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Evaluation of SPLU (*Stasiun Pengisian Listrik Umum*) Energy Efficiency Based on Consumption Data and Distribution System Losses Simulation

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SPLU; Energy Efficiency; Distribution System Losses; I^2R; Matlab Simulation; Feeder Length

Abstract

The rapid expansion of electric charging stations (*Stasiun Pengisian Listrik Umum* [SPLUs]) presents challenges for distribution system efficiency because high charging currents and extended feeder lengths can increase power losses. This study aimed to evaluate SPLU energy efficiency, quantify distribution system losses, and identify operational limitations based on load current and feeder length. A quantitative approach was applied by combining analytical calculations using the I^2R loss equation with MATLAB R2025b time-domain simulations. A single-phase circuit was evaluated under 16 scenarios involving feeder lengths of 1, 3, 5, and 10 km and load currents of 10, 20, 32, and 50 A. Analytical and simulation results were compared using percentage error analysis. The simulation results showed an average error of 0.025%, demonstrating consistency with the analytical model. Power losses increased quadratically with load current and linearly with feeder length. System efficiency ranged from 98.908% in the 1 km–10 A scenario to 45.418% in the 10 km–50 A scenario. Efficiency decreased below the 90% operational threshold when feeder lengths exceeded 3 km at currents above 20 A. These findings confirmed that the interaction between load current and feeder length was the primary determinant of SPLU efficiency. Therefore, SPLUs should be installed near distribution substations, while current limitations and larger conductor sizes should be considered for longer feeders.

INTRODUCTION

The global energy sector transformation toward a low-carbon emission system has become a strategic agenda in recent decades, particularly in supporting the 2060 Net Zero Emission (NZE) target. One concrete manifestation of this transformation is the accelerated adoption of electric vehicles, which directly increases the demand for charging infrastructure, including Public Electric Vehicle Charging Stations (*Stasiun Pengisian Kendaraan Listrik Umum* [SPKLU]) and Public Electric Utility Stations (*Stasiun Pengisian Listrik Umum* [SPLU]). In Indonesia, the development of this infrastructure has shown a consistent upward trend, both in terms of the number of installed units and the volume of distributed energy

(IEA, 2023; PT PLN, 2025). The national electric vehicle roadmap has established ambitious targets for charging infrastructure deployment across Indonesia by 2030, reflecting the government's commitment to accelerating the clean energy transition in the transportation sector (KESDM, 2022).

The growth of SPLU as a new load within distribution systems introduces technical challenges that require careful consideration. Distribution systems in Indonesia generally operate with radial configurations and unidirectional power flows (Gönen, 2014); therefore, the addition of high-current loads such as SPLU can significantly increase power losses within the network. In addition to load current magnitude, feeder length and conductor characteristics are dominant variables affecting electrical losses. In medium-voltage distribution systems, technical losses have been reported to reach 6%–13% of total distributed energy, depending on network configuration and operating conditions (Gönen, 2014). Locating SPLU facilities far from distribution substations increases total line resistance, thereby increasing power losses and reducing energy delivery efficiency. This condition requires attention to maintain distribution system reliability and performance (Majumdar et al., 2022).

Previous studies have demonstrated that electric vehicle load penetration significantly affects power losses and voltage profiles in distribution systems. Majumdar et al. (2022), through a simulation-based approach, showed that electric vehicle charging loads can significantly increase system losses, particularly in distribution networks with long feeders. Similarly, Syafruddin et al. (2023), who evaluated distribution network and transformer performance at public SPKLU facilities, confirmed that electric vehicle charging loads affect downstream network performance. Furthermore, Deb et al. (2018) investigated the optimal placement of electric vehicle charging stations under distribution network constraints and demonstrated that inappropriate placement can lead to substantial efficiency degradation. Habib et al. (2018) also confirmed that the interaction between charging current magnitude and feeder distance determines the level of power losses, with the quadratic relationship between current and losses representing the dominant factor. However, most existing studies remain focused on specific network configurations and have not systematically examined how simultaneous variations in load current and feeder length affect losses in SPLU supply systems, particularly within the PT PLN (Persero) UP3 Sidoarjo distribution network context.

Considering the limited availability of real-time SPLU operational data during the internship period at PT PLN (Persero) UP3 Sidoarjo, this study employed an analytical-simulation approach. Energy efficiency and power losses were evaluated through mathematical calculations and numerical time-domain simulations using MATLAB with representative load scenarios based on general SPLU technical specifications and literature parameters (MathWorks, 2025). The distribution system supplying the SPLU was represented using a single-phase equivalent model, consistent with the research scope focusing on I^2R losses without evaluating interphase load imbalance. The limitation regarding the unavailability of real-time operational data was explicitly acknowledged. Kersting (2012) supported this approach by demonstrating that single-phase equivalent models are widely accepted for feeder-level loss analysis in balanced low-voltage distribution systems. This study aimed to evaluate SPLU energy efficiency and assess distribution system losses through analytical calculations and MATLAB-based numerical simulations, while identifying the dominant factors affecting efficiency and power losses. The results were expected to provide technical recommendations for PT PLN (Persero) UP3 Sidoarjo in planning efficient SPLU placement and supporting the achievement of Sustainable Development Goal 7 (SDG 7) on affordable and clean energy.

The novelty of this study lies in its systematic evaluation of SPLU energy efficiency through 16 parametric scenarios combining four feeder lengths (1, 3, 5, and 10 km) and four load-current levels (10, 20, 32, and 50 A). Unlike previous studies that primarily focused on aggregate electric vehicle penetration or optimization algorithms, this research isolated the physical effects of load current and feeder length using an I^2R-based analytical model and MATLAB numerical time-domain simulation. The simulation represented the supply feeder as a single-phase equivalent circuit and applied consistent electrical parameters across all scenarios, enabling direct comparison between analytical and numerical results. Model accuracy was evaluated using percentage error analysis, while efficiency values were analyzed to identify technically acceptable and inefficient operating combinations.

Accordingly, this research aimed to evaluate the energy efficiency of distribution systems supplying SPLU facilities and quantify power losses generated under different combinations of feeder length and load current. The specific objectives were to calculate line losses analytically, reproduce equivalent operating conditions through MATLAB time-domain simulation, validate the numerical model against analytical results, determine the relative influence of load current and feeder length, and identify operating conditions capable of maintaining acceptable energy efficiency levels. The study also sought to determine whether load current or feeder length represented the more influential planning variable and to formulate practical recommendations for SPLU placement and operation within the PT PLN (Persero) UP3 Sidoarjo distribution network.

This research contributes theoretically by providing a structured explanation of the quadratic relationship between charging current and technical losses, as well as the linear relationship between feeder length and conductor resistance. Methodologically, it demonstrates the integration of analytical calculations with numerical time-domain simulations when comprehensive field measurements are unavailable. Practically, the findings are expected to assist PT PLN (Persero) UP3 Sidoarjo in determining appropriate SPLU locations, establishing charging-current limitations, selecting suitable conductor capacities, and prioritizing feeders requiring reinforcement. The resulting evidence may also support utilities, infrastructure developers, and policymakers in expanding charging networks that are geographically accessible, technically efficient, economically sustainable, and aligned with Indonesia’s clean energy transition.

METHOD

This study employed a quantitative approach based on electrical power system analysis, combining analytical calculations and numerical time-domain simulations using MATLAB. The analytical method was used to calculate SPLU energy efficiency and power losses based on fundamental power system equations, while the numerical simulation method was applied to validate the calculation results through a single-phase equivalent circuit model (Saadat, 2010). A comparative approach was also applied by comparing analytical and simulation results to assess model accuracy and consistency between theoretical calculations and simulated conditions. The overall research methodology was presented in the flowchart shown in Figure 1.

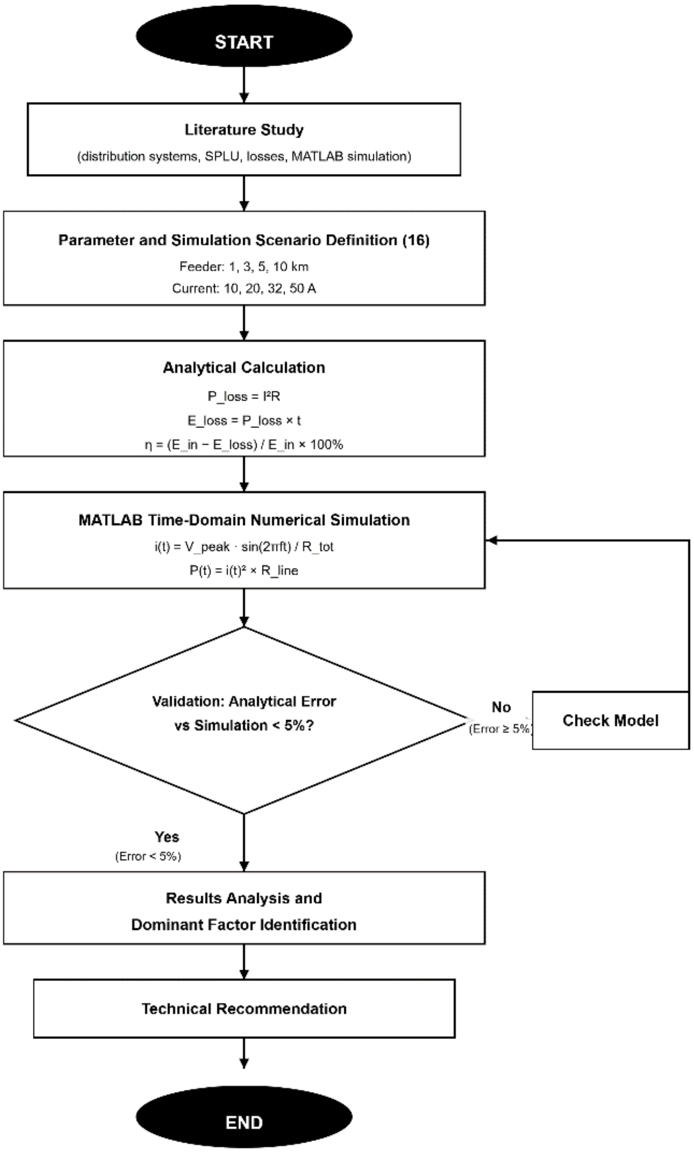

Figure 1. Research Methodology Flowchart

System Parameters and Simulation Scenarios

The simulated system represents a low-voltage distribution feeder segment supplying a single SPLU load point. Line resistance is determined based on the characteristics of AAAC 150 mm² conductor at 0.2162 Ω/km, which is commonly used in PLN 20 kV distribution networks (PT PLN, 2010). Feeder length variations are set at four values: 1 km, 3 km, 5 km, and 10 km, representing SPLU placement conditions at different distances from the distribution substation. Load current variations are set at four values: 10 A, 20 A, 32 A, and 50 A, representing SPLU loading levels from light conditions to near semi-fast charging capacity (IEA, 2023). The combination of four feeder length variations and four load current variations produces 16 parametric simulation scenarios. Phase voltage is set at 220 V (RMS) according to Indonesian low-voltage distribution standards, power factor $\cos\varphi = 0.9$, and reference operating time t = 1 hour for energy calculation purposes. Dharmakeerthi et al. (2014) confirms that these parameter ranges are representative of typical low-voltage distribution conditions serving EV charging loads in urban areas of developing countries.

The load resistance in each scenario is compensated against line resistance using the equation Rload = V/Inom – Rline, ensuring that the actual current in the circuit exactly equals the nominal target current and maintaining full consistency between analytical and simulation approaches. This compensation method is adopted from established power circuit analysis practice (Saadat, 2010) and ensures that the I^2R analytical formula and the numerical circuit simulation use identical current values, producing physically meaningful and directly comparable results.

Analytical Equations

Active power losses in the distribution line are calculated using the fundamental technical loss equation of the distribution system:

$$P_{loss} = I^2 \times R \qquad (1)$$

where Ploss is the active power losses (W), I is the load current (A), and R is the total line resistance (Ω), which is the product of resistance per kilometer and feeder length. This equation shows that losses are quadratic with respect to load current, so increasing SPLU load will significantly impact loss increase (Gönen, 2014). The energy lost during the operating period is calculated using:

$$E_{loss} = P_{loss} \times t \qquad (2)$$

where t is the operating time (hours), giving Eloss the unit of Wh. This equation provides an accumulation picture of losses over a specific period that can be used to evaluate the impact of energy losses on a daily or monthly basis. The energy efficiency of the distribution system supplying SPLU is calculated as:

$$\eta = (E_{in} - E_{loss}) / E_{in} \times 100\% \qquad (3)$$

where Ein is the energy supplied from the source side (Wh), calculated as Ein = V × I × cosφ × t. Equation (3) specifically evaluates the distribution system side efficiency, not the efficiency of the SPLU charging device itself, consistent with the research scope limitations (Majumdar et al., 2022).

C. MATLAB Numerical Time-Domain Simulation

Simulation is performed numerically in MATLAB R2025b with a time step of $dt = 10^{-5}$ seconds over 5 cycles (0.1 seconds) using an ideal single-phase AC voltage source model (MathWorks, 2025). Instantaneous current is calculated using the single-phase equivalent circuit equation based on Ohm's law:

$$i(t) = (V_{peak} \times \sin(2\pi ft)) / (R_{line} + R_{load}) \qquad (4)$$

where $V_{peak} = 220\sqrt{2} = 311.13$ V and f = 50 Hz. Instantaneous power losses are calculated as $P_{loss}(t) = i(t)^2 \times R_{line}$, then averaged in steady-state conditions starting from cycle 3 to avoid the influence of initial transients. Chapra & Canale (2015) validates that this time-domain averaging approach for resistive AC circuits produces results that are mathematically equivalent to the $I_{rms}^2 \times R$ formula with negligible discretization error at sufficiently small time steps. The average power losses in steady-state for a sinusoidal signal in a purely resistive circuit is theoretically identical to the value of I^2R using Irms, so this approach is theoretically equivalent to Equation (1). All 16 scenarios are executed automatically through a MATLAB script that performs loop iteration over all parameter combinations, with results stored in tables and CSV files for further analysis.

Validation Method

Model validation is performed by calculating the percentage error between analytical and simulation results using the formula:

Error (%) = |Ploss_analytic – Ploss_simulation| / Ploss_analytic × 100% (5)

This error is calculated for each of the 16 scenarios and then averaged to obtain the overall model average error. The model is declared valid if the average error is below the 5% tolerance threshold set as the model validity indicator. This validation threshold is consistent with commonly accepted practices in numerical simulation studies of electrical distribution systems (Gönen, 2014; Saadat, 2010).

RESULTS AND DISCUSSION

Analytical Calculation Results and Simulation Validation

Based on the methodology described in the previous section, analytical calculations using Equations (1)–(3) and MATLAB numerical time-domain simulation using Equation (4) were performed for all 16 parametric scenarios. The complete results are presented in Table 1. Validation against all 16 scenarios yielded an average error of 0.025%, far below the 5% tolerance threshold established as the model validity indicator, so the simulation model is declared validated. This very small error is caused by the fine time discretization (dt = 10^{-5} s) that approximates sinusoidal integrals with very high accuracy, and confirms that numerical simulation is capable of reproducing analytical calculation results with high precision (MathWorks, 2025).

Table 1. Analytical Calculation and Simulation Results for 16 Scenarios

Feeder	Rline (Ω)	I (A)	Rload (Ω)	Ploss analitis (W)	Ploss simulasi (W)	Eloss (Wh)	Ein (Wh)	η (%)	Error (%)
1 km	0.2162	10	21.784	21.62	21.615	21.615	1980	98.908	0.025
		20	10.784	86.48	86.458	86.458	3960	97.817	0.025
		32	6.659	221.39	221.330	221.330	6336	96.507	0.025
		50	4.184	540.50	540.360	540.360	9900	94.542	0.025
3 km	0.6486	10	21.351	64.86	64.844	64.844	1980	96.725	0.025
		20	10.351	259.44	259.380	259.380	3960	93.450	0.025
		32	6.226	664.17	664.000	664.000	6336	89.520	0.025
		50	3.751	1621.50	1621.100	1621.100	9900	83.625	0.025
5 km	1.0810	10	20.919	108.10	108.070	108.070	1980	94.542	0.025
		20	9.919	432.40	432.290	432.290	3960	89.084	0.025
		32	5.794	1106.90	1106.700	1106.700	6336	82.534	0.025
		50	3.319	2702.50	2701.800	2701.800	9900	72.709	0.025
10 km	2.1620	10	19.838	216.20	216.150	216.150	1980	89.084	0.025
		20	8.838	864.80	864.580	864.580	3960	78.167	0.025
		32	4.713	2213.90	2213.300	2213.300	6336	65.067	0.025
		50	2.238	5405.00	5403.600	5403.600	9900	45.418	0.025

Analysis of Load Current Effect on Losses

The results in Table 1 confirm empirically that power losses are quadratic with respect to load current, consistent with the I^2 relationship in Equation (1). As a representative example, at the 5 km feeder, increasing current from 10 A to 20 A (2× increase) raises Ploss from 108.07 W to 432.29 W (4× increase), while increasing from 10 A to 50 A (5× increase) raises Ploss to 2,701.8 W (25× increase). This multiplication pattern is consistent across all feeder length variations and directly reflects the quadratic nature of I^2 that constitutes the core of the technical loss equation in distribution systems (Gönen, 2014). Clement-Nyns et al. (2010) similarly reported that EV charging loads with higher current ratings create disproportionately larger losses compared to conventional loads, emphasizing the need for current management strategies in networks serving charging infrastructure.

The quadratic pattern is clearly visible in Figure 2, which displays power losses against feeder length for all current groups. The four curves representing 10 A, 20 A, 32 A, and 50 A show increasingly widening gaps as feeder length increases, with the I = 50 A curve positioned far above the others, reaching Ploss = 5,403.6 W at the 10 km feeder more than 25 times higher than the I = 10 A scenario on the same feeder (216.15 W). This finding is highly significant from a practical standpoint: semi-fast charging mode with currents of 32–50 A, which is increasingly being implemented on modern SPKLU, generates losses that are far greater than slow charging mode at 10–20 A, even at the same feeder length.

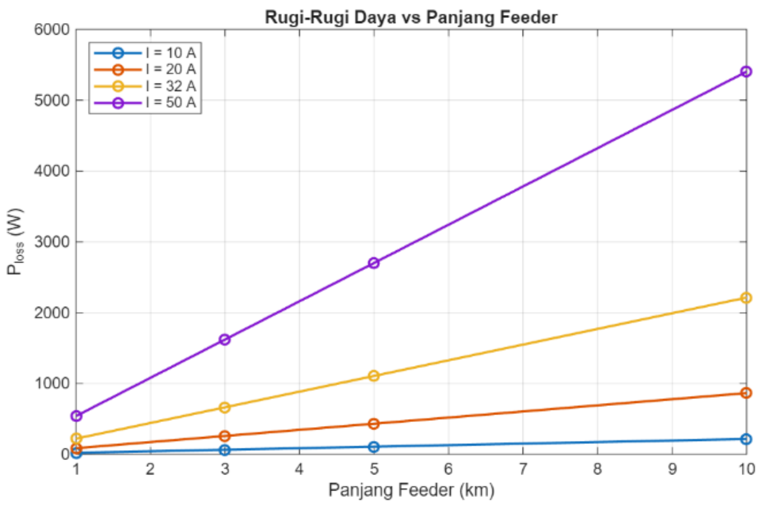

Figure 2. Simulation Power Losses vs. Feeder Length at Various Load Currents

Analysis of Feeder Length Effect on Losses and Efficiency

For the same load current, losses increase linearly with feeder length because total line resistance Rline = r × L is directly proportional to length L. At 20 A load current, Ploss increases proportionally from 86.46 W (1 km) to 259.38 W (3 km), then 432.29 W (5 km), reaching 864.58 W at the 10 km feeder. The multiplication ratios between values are consistent with Rline ratios: from 1 km to 3 km the resistance triples and losses triple accordingly, and from 1 km to 10 km the resistance increases 10-fold and losses increase 10-fold as well. This perfect linearity holds consistently across all 16 scenarios and confirms the physical validity of the model (Saadat, 2010). (Awasthi et al., 2017) similarly demonstrated this linear relationship between feeder distance and distribution losses in urban EV charging network studies, validating the fundamental I^2R analysis approach used in this study.

The combined impact of both variables on efficiency is shown in Figure 3. All curves show an increasingly steep downward trend as feeder length and load current increase. At low current (I = 10 A), efficiency remains relatively high across the entire tested feeder range, from 98.908% at 1 km to 89.084% at 10 km, indicating that even at the greatest distance the losses are still within operationally acceptable bounds. This situation changes drastically at high current (I = 50 A), where efficiency drops sharply from 94.542% at the 1 km feeder to only 45.418% at the 10 km feeder. This means that more than half of the energy supplied from the distribution substation is lost as heat in the line conductors before reaching the SPLU charging point — a condition that is completely unacceptable from both technical and economic perspectives (Majumdar et al., 2022).

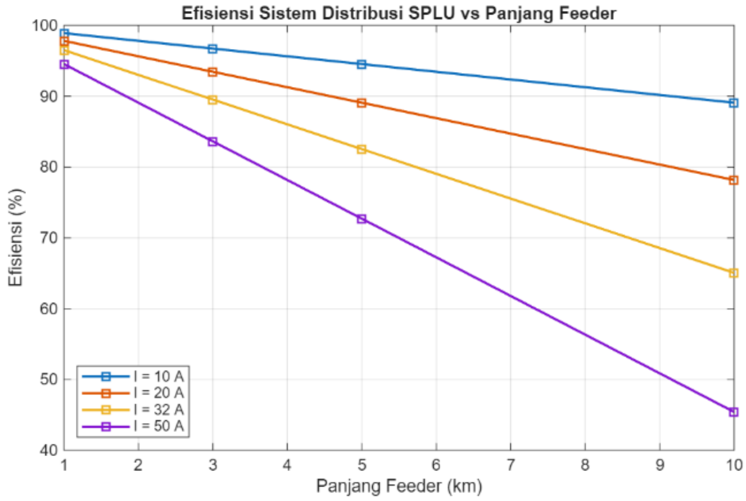

Figure 3. SPLU Distribution System Efficiency vs. Feeder Length at Various Load Currents

Operational Boundary Identification

Based on Figure 3 and Table 1, the operational boundaries of the distribution system supplying SPLU can be identified based on a minimum efficiency threshold of 90%. Setting this threshold as the minimum acceptable operational boundary, which is consistent with distribution system performance evaluation practice (Gönen, 2014), the following operational limits are established. At 10 A load current, all tested feeder lengths (1–10 km) still produce efficiency above 89%, with the lowest value of 89.084% at the 10 km feeder approaching the boundary. At 20 A load current, the feeder length that still maintains efficiency above 90% is approximately 3 km (93.450%), while at 5 km efficiency has already dropped to 89.084%. At 32 A load current, only the 1 km feeder (96.507%) is comfortably above 90%, while the 3 km feeder is already at 89.520% nearly touching the boundary. At 50 A load current representing semi-fast charging, even the 3 km feeder produces only 83.625% efficiency, and the 10 km feeder produces an extremely low efficiency of 45.418%.

These results provide a clear picture that the simultaneous interaction between high load current and long feeder produces an impact far greater than merely summing both factors separately, because the quadratic nature of current amplifies every increase in feeder length. The extreme scenario of 10 km with 50 A current is not only highly inefficient, but also operationally unrealistic because the resulting voltage drop would far exceed allowable voltage tolerance limits specified in distribution system standards (PT PLN, 2010; IEEE, 2014).

Comparison with Literature

Comparison with the 6%–13% distribution losses range reported by Gönen (2014) shows that the 3 km feeder scenarios with 20–32 A currents producing losses of 6.55%–10.48% fall exactly within that range, indicating these parameter combinations represent realistic operational conditions for distribution networks serving SPLU in urban areas such as UP3 Sidoarjo. Scenarios outside this range, particularly feeder lengths exceeding 5 km with currents above 32 A, represent technically extreme conditions requiring network intervention. This finding aligns with Majumdar et al. (2022) who also identified feeder length as a major factor in loss increases due to electric vehicle loads, and with Dharmakeerthi et al. (2014) who reported that high-current EV charging loads are the primary driver of efficiency degradation in distribution networks of developing countries. Furthermore, Prakash & Khatod (2016) confirms that validated numerical simulation approaches produce results consistent with field measurements when the circuit parameters are accurately modeled, lending further credibility to the simulation methodology employed in this study.

Dominant Factor Identification and Technical Implications

The overall results indicate that the dominant factor determining the efficiency of the distribution system supplying SPLU is the simultaneous interaction between load current and feeder length, not either variable in isolation. Losses are quadratic with respect to I and linear with respect to L, so increasing both simultaneously produces a compounding impact. The most effective strategy for maintaining efficiency is therefore to limit feeder length (prioritizing SPLU placement near distribution substations) while simultaneously implementing charging current limits at SPLU locations that geographically cannot avoid being far from the supply source. This dual-strategy approach is consistent with recommendations from Clement-Nyns et al. (2010) and Awasthi et al. (2017), who concluded that integrated spatial planning and demand-side management are essential for maintaining distribution efficiency in networks with high EV charging penetration. The practical implications for PT PLN (Persero) UP3 Sidoarjo are clear: SPLU placement planning must consider feeder distance as a primary technical constraint from the earliest planning stages, with a recommended maximum distance of 3 km from the nearest distribution substation for charging currents up to 20 A, and no more than 1 km for semi-fast charging at 50 A.

CONCLUSION

This study successfully evaluated SPLU energy efficiency and distribution system power losses through an I^2R analytical approach and MATLAB-based numerical time-domain simulations across 16 parametric scenarios. The simulation model was validated with an average error of 0.025% compared with analytical calculations, which was substantially below the 5% tolerance threshold. This result confirmed that the numerical time-domain simulation method was capable of reproducing I^2R calculation results with high accuracy and could be reliably applied as a validation approach for distribution system loss analysis (MathWorks, 2025).

Three main findings were obtained from the analysis. First, power losses increased quadratically with load current; a fivefold increase in current from 10 A to 50 A resulted in a

25-fold increase in losses on the same feeder, confirming the critical influence of charging current magnitude on SPLU loss management. Second, power losses increased linearly with feeder length due to the direct relationship between feeder length and line resistance, making feeder length a predictable and controllable planning parameter. Third, the interaction between load current and feeder length determined overall system efficiency, which ranged from 98.91% in the best-case scenario (1 km/10 A) to 45.42% in the worst-case scenario (10 km/50 A). The 90% minimum efficiency threshold was exceeded when feeder lengths were greater than 3 km with load currents above 20 A. These findings were consistent with previous studies on the impact of electric vehicle charging loads on distribution networks (Majumdar et al., 2022; Syafruddin et al., 2023) and extended existing research by providing a systematic parametric evaluation of efficiency under combined feeder-length and load-current conditions.

Based on these findings, PT PLN (Persero) UP3 Sidoarjo is recommended to prioritize SPLU placement within a maximum radius of 3 km from the nearest distribution substation, apply charging-current limitations for SPLU locations exceeding 5 km from the supply source, and consider the use of larger conductor cross-sectional areas for feeders supplying high-load SPLU clusters. This study was primarily limited by the unavailability of real-time SPLU operational log data; therefore, future research should validate the findings using actual field operational data to confirm and extend the results under real distribution system conditions.

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