor line with a 70 mm² cross-sectional area; (3) the service drop as the most downstream point of the distribution system; and (4) the electrical load characteristics installed at SMK Ponpes Manba'ul'Ulum, comprising four buildings with a total load of 18,210 W.

The data analysis technique employed is descriptive statistical analysis combined with mathematical technical calculation of voltage drop. Descriptive statistical analysis is used to process voltage measurement data obtained from the field, including the calculation of mean, minimum, and maximum values for each measured variable. Technical calculation analysis encompasses: (a) conductor resistance calculation using the formula $R = \rho \times (l/A)$; (b) voltage drop calculation using the formula $\Delta V = I \times (R \times \cos\phi + X \times \sin\phi)$; and (c) percentage voltage drop calculation using the formula $\% \Delta V = (\Delta V / V) \times 100\%$. The results are then evaluated against SPLN No. 1/1995 (permissible voltage variation: +5% to -10% of nominal) and SPLN 72:1987 (permissible voltage drop: 5–10%). Voltage drop analysis based on field primary data is conducted by identifying the key technical variables influencing voltage drop magnitude, which are then integrated into mathematical equations to produce accurate voltage drop values that can be compared against applicable standards (Ikhsan et al., 2025).

RESULTS AND DISCUSSION

Electronic Load Inventory Per Building

Field observation of the four buildings connected to the main electrical panel at SMK Ponpes Manba'ul'Ulum Cirebon produced a detailed electronic load inventory. Building 1 recorded a total installed load of 7,833 W, consisting of 26 room lights, 5 air conditioning units, 17 laptops, 3 fans, 11 outdoor lights, 2 desktop computers, 1 water dispenser, 1 speaker unit, 2 electric air compressors, and 1 water pump. Building 2 recorded the highest total load among all four buildings at 8,186 W,

encompassing 20 categories of equipment ranging from air conditioning units to office equipment and CCTV security systems. Building 3 had a total load of 2,080 W dominated by 2 air conditioning units, while Building 4 recorded the minimum load of 111 W consisting solely of room lights and outdoor lights. The cumulative total load of all four buildings connected to the main panel was 18,210 W. Unbalanced loading in a distribution system—wherein the load supplied to each phase is unequal—constitutes one of the technical causes contributing to voltage drop and power losses, which can ultimately damage customer equipment if left unresolved (La Elo et al., 2023).

Table 1. Summary of Total Electronic Load Per Building

Building	Total Load (W)	No. of Load Types	Dominant Load
Building 1	7,833	10 types	AC (3,750 W)
Building 2	8,186	19 types	AC (3,750 W)
Building 3	2,080	7 types	AC (1,500 W)
Building 4	111	2 types	Lights (111 W)
Total	18,210	—	—

Grounding Resistance Measurement

Grounding resistance testing was performed using a Digital Earth Tester, Kyoritsu KEW 4105A, at the 20 Ohm scale. The measured result was 2.27 Ohm. Based on the applicable technical standard, the maximum permissible grounding resistance threshold is 5 Ohm; accordingly, a value of 2.27 Ohm indicates that the grounding system at SMK Ponpes Manba'ul'Ulum remains in good condition and does not contribute as a direct causal factor to the observed voltage drop phenomenon. Insulation resistance testing is performed to ensure that an electrical installation is free of short circuits, ground faults, or improper grounding connections, and the measured insulation resistance value is compared against the minimum acceptable value to determine the pass or fail status of the installation under test (Kim et al., 2020).

Insulation Resistance Test Results

Insulation resistance testing was conducted using a Digital Insulation Tester, Kyoritsu 3007A, at the 1000 V scale, through a three-stage scale selection procedure (250 V, 500 V, and 1000 V). At the scale selection stage, all three test voltage levels produced infinite readings, indicating that testing could proceed at the highest scale. The minimum insulation resistance value required is 0.2 MOhm, derived from the formula: $1,000 \text{ Ohm} \times \text{operating voltage} = 1,000 \times 220 = 220,000 \text{ Ohm}$ (0.2 MOhm). The insulation resistance test results showed significant variation across measurement points, with anomalous zero values recorded at N-T, T-G, and N-G test points.

Table 2. Insulation Resistance Test Results

No.	Test Target	Scale (V)	Result (MOhm)
1	N – R	1000	0.1
2	N – S	1000	0.2 – 0.3
3	N – T	1000	0 *
4	R – S	1000	0.2 – 0.3

5	R – T	1000	0.1
6	S – T	1000	0.2
7	R – G	1000	0.1
8	S – G	1000	0.2
9	T – G	1000	0 *
10	N – G	1000	0 *

(* = anomalous value below the 0.2 MOhm standard)

Transformer Loading Data at Substation CKPB

Based on data obtained from PT PLN (Persero) ULP Sumber, Cirebon Regency, SMK Ponpes Manba'ul'Ulum is connected to the distribution transformer at Substation CKPB, rated at 100 kVA with a primary/secondary voltage of 20 kV/400 V. Current measurements yielded the following values: IR = 105 A, IS = 149 A, IT = 141 A, and IN = 79 A. The transformer loading percentage was calculated through the following equations.

$$\text{Average current: } I(\text{avg}) = (IR + IS + IT) / 3 = (105 + 149 + 141) / 3 = 395 / 3 = 131.66 \text{ A}$$

$$\text{Full load current: } I(\text{FL}) = VA / (\text{sqrt}(3) \times V) = 100,000 / (1.732 \times 400) = 100,000 / 692.8 = 144.34 \text{ A}$$

$$\text{Loading percentage: } \% \text{ Loading} = (131.66 / 144.34) \times 100\% = 91.20\%$$

The calculation confirms that Substation CKPB is experiencing overload, as its loading percentage of 91.20% exceeds the maximum permissible limit of 80% of nominal transformer capacity as stipulated by SPLN.

Per-Phase Voltage Data Prior to Uprating

Voltage monitoring was conducted over seven consecutive days (5–11 April 2021) at three measurement times per day. The measured voltage data reveal that Phase R consistently experienced below-standard voltage levels, particularly during daytime hours (12:00). The lowest Phase R voltage was recorded on 7 April 2021 at 12:00, measuring 190.93 V.

Table 3. Per-Phase Voltage Data Prior to Uprating

No.	Date	Time	Phase R (V)	Phase S (V)	Phase T (V)
1	05 Apr 2021	07:00	218.91	218.72	202.94
		12:00	194.36	222.50	211.36
		17:00	218.96	218.48	206.11
2	06 Apr 2021	07:00	210.08	221.96	204.89
		12:00	196.75	216.02	202.89
		17:00	210.65	220.02	218.52
3	07 Apr 2021	07:00	203.56	219.78	227.89

		12:00	190.93 *	224.00	226.58
		17:00	203.64	220.12	218.19
4	08 Apr 2021	07:00	214.09	219.98	220.87
		12:00	203.38	213.21	208.51
		17:00	217.87	220.89	215.13
5	09 Apr 2021	07:00	214.82	221.78	219.10
		12:00	205.14	214.37	198.40
		17:00	212.85	225.85	217.09
6	10 Apr 2021	07:00	215.78	221.13	225.18
		12:00	207.12	215.98	203.45
		17:00	219.78	218.55	220.89
7	11 Apr 2021	07:00	209.89	219.35	219.19
		12:00	205.98	204.80	209.33
		17:00	210.85	220.02	220.19

(* = minimum Phase R value)

Voltage Drop Calculation Prior to Uprating

Technical conductor parameters used in the calculation: resistivity (ρ) = 28.25 Ohm.mm²/km; specific reactance = 0.1 Ohm/km; cross-sectional area (A) = 70 mm²; conductor length (l) = 710 m = 0.71 km; $\cos\phi = 0.8$; $\sin\phi = 0.6$.

Conductor resistance: $R = \rho \times (l / A) = 28.25 \times (0.71 / 70) = 0.286$ Ohm

Line reactance: $X = 0.1 \times 0.71 = 0.071$ Ohm

Voltage drop (using Phase R current I = 105 A):

$\Delta V = I \times (R \times \cos\phi + X \times \sin\phi) = 105 \times (0.286 \times 0.8 + 0.071 \times 0.6) = 105 \times 0.2714 = 28.49$ V

Percentage voltage drop:

$\% \Delta V = (\Delta V / V) \times 100\% = (28.49 / 190.93) \times 100\% = 14.92\%$

A percentage voltage drop of 14.92% far exceeds the tolerance limits set by SPLN 72:1987, thereby confirming the critical condition of the distribution network supplying SMK Ponpes Manba'ul'Ulum Cirebon.

Post-Uprating Transformer Results

The transformer uprating process was carried out on 10 May 2021, increasing capacity from 100 kVA to 160 kVA, accompanied by load splitting and the addition of a new distribution feeder. Following uprating, the load at Substation CKPB was distributed across two feeders: Feeder 1 (IR = 50 A, IS = 76 A, IT = 73 A) and Feeder 2 (IR = 55 A, IS = 73 A, IT = 68 A).

Full load current of the 160 kVA transformer: $I(FL) = 160,000 / (\sqrt{3} \times 400) = 160,000 / 692.8 = 230.94$ A

Post-uprating loading percentage: $\% \text{ Loading} = (131.66 / 230.94) \times 100\% = 57.10\%$

Post-uprating voltage drop (using Feeder 1 Phase R current I = 50 A):

$\Delta V = 50 \times (0.286 \times 0.8 + 0.071 \times 0.6) = 50 \times 0.2714 = 13.57$ V

$\% \Delta V = (13.57 / 214.09) \times 100\% = 6.33\%$

Table 4. Comparison of Network Conditions Before and After Transformer Uprating

Parameter	Before Uprating	After Uprating	Change
Transformer Capacity	100 kVA	160 kVA	+60 kVA
Loading Percentage	91.20%	57.10%	-34.10%
Voltage Drop (V)	28.49 V	13.57 V	-14.92 V
Voltage Drop (%)	14.92%	6.33%	-8.59%
Min. Phase R Voltage	190.93 V	214.09 V	+23.16 V

DISCUSSION

Identification of Voltage Drop Causes

Based on the complete dataset obtained from field observation, technical measurement, and PLN data analysis, one dominant factor has been empirically proven as the primary cause of voltage drop at SMK Ponpes Manba'ul'Ulum Cirebon: overloading of the distribution transformer at Substation CKPB. The transformer loading percentage of 91.20% far exceeds the SPLN limit of 80%, constituting the root cause of the severe voltage drop in the low-voltage network. When a transformer operates beyond its recommended capacity, its efficiency decreases and its temperature rises; significant inter-phase voltage drop on the customer side is strongly influenced by transformer overload conditions, and this situation requires immediate remediation (Wang et al., 2023).

In addition to transformer overload as the primary factor, the 710-meter conductor length also contributes significantly to the magnitude of the voltage drop. Based on the fundamental theory of distribution systems, the conductor resistance calculated via $R = \rho \times (l/A)$ yields 0.286 Ohm for a conductor with a resistivity of 28.25 Ohm.mm²/km, a length of 0.71 km, and a cross-sectional area of 70 mm². This resistance value, when multiplied by the load current components with respect to the power factor ($\cos\phi = 0.8$) and the line reactance, produces a cumulative voltage drop. Voltage variation is fundamentally caused by the relationship between voltage and reactive power, whereby the voltage drop across a conductor is directly proportional to the reactive power flowing through it (Nadia et al., 2024).

The third factor warranting attention is load imbalance, as indicated by the disparity in current across the three phases: $I_R = 105$ A, $I_S = 149$ A, and $I_T = 141$ A, with a maximum phase difference of 44 A. This condition produces a neutral current (I_N) of 79 A, which is a significant indicator of load imbalance. Voltage drop in low-voltage distribution networks results from voltage losses due to electrical resistance (R) and reactance (X) of the line; uneven load currents across each phase produce different voltage drops per phase, and per SPLN No. 56-1/1993, the permissible voltage drop in a service drop (SR) is a maximum of 1% of nominal voltage (Pardosi & Nasution, 2024).

The fourth identified factor is the anomalous insulation resistance condition. Several insulation resistance test points recorded values of 0 MOhm at N-T, T-G, and N-G, and values of 0.1 MOhm at other points below the minimum standard of 0.2 MOhm. Inadequate insulation conditions can cause current leakage, which contributes to an increase in the total current that must be supplied by the transformer, thereby indirectly exacerbating the overload condition and voltage drop. Voltage quality is one of the primary indicators of distribution system reliability, wherein excessive voltage drop reduces service quality and directly impacts the performance of customer electrical equipment (Adegoke et al., 2024).

Evaluation of Voltage Drop Against SPLN Standards

The pre-uprating voltage drop percentage of 14.92% constitutes a severe deviation categorized as a critical condition under applicable electrical standards. SPLN 72:1987 stipulates a permissible voltage drop tolerance of 5% to 10% of nominal voltage, such that conditions approaching or exceeding this threshold indicate a deterioration of electricity service quality requiring immediate remediation (Bachari et al., 2024). The value of 14.92% exceeds the upper SPLN tolerance limit by 48.8% in relative terms, indicating a severity level requiring comprehensive and immediate corrective action. As a consequence, the minimum measured voltage on Phase R at the customer side reached only 190.93 V—significantly below the minimum service voltage threshold of 198 V (–10% of 220 V nominal) stipulated by SPLN No. 1/1995.

Comparison with prior studies reveals that the severity of voltage drop found at SMK Ponpes Manba'ul'Ulum is relatively higher than findings at similar study objects. A study at the Ambon State Polytechnic distribution substation found a maximum voltage drop of 8.56%, while a study at the ULP Tanah Jawa distribution network recorded considerably lower values. This significant difference is confirmed by the high overloading percentage of the transformer at SMK Ponpes Manba'ul'Ulum (91.20%), which constitutes the determining factor. Transformer overload reduces conversion efficiency; as an essential component in the power system, a transformer must operate under safe

conditions to guarantee the reliability and economic efficiency of electrical power supply to customers (Mbembati & Bakiri, 2023).

Effectiveness of the Transformer Uprating Solution

The transformer uprating process from 100 kVA to 160 kVA, combined with load splitting and the addition of a new feeder, was proven effective in significantly addressing the voltage drop problem. The reduction in loading percentage from 91.20% to 57.10% brought the transformer's operational condition into a safe zone well below the SPLN maximum limit of 80%. Per PT PLN (Persero) regulations, a transformer must not exceed 80% of its nominal capacity; when a transformer is overloaded, transformer insertion or capacity uprating constitutes the appropriate and effective technical solution for distributing load more evenly (Prastia et al., 2024).

The reduction in voltage drop from 14.92% to 6.33% post-uprating represents a substantial improvement, although the residual value of 6.33% remains slightly above the lower SPLN 72:1987 tolerance limit of 5% for overhead radial low-voltage networks. This finding indicates that while transformer uprating successfully addressed the primary cause of voltage drop, the contributions of the 710-meter line length and conductor impedance characteristics have not been fully eliminated by the uprating intervention alone. Installing a higher-capacity transformer has been proven to significantly improve the voltage profile; however, optimal voltage improvement requires a comprehensive evaluation encompassing not only transformer capacity but also network configuration, conductor specifications, and the overall load distribution pattern (Wicaksono et al., 2023). To achieve voltage quality fully compliant with SPLN standards, additional remedial actions are warranted, including an evaluation of the potential for conductor uprating from 70 mm² to a larger cross-section, periodic inter-phase load balancing by PT PLN (Persero) ULP Sumber, and remediation of conductor insulation anomalies at the test points exhibiting zero MOhm readings.

CONCLUSION

Based on the comprehensive results and data analysis conducted on the voltage drop phenomenon at SMK Ponpes Manba'ul'Ulum Cirebon, three principal conclusions are drawn in response to the research questions.

First, the primary cause of voltage drop at SMK Ponpes Manba'ul'Ulum Cirebon is transformer overload at Substation CKPB operated by PT PLN (Persero) ULP Sumber, with a loading percentage of 91.20% against a nominal capacity of 100 kVA, exceeding the SPLN maximum permissible limit of 80%. Contributing factors include: a 710-meter conductor length with a 70 mm² cross-sectional area producing a line resistance of 0.286 Ohm; inter-phase load imbalance with a maximum current difference of 44 A between Phase R and Phase S; and insulation resistance anomalies at several test points (N-T, T-G, and N-G readings of 0 MOhm). The grounding system was confirmed to be in good condition (2.27 Ohm) and does not contribute as a causal factor.

Second, the evaluation of voltage drop was performed through three complementary approaches: (a) direct voltage measurement at the customer side via kWh meter codes over seven consecutive days at three measurement times per day; (b) analytical calculation using the voltage drop formula $\Delta V = I \times (R \times \cos\phi + X \times \sin\phi)$; and (c) comparison of results against applicable SPLN standards. The evaluation indicates that, prior to uprating, the Phase R voltage profile consistently fell below the 220 V standard during daytime hours, recording a minimum value of 190.93 V on 7 April 2021 at 12:00, representing a deviation of 13.21% from the nominal voltage. Following uprating, the voltage profile improved markedly across all three phases.

Third, the voltage drop at SMK Ponpes Manba'ul'Ulum Cirebon prior to transformer uprating was 28.49 V or 14.92% of nominal voltage, far exceeding the SPLN 72:1987 tolerance of 5–10%. Following uprating from 100 kVA to 160 kVA with load splitting and an additional feeder, voltage drop was reduced to 13.57 V or 6.33%, representing an improvement of 8.59 percentage points (57.57% relative reduction). Nevertheless, the residual value of 6.33% remains slightly above the 5% lower SPLN 72:1987 limit, necessitating the following further actions: evaluation of the potential for conductor uprating from 70 mm² to a larger cross-section; periodic inter-phase load redistribution by

PT PLN (Persero) ULP Sumber; and remediation of conductor insulation at test points exhibiting anomalous resistance values.

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