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RESEARCH ARTICLE

Study of Reducing Transmission Losses in Java-Bali System with the Addition of Capacitors along with Optimal Capacitor Placement Methods Using Quasi-Dynamic Simulation

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Abstract

The Java-Bali electricity system is the largest electricity system in Indonesia which consists of 5 areas including Jakarta-Banten area, West Java area, Central Java area, East Java area and Bali area. This system is operated to meet the economic, reliability, quality, and green principles. In the case of economics, one of the essential aims is minimization of transmission losses due to importance in system improvement to increase system operational efficiency to the possible extent. Transmission losses are an inevitable part of the electric power transfer process from generation stations to consumers. The power losses in a transmission line are inversely proportional to the square of the line voltage. This implies that lower line voltages result in higher power losses. Therefore, it is crucial to maintain optimal voltage levels to minimize transmission losses and ensure efficient energy delivery across the power system. One effective way to achieve this is by integrating capacitors into the system. In this study, we have explored two methods that aim to pinpoint the most advantageous locations for the integration of new capacitors. The goal is to optimize capacitor planning, with an emphasis not only on improving voltage levels but also on minimizing transmission losses within the Java-Bali system. The research results indicate that implementing two proposed methods can significantly reduce transmission losses in The Java-Bali system. Method-1 involves identifying the lowest voltage over the course of a year, while Method-2 focuses on the lowest voltage value within the first quartile (Q1/25%) during the same period. Method-1 yields superior results, where the utilization of the new capacitors are more effective compared to Method-2.

Keywords: economic, electrical system efficiency, transmission losses, capacitors, optimal capacitor placement methods, quasi-dynamic

1. Introduction

In Indonesia, there are several electricity systems which are divided into several regions, including Java-Bali system, Sumatera system, Kalimantan system, Maluku system, Papua system and various isolated systems. The Java-Bali electricity system is the largest electricity system in Indonesia which consists of 5 areas including Jakarta-Banten area, West Java area, Central Java area, East Java area and Bali area. This system is operated to meet the economic, reliability, quality, and green principles.

In the case of economic and quality, one of the essential aims is minimization of transmission losses due to its importance in system improvement to increase system operational efficiency to the possible extent [1]. Transmission losses occur during the transfer of electric power from generating stations to consumers. These transmission losses are caused due to factors such resistance in conductors, magnetic losses in transformers, and other transmission network equipment. These losses represent the portion of energy that remains uncompensated by users. In an electrical transmission network, a deficiency in reactive power leads to a decrease in bus voltage and an increase in losses [1]. Maintaining optimal voltage levels is essential for minimizing transmission losses and ensuring efficient energy delivery across the power system [2]]. Capacitors play a vital role in power systems, contributing to both voltage enhancement and reduction of transmission losses. Capacitors inject reactive power to raise voltage levels especially during peak load conditions. By compensating reactive power and maintaining voltage support, capacitors minimize voltage drop along transmission lines. Optimal capacitors placement will optimize system performance, resulting in voltage enhancement and efficient energy delivery [3].

In Indonesia, in this case the Java-Bali electricity system, the transmission losses value is targeted by the government every year. For example, in 2023, the transmission losses value targeted by the government is 1.93%, but the realization is 1.95%. Therefore, given the growing concern over transmission losses in the Java-Bali system, this is an area that warrants further investigation. There is some research that has been conducted on the optimal placement of capacitors in electrical power systems. Reference [1] has explored the use of genetic algorithms for determining the optimal capacitor placement in electrical transmission systems. Reference [4] elucidates various strategies for optimal capacitor placement and sizing in transmission networks, paving the way for enhanced results through further research in this area. This research introduces two methods aimed at identifying the most optimal locations for the addition of new capacitors. The objective is to optimize capacitor planning, with a focus not only on enhancing voltage levels but also on reducing transmission losses within the Java-Bali system.

2. Power System Transmission Losses Analysis

2.1 Load Flow Analysis

Load flow analysis, also referred to as a power flow study, plays a critical role in power systems. It examines steady-state conditions, analyzing voltage magnitudes, angles, and real or reactive power. The Newton-Raphson method is used to solve the nonlinear equations of the load flow [5].

Numerical analysis, which solves algebraic simultaneous equations, serves as the foundation for addressing performance equations in computer-aided electrical power system analyses. Specifically, this applies to load flow analysis. The initial step involves constructing the Y-bus admittance matrix using input data related to transmission lines and transformers [6]. The nodal equations for a power system network, utilizing the Y bus, can be expressed as follows:

$$I = Y_{Bus}I \quad (1)$$

The nodal equation can be expressed in a generalized manner for an n-bus system.

$$I_i = \sum_{j=1}^{n} Y_{ij}V_j \text{ for } i = 1, 2, 3, n \quad (2)$$

The complex power supplied to bus i is:

$$P_i + jQ_i = V_i I_i^* \quad (3)$$

$$I_i = \frac{P_i + jQ_i}{V_i^*} \quad (4)$$

This equation below provides the expression for I_i by substituting it in terms of P_i and Q_i as follows:

$$\frac{P_i + jQ_i}{V_i^*} = V_i \sum_{j=1}^{n} Y_{ij} - \sum_{j=1}^{n} Y_{ij}V_j j \neq i \quad (5)$$

P is the real power at the i bus, Q is the reactive power, V is the voltage, I is the complex conjugate of source current injected into the bus.

This research employs Newton-Raphson method for load flow problem-solving. Therefore, it is essential to revisit the fundamental structures of Newton-Raphson method. The Newton-Raphson method, named after Isaac Newton and Joseph Raphson, traces its origins back to the late 1960s [7]. This iterative technique approximates a set of nonlinear simultaneous equations by transforming them into a system of linear simultaneous equations using Taylor's series expansion. Widely employed for load flow analysis, the Newton-Raphson approach exhibits robust convergence properties compared to alternative methods. It reliably handles cases that might diverge with other popular approaches [8]. When the initial assumption is close to the solution, results are swiftly obtained. However, if the initial guess deviates significantly from the solution, convergence may take longer [9]. This method is commonly used for solving nonlinear equations in load flow analysis.

The admittance matrix plays a crucial role in formulating equations related to the currents entering a power system.

Equation 2 is represented in polar form, where the complex unit j incorporates bus i:

$$I_i = \sum_{j=1}^{n} |Y_{ij}||V_i| < \theta_{ij} + \delta_j \tag{6}$$

The real power and reactive power at bus i:

$$P_i - jQ_i = V_i^* I_i \tag{7}$$

By replacing the value of I_i in Equation 6 with the expression from Equation 7:

$$P_i - jQ_i = |V_i| < -\delta_j \sum_{j=1}^{n} |Y_{ij}||V_i| < \theta_{ij} + \delta_j \tag{8}$$

The real and imaginary components are disentangled:

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \tag{9}$$

$$Q_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \tag{10}$$

The system of nonlinear algebraic equations represented by Equations 9 and 10 involves the voltage magnitude in per unit and the phase angle δ in radians. These equations are expanded using Taylor's series around the initial estimate, with higher-order terms neglected. Notably, the slack bus's voltage magnitude and angle elements are excluded since they are already known. By taking partial derivatives of Equations 9 and 10, we derive the Jacobian matrix elements, establishing a linearized relationship between small changes in voltage magnitude and angle. The resulting equation can be expressed in matrix form as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_3 \\ J_2 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix}$$

The latest approximation for bus voltage has been obtained.

$$\delta^{(k+1)} = \delta_1^{(k)} + \Delta\delta_i^{(k)} \tag{12}$$

$$|V^{(k+1)}| = |V^{(k)}| + \Delta|V_i^{(k)}| \tag{13}$$

2.2 Transmission Losses Calculation

Transmission losses pose a formidable challenge for operators within electric power systems. These losses manifest when energy procured from generators dissipates during the intricate process of delivering electricity to end-users. Regrettably, this dissipated energy remains irrecoverable and cannot be marketed to consumers. The magnitude of transmission losses hinges upon the current coursing through the transmission lines and the inherent resistance of these segments.

For a specific type of conductor and a given transmission length, the extent of transmission losses is intrinsically tied to the prevailing current magnitude. When catering to loads characterized by constant active power demands, the current flow is intricately linked to the voltage level at the load side [10]. Notably, if the voltage at the load side is diminished, an accompanying surge in current ensues, and vice versa.

Equation 15 corroborates this relationship, revealing that heightened current levels correspond to amplified transmission losses. Consequently, the strategic deployment of capacitors aimed at enhancing voltage and power factors can significantly mitigate these losses [1].

$$P_{\text{Gen}} = P_{\text{Load}} + P_{\text{Loss}} \tag{14}$$

$$P_{\text{Loss}} = I^2 R \tag{15}$$

$$P_{\text{Load}} = V \times I \tag{16}$$

3. Research Methods

3.1 The Java-Bali Electricity System

Figure 1 illustrates the current state of the Java-Bali electrical system which consists of 5 areas including Jakarta-Banten area, West Java area, Central Java area, East Java area and Bali area. At present, this system includes 419 substations that deliver power to customers, boasting a total transformer capacity of 61,068 MVA. This system has a peak load of 32,032 MW, with a net generating capacity of 43,350 MW [11]. In 2023, the transmission losses in the Java-Bali electricity system amounted to 1.95%, slightly above the government's target of 1.93%.

This study conducts a case study focused on the projected conditions of the Java-Bali system in 2025. The choice of 2025 as the case study year is strategic, as it allows for additional input in determining the most optimal placement of capacitors. This is particularly relevant because the procurement of new capacitors planned for 2025 has not yet commenced, whereas the projects for new capacitors in 2024 are already underway.

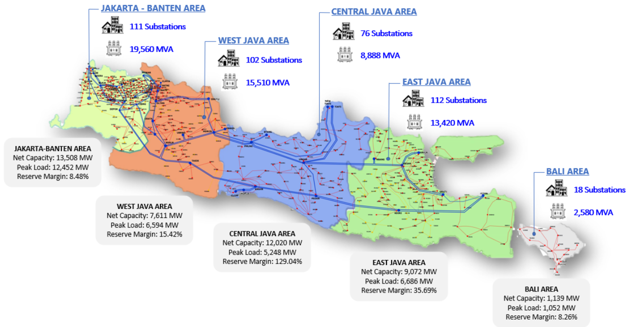


Figure 1. The Java-Bali Electricity System. [7]

3.2 Transmission Losses Calculation Using Quasi-Dynamic Simulation

Nowadays, Quasi-dynamic simulation is widely used in international power systems to analyze the impact of intermittent generation. Unlike traditional deterministic methods, quasi-dynamic simulation considers specific time frames (e.g., day, week, month, year) and factors in system load curves, generation profiles, and renewables' operation. While it requires more data and complex models, this approach provides a realistic estimation of generation behavior. Quasi-dynamic simulation enhances our understanding of power system dynamics, ensuring efficient and reliable energy delivery [12].

Quasi-dynamic simulation is a method used in power systems to simulate power flow at multiple (or many) time points sequentially, also known as time series analysis. Quasi-dynamic simulation can be applied for short-, medium-, or long-term analysis. In this approach, simulation parameters are modeled over time based on load profiles, predetermined generation data, and the development of power infrastructure according to expansion phases. The purpose of quasi-dynamic simulation is to obtain a broader understanding of the condition of an electrical power system. By doing so, it aims to achieve more accurate and precise results in system planning studies [13].

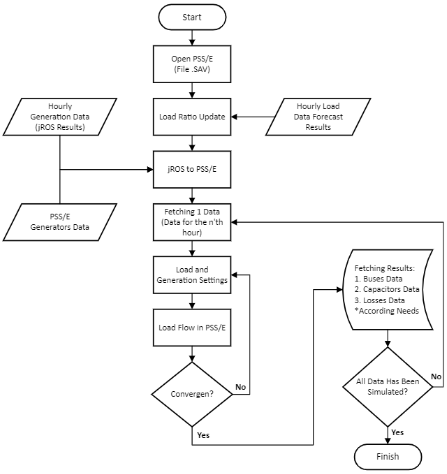


Figure 2. Quasi-Dynamic Simulation Flowchart

In this study, transmission losses calculations are performed using quasi-dynamic simulation. In Figure 2, we observe the flowchart of the quasi-dynamic simulation employed in this paper. The analysis will be conducted using certain tools and software, jROS will be employed to execute the generator production optimization simulation, while PSS/E will be used for performing the load flow. Python, as a programming language, will be utilized to execute a quasi-dynamic simulation on PSS/E. The quasi-dynamic simulation spans 8760 times throughout the year of 2025. The data utilized over the span of 8760 hours comprises hourly simulation results from generator production optimization and load forecast outcomes for the entire year of 2025. During this period, data related to buses, capacitors, and losses are collected.

To assess the impact of installing new capacitors on transmission losses, we conduct simulations for each year, totaling four iterations. These iterations include the following scenarios: prior to adding new capacitors; after adding new capacitors with placement following the business-as-usual approach; after adding new capacitors with placement using the proposed method-1; and then after adding new capacitors with placement using the proposed method-2.

3.3 Optimal Capacitor Placement Proposed Methods

In the strategic planning of the Java-Bali electricity system, the addition of new capacitors is primarily aimed at improving the voltage levels within specific subsystems. Considering the increasing concerns about transmission losses within the Java-Bali system, this aspect certainly merits a more in-depth investigation. In 2023, the transmission losses in the Java-Bali electricity system amounted to 1.95%, slightly above the government's target of 1.93%.

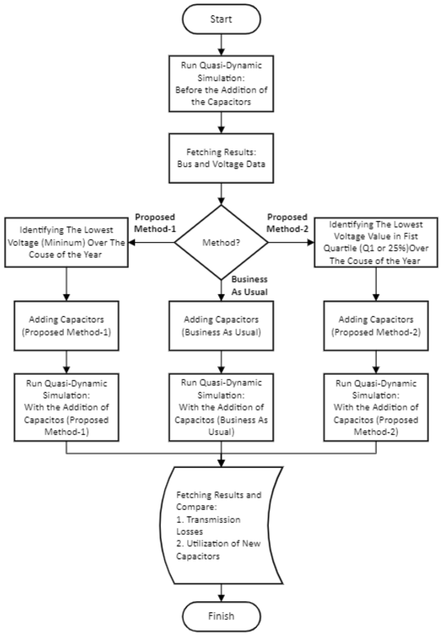


Figure 3. Optimal Capacitor Placement Methods

This research introduces two methods aimed at identifying the most optimal locations for the addition of new capacitors. The objective is to optimize capacitor planning, with a focus not only on enhancing voltage levels but also on reducing transmission losses within the Java-Bali system.

Figure 3 shows optimal capacitor placement proposed methods. Method-1 is implemented by identifying the lowest voltage over the course of a year, in this research specifically in 2025 from the results of quasi-dynamic simulations. The total number of buses with installed capacitors, as well as the capacity of these capacitors, are tailored to align with the company's procurement capabilities for new capacitors. In addition, Method-2 is implemented by identifying the lowest voltage value in the first quartile (Q1/25%) based on the results of quasi-dynamic simulations. The total number of installed bus capacitors and their capacities are also adjusted according to the company's capability to procure new capacitors.

4. Results and Discussions

The results of this research yield several key findings. Firstly, it provides calculated transmission losses for the Java-Bali electricity system across various scenarios. Secondly, it identifies the most optimal method for new capacitor placement. Lastly, it presents the outcomes of new capacitor utilization in scenarios that involve additional capacitors.

4.1 Scenario A: Before the Addition of New Capacitors

Figure 4 presents the results of transmission loss calculations for the Java–Bali system in 2025, prior to the addition of capacitors. These calculations are performed hourly throughout the year and summarized monthly. The cumulative loss for the entire year of 2025 is 1.91%. The highest losses in 2025 are anticipated to occur from September to November, attributable to the higher system load during these three months compared to other months.

Transmission losses are heavily influenced by the transfer between areas and the configuration. This will also significantly impact on the voltage within the Java–Bali system. The lower the voltage, the greater the transmission losses within the system. Therefore, we will also investigate the voltage results in several subsystems that have relatively low voltages, as depicted in Figure 5, and Figure 6.

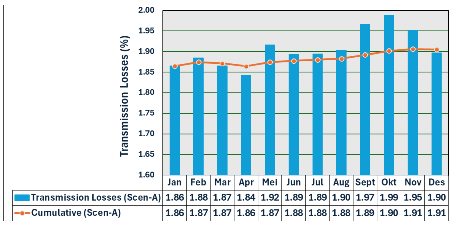


Figure 4. Transmission Losses of the Java-Bali System Before the Addition of New Capacitors in the Year 2025.

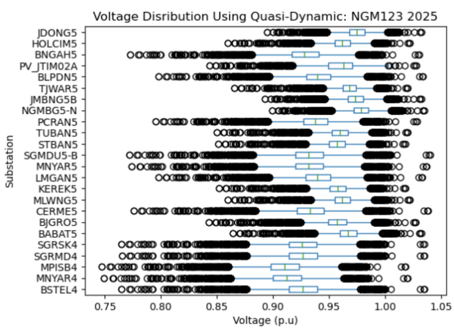


Figure 5. Voltage Distribution Using Quasi-Dynamic in Sub System of Ngimbang 1,2,3.

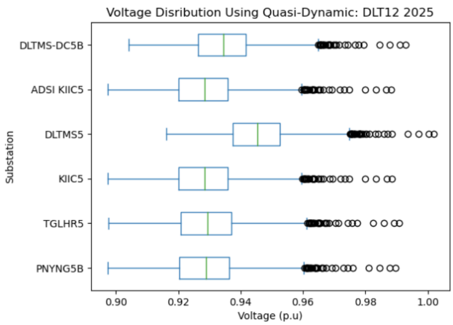


Figure 6. Voltage Distribution Using Quasi-Dynamic in Sub System of Deltamas 1,2.

Figure 5 and Figure 6 display the results of hourly voltage values across various subsystems throughout 2025. These results will serve as the initial basis for determining capacitor installation, which will subsequently be followed by the proposed methods, namely method-1 and method-2. The Java-Bali electricity system permits a voltage limit of +5% to -10% of the nominal voltage for a voltage level of 150 kV. This limit is established by the network rules of the Java-Bali electricity system, as outlined in Regulation No. 20 of 2020 by the Minister of Energy and Mineral Resources. It is also necessary to examine the resulting voltage value data for all subsystems and summarize the lowest voltage data and 1st quartile for all substations in the Java, Madura, and Bali systems. This is to ensure that the proposed method can be implemented effectively.

4.2 Scenario B: With the Addition of New Capacitors (Business as Usual)

For the year 2025, the operation of additional capacitors has been studied. However, the integration of these capacitors into the system is primarily planned to address voltage issues in several subsystems across different regions, not to reduce transmission losses. Despite this, the focus of this study is to examine the impact of capacitor addition on the reduction of transmission losses.

Therefore, by planning the integration of existing capacitors, calculations for transmission losses are conducted. Table 1 shows the additional capacitors in 2025 with the scenario business as usual. The results of these transmission loss calculations are depicted in Figure 7. These calculations are performed hourly throughout the year and summarized monthly. The cumulative loss for the entire year 2025 is 1.90%.

Table 1. The Additional Capacitors in 2025 (Business as Usual)

No	Substation	Area	Unit	Voltage (kV)	Capacity (MVAr)
1.	Cikedung	West Java	1	150	50
2.	Jatibarang	West Java	1	150	50
3.	Teluk Jambe II	West Java	1	150	50
4.	Purworejo	Central Java	1	150	50
5.	Wonosobo	Central Java	1	150	50
6.	Blora	Central Java	1	150	50
7.	Rayum	Central Java	1	150	50
8.	New Pacitan	East Java	1	150	50
9.	Paciran	East Java	1	150	50
10.	Guluk – Guluk	East Java	1	150	50
11.	New Nganjuk	East Java	1	150	25
12.	New Nganjuk	East Java	1	150	25
13.	Karangkates	East Java	1	150	10
14.	Sengkaling	East Java	1	150	50
15.	Petrokimia	East Java	1	150	50

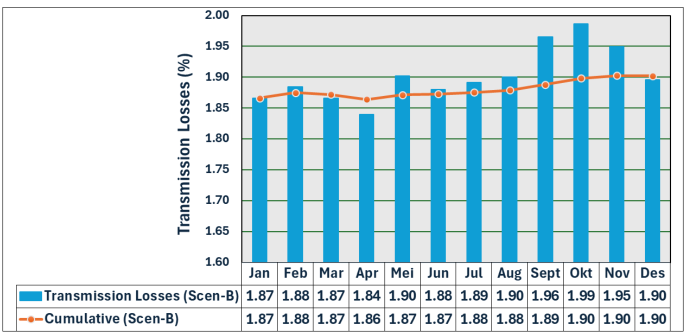


Figure 7. Transmission Losses of the Java-Bali System with the Addition of New Capacitors with Business as Usual in the Year 2025.

We also perform computations or simulations to assess the usage of new capacitors, specifically, their operational duration throughout the year as shown in Figure 8. In the graph, the green color signifies the duration, in hours, that the capacitor is active within a year. Conversely, the purple color indicates the hours when the capacitor is inactive. For instance, when a 50 MVAr capacitor is integrated into the Jatibarang substation, it is operational for 8552 hours and is non-operational for 208 hours throughout 2025, etc.

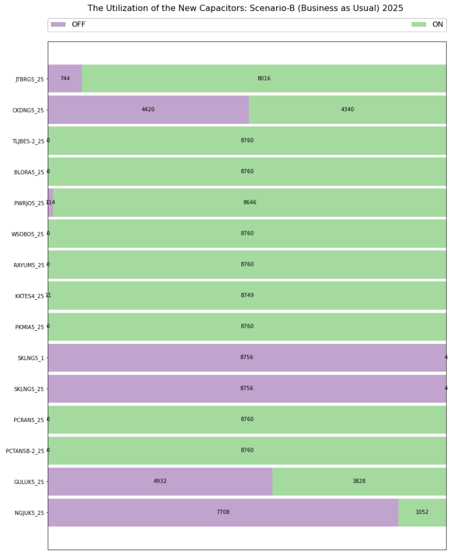


Figure 8. The Utilization of the New Capacitors (Business as Usual) in the Year 2025.

4.3 Scenario C: With the Addition of New Capacitors (Optimal Placement Method-1)

Method-1 is implemented by identifying the lowest voltage over the course of a year, in this research specifically in 2025 from the results of quasi-dynamic simulations. The total number of buses with installed capacitors, as well as the capacity of these capacitors, are tailored to align with the company's procurement capabilities for new capacitors. In this case, the total number of capacitor units and their respective capacities follow the business-as-usual scenario.

Table 2 shows the additional capacitors in 2025 with the scenario of proposed method 1. The results of these transmission loss calculations are depicted in Figure 9. These calculations are performed hourly throughout the year and summarized monthly. The cumulative loss for the entire year 2025 is 1.87%.

We also perform computations or simulations to assess the usage of new capacitors, specifically, their operational duration throughout the year as shown in Figure 10. In the graph, the green color signifies the duration, in hours, that the capacitor is active within a year. Conversely, the purple color indicates the hours when the capacitor is inactive. For instance, when a 50 MVAr capacitor is integrated into the Kiarapayung substation, it is operational for 8760 hours throughout 2025, etc.

Table 2. The Additional Capacitors in 2025 (Proposed Method-1)

No	Substation	Area	Unit	Voltage (kV)	Capacity (MVAr)
1.	Telukjambe II	West Java	1	150	50
2.	Pinayungan	West Java	1	150	50
3.	Tegal Herang	West Java	1	150	50
4.	Kiarapayung	West Java	1	150	50
5.	Semanu	Central Java	1	150	50
6.	Bantul	Central Java	1	150	50
7.	Seragen	Central Java	1	150	50
8.	Maspion	East Java	1	70	25
9.	Manyar	East Java	1	70	25
10.	Semen Gresik	East Java	1	70	10
11.	Segoromadu	East Java	1	150	50
12.	Manyar	East Java	1	150	50
13.	Miwon	East Java	1	150	50
14.	Ngoro	East Java	1	150	50
15.	KIS	East Java	1	150	50

4.4 Scenario D: With the Addition of New Capacitors (Optimal Placement Method-2)

Method-2 is implemented by identifying the lowest voltage value in the first quartile (Q1/25%) based on the results of quasi-dynamic simulations. The total number of installed bus capacitors and their capacities are also adjusted according to the company's capability to procure new capacitors. In this case, the total number of capacitor units and their respective capacities follow the business-as-usual scenario.

Table 3 shows the additional capacitors in 2025 with the scenario of proposed method 2. The results of these transmission loss calculations are depicted in Figure 11. These calculations are performed hourly throughout the year and summarized monthly. The cumulative loss for the entire year 2025 is 1.87%.

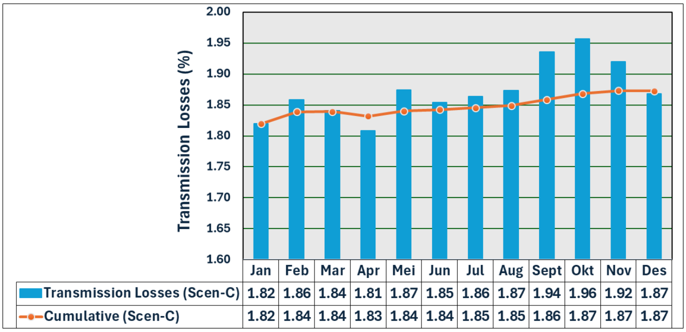


Figure 9. Transmission Losses of the Java-Bali System with the Addition of New Capacitors with Optimal Placement Method-1 in the Year 2025.

Table 3. The Additional Capacitors in 2025 (Proposed Method-2)

No	Substation	Area	Unit	Voltage (kV)	Capacity (MVAr)
1.	KIIC	West Java	1	150	50
2.	Telukjambe	West Java	1	150	50
3.	Honda	West Java	1	150	50
4.	Peruri	West Java	1	150	50
5.	Wates	Central Java	1	150	50
6.	Purworejo	Central Java	1	150	50
7.	Kebumen	Central Java	1	150	50
8.	Maspion	East Java	1	70	25
9.	Bstel	East Java	1	70	25
10.	Segoromadu	East Java	1	70	10
11.	Bungah	East Java	1	150	50
12.	Manyar	East Java	1	150	50
13.	New Porong	East Java	1	150	50
14.	Babat	East Java	1	150	50
15.	Driyorejo	East Java	1	150	50

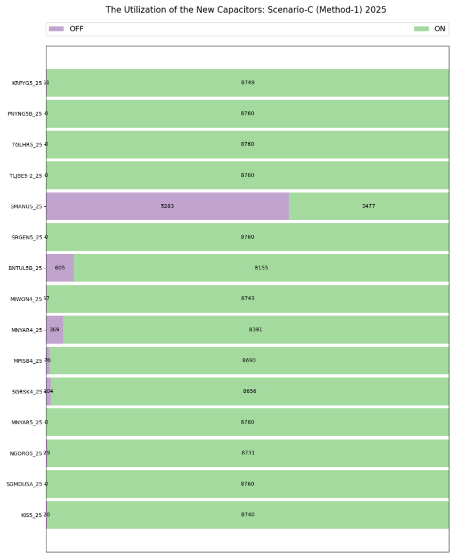
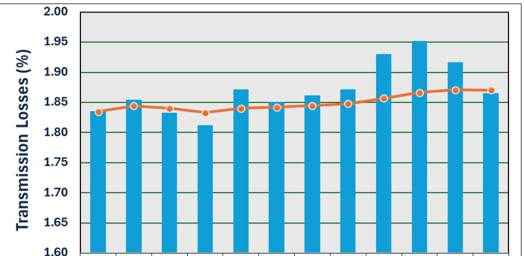


Figure 10. The Utilization of the New Capacitors (Optimal Placement Method-1) in the Year 2025.



	Jan	Feb	Mar	Apr	Mei	Jun	Jul	Aug	Sept	Okt	Nov	Des
Transmission Losses (Scen-B)	1.83	1.85	1.83	1.81	1.87	1.85	1.86	1.87	1.93	1.95	1.92	1.86
Cumulative (Scen-B)	1.83	1.84	1.84	1.83	1.84	1.84	1.84	1.85	1.86	1.87	1.87	1.87

Figure 11. Transmission Losses of the Java-Bali System with the Addition of New Capacitors with Optimal Placement Method-2 in the Year 2025.

We also perform computations or simulations to assess the usage of new capacitors, specifically, their operational duration throughout the year as shown in Figure 12. In the graph, the green color signifies the duration, in hours, that the capacitor is active within a year. Conversely, the purple color indicates the hours when the capacitor is inactive. For instance, when a 50 MVAr capacitor is integrated into the Kiarapayung substation, it is operational for 8760 hours throughout 2025, etc.

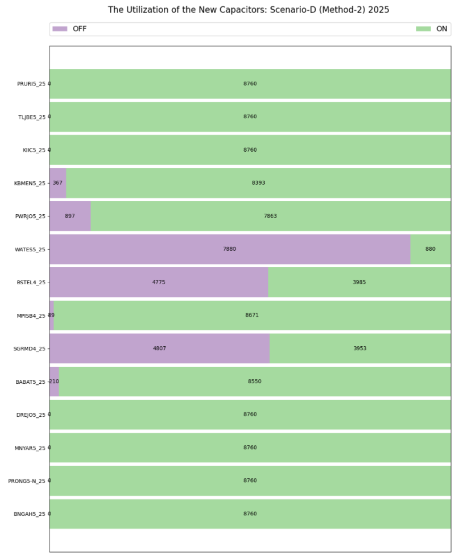


Figure 12. The Utilization of the New Capacitors (Optimal Placement Method-2) in the Year 2025.

5. Conclusion

In summary, the Java-Bali electricity system, which encompasses five regions including Jakarta-Banten, West Java, Central Java, East Java, and Bali, stands as Indonesia's largest electricity network. This system operates with the objectives of economic viability, reliability, quality, and environmental sustainability. Among these goals, ensuring economic and efficiency is paramount, and a key aspect involves minimizing transmission losses. These losses significantly impact system efficiency and overall performance.

Within the Java-Bali electricity system, the government sets an annual target for transmission losses. For instance, in 2023, the government aimed for a transmission loss value of 1.93%, but the actual realization was 1.95%. Given the mounting concern over transmission losses in this system, further investigation is warranted. Optimal voltage levels play a critical role in reducing these losses and ensuring efficient energy delivery throughout the power grid. One effective strategy is the integration of capacitors into the system.

In our study, we explored two methods to identify the most advantageous locations for integrating new capacitors. The objective is to optimize capacitor placement, not only for voltage improvement but also for minimizing transmission losses within the Java-Bali system. Method-1 involves identifying the lowest voltage over the course of a year, while Method-2 focuses on the lowest voltage value within the first quartile (Q1/25%) during the same period. The research findings suggest that the implementation of the two proposed methods can significantly decrease transmission losses in the Java-Bali system by up to 0.4% throughout 2025. However, the first method yields superior results, as evidenced in Figure 10, which illustrates the utilization of the new capacitors. According to Method-1, 14 out of the 15 new capacitors were in use for more than 8000 hours throughout 2025, with only one capacitor being used for around 3000 hours. In contrast, Method-2 reveals that 10 out of the 14 new capacitors were in use for more than 8000 hours throughout 2025, one new capacitor was in use for around 7000 hours, and the remaining capacitors were in use for less than 4000 hours.

Building on this research, future studies could delve deeper into the impact of various factors on transmission losses and voltage levels in the Java-Bali electricity system. For instance, the effect of load variations, renewable energy integration, and grid infrastructure upgrades could be explored. Additionally, the development of more sophisticated algorithms for optimal capacitor placement could be investigated, considering dynamic system conditions and real-time data. Comparative studies could also be conducted to evaluate the performance of the Java-Bali electricity system against other major electricity networks around the world. These research directions would not only contribute to academic literature but also provide practical insights for policymakers and industry practitioners in their efforts to enhance the efficiency and sustainability of power systems.

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