



Power Factor Correction Analysis in a 0.4 kV Distribution System Using Capacitor Banks Based on the Individual Compensation Method

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ABSTRACT

Power factor (PF) is an important parameter that reflects the efficiency of electrical energy utilization in alternating current (AC) systems, representing the ratio between active power (kW) and apparent power (kVA). A low power factor increases distribution-network current and may increase resistive losses and reactive-energy charges. This study analyzes power factor correction at the SS-05B 0.4 kV distribution bus supplying an 800 kW induction motor using the individual compensation method. The base-case ETAP load-flow result reports a power factor of 70.00% and reactive power demand of 858.14 kvar at SS-05B. A 739 kvar capacitor bank was then applied, reducing the reported reactive power demand to 119.12 kvar. The compensated simulation shows an increase in SS-05B power factor to 97.65%, an increase in bus voltage from 94.11% to 95.45%, and a reduction in feeder current from 1845 A to 1819 A. At the upstream SS-04B bus, power factor increases from 80.30% to 89.25% and total current decreases from 5417 A to 4827 A. These results demonstrate the technical effectiveness of localized reactive-power compensation under the simulated operating condition. For practical implementation, harmonic-resonance assessment and appropriate detuning measures should be considered, particularly because a large capacitor bank is connected to a low-voltage network containing power-electronic and photovoltaic equipment.

Keywords: Power Factor Correction; Capacitor Bank; Individual Compensation; Reactive Power Compensation; Energy Efficiency.

1. Introduction

Modern power systems are required to deliver electrical energy to industrial and commercial consumers in an efficient, reliable, and economical manner. One of the most important indicators used to evaluate the efficiency of electrical energy utilization in alternating current (AC) systems is the power factor (PF), which is defined as the ratio between active power (kW) consumed by the load and apparent power (kVA) supplied by the source. The power factor ranges from 0 to 1, where values closer to unity indicate more efficient and optimal utilization of electrical energy. Mathematically, the power factor is expressed as the cosine of the phase angle between voltage and current ($\cos\phi$), where a smaller phase angle corresponds to a lower reactive power component in the system [1-3].

In electrical installations dominated by inductive loads such as electric motors, transformers, and power electronic equipment, the power factor tends to be low due to the significant reactive power (VAR) demand. Inductive loads cause the current to lag behind the voltage, resulting in a lagging power factor [4]. A low power factor increases the current required to deliver the same amount of active power, thereby increasing power losses (I^2R losses), reducing the effective capacity of distribution networks, and causing significant voltage drops in distribution buses[5,6]. Recent

studies have reported that industrial distribution systems operating with power factors below 0.85 experience technical losses that are approximately 15–25% higher than systems operating near unity power factor [7,8]. Furthermore, electricity providers such as PT PLN (Persero) impose penalties for excessive reactive energy consumption (kVarh) when customers operate below the minimum power factor requirement of 0.85, making low power factor a direct contributor to increased operational costs[9,10].

Several techniques have been developed to improve power factor performance. In general, reactive power compensation can be implemented using three primary approaches: (1) individual compensation, where capacitors are installed directly at each inductive load; (2) group compensation, where capacitor banks are installed at distribution panels supplying a group of loads; and (3) centralized compensation, where capacitor banks are installed at the main distribution panel or substation[11-13]. In addition to conventional capacitor banks, modern compensation technologies such as Static VAR Compensators (SVCs), Static Synchronous Compensators (STATCOMs), and microcontroller-based automatic capacitor banks have been widely investigated in recent studies[11,13,14]. The selection of an appropriate compensation method depends on load characteristics, network configuration, and the desired technical objectives.

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For large localized induction motor loads, the individual compensation method is considered highly effective because reactive power is compensated directly at the load, eliminating the reactive current component throughout the distribution path supplying the load [15-17].

This study analyzes power factor correction at the SS-05B 0.4 kV distribution bus supplying an 800-kW induction motor using individual compensation. The investigated system is a dual-source network supplied by a utility grid and a 10 MW local power plant. The main contributions are: (1) consistent use of the ETAP-reported reactive-power values before and after compensation to quantify the required local compensation; (2) before-and-after load-flow evaluation of power factor, voltage, feeder current, and reactive power; and (3) practical assessment of the implementation limitations, including harmonic-resonance risk and the need for verified economic inputs before claiming a payback period.

The remainder of this paper is organized as follows. Section 2 presents the research methodology, system description, mathematical modelling, assumptions, and boundary conditions. Section 3 discusses the load flow simulation results, reactive power compensation calculations, and the impact of power factor improvement on key electrical parameters of the distribution system. Finally, Section 4 summarizes the conclusions and provides recommendations for future research.

2. Methods and modelling

2.1. Methodological framework

This study commenced with the collection, verification, and compilation of electrical system data required for the analysis. The data included the single-line diagram of the distribution network, load demand data at each bus, system operating parameters, and the initial power factor values obtained from the base-case load flow simulation. These data served as the foundation for developing an accurate system model and evaluating the operating performance of the electrical distribution network under existing conditions. Furthermore, the collected information was analyzed to identify the distribution of active and reactive power throughout the system, as well as the buses that experienced significant reactive power deficiencies.

The next stage involved performing an initial load flow analysis to determine the electrical characteristics of each bus within the network. The results were used to identify critical buses whose power factor values were below the minimum requirement specified by the SPLN Standard, namely 0.85 [18 - 20]. A low power factor indicates excessive reactive power consumption, which can increase line current, voltage drops, power losses, and overall system inefficiency. Based on the initial analysis, bus SS-05B was identified as the most critical bus in the system, exhibiting a power factor of only 0.70. This condition indicates a substantial need for reactive power compensation to improve the operating performance of the distribution system.

After identifying SS-05B as the critical bus, the compensation requirement was quantified from the reactive-power values reported by the ETAP load-flow cases. The base-case reactive power at SS-05B was 858.14 kvar, while the compensated case reported 119.12 kvar. Their difference,

739.02 kvar, represents the local reactive-power compensation provided by the capacitor bank.

Once the required capacitor bank rating was obtained, the capacitor bank was virtually installed at bus SS-05B within the electrical system model. The placement of the capacitor bank at the critical bus was intended to provide localized reactive power support, thereby reducing reactive power flow through the feeders and improving voltage regulation. This approach is widely adopted in power distribution systems because it effectively enhances system performance while minimizing unnecessary reactive power circulation within the network [21, 22].

Subsequently, load flow simulations were carried out under two operating scenarios: before and after capacitor bank installation. The simulation results were then compared to evaluate the effectiveness of reactive power compensation. Several performance indicators were analyzed, including power factor improvement, voltage profile enhancement at each bus, reduction of line current, and overall system operating efficiency. Particular attention was given to the changes occurring at bus SS-05B and neighboring buses to assess the extent of the compensation impact on the distribution network.

The post-compensation results were examined to assess power-factor improvement, voltage-profile change, and current reduction. Any reduction in I^2R loss is treated as an engineering estimate derived from the current change rather than a measured energy-saving value. Practical application also requires harmonic-resonance assessment because the low-voltage system includes power-electronic and photovoltaic equipment.

The research methodology follows the standard load flow analysis approach widely adopted in recent power distribution system studies [23]. This method provides a systematic framework for evaluating system operating conditions, identifying power quality issues, and determining appropriate corrective actions through reactive power compensation. The electrical system configuration analyzed in this study is illustrated in Figure 1.

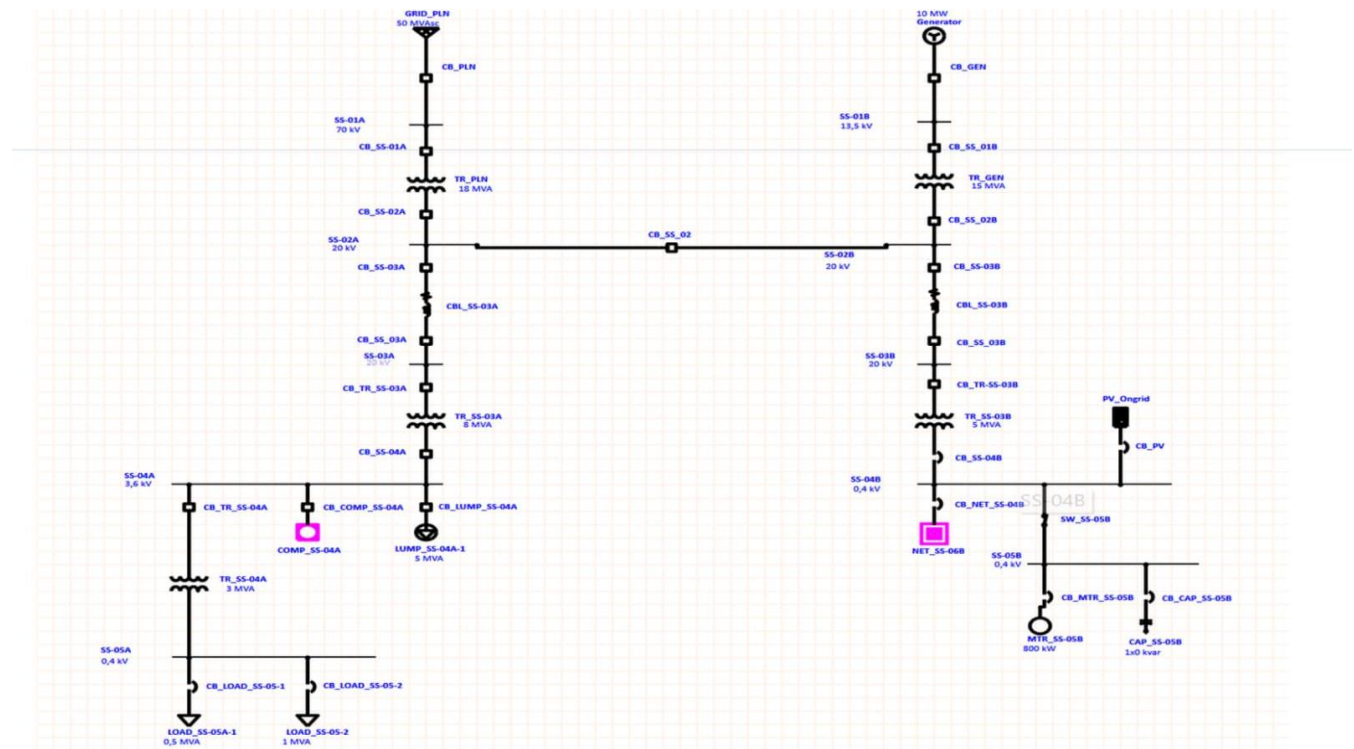


Fig.1. Single-line diagram of the electrical distribution system under study.

2.2. System description

The system analysed in this study is an electrical power distribution network with a dual-feeder topology consisting of two main supply sources. The first source is the utility grid (GRID_PLN, 50 MVA_{sc}) operating at 70 kV, which is stepped down through the TR_PLN transformer rated at 18 MVA and connected to buses SS-01A and SS-02A at the 20 kV level. The second source is a local power plant represented by a 10 MW generator operating at 13.5 kV. The generator is connected through the TR_GEN transformer rated at 15 MVA to buses SS-01B and SS-02B and is interconnected with the utility side via the CB_SS_02 circuit breaker at the 20 kV voltage level.

The voltage from both supply sides is subsequently stepped down through distribution transformers to serve lower-voltage buses. On Side A, the TR_SS-03A transformer rated at 8 MVA supplies bus SS-04A at 3.6 kV, which serves a 5 MVA lumped load and a synchronous compensator (COMP_SS-04A). On Side B, the TR_SS-03B transformer rated at 5 MVA supplies bus SS-04B at 0.4 kV, which functions as the primary low-voltage distribution bus.

Bus SS-04B is connected to bus SS-05B through the SW_SS-05B switch. Bus SS-05B operates at 0.4 kV and supplies the main load of the study, namely an induction motor (MTR_SS-05B) rated at 800 kW with an initial power factor of 0.70. In addition, bus SS-04B is connected to the NET_SS-06B distribution network through the CB NET SS-04B circuit breaker.

The system is also equipped with an on-grid photovoltaic (PV) generation unit (PV_Ongrid) connected to bus SS-04B through the CB_PV circuit breaker. The integration of distributed photovoltaic generation enriches the network configuration and reflects the trend toward renewable energy integration and sustainable system operation [14].

2.3. Mathematical modelling

The theoretical basis of power factor correction can be explained using the power triangle concept, where apparent power (S, kVA) is the vector sum of active power (P, kW) and reactive power (Q, kvar). The power factor (PF) is defined as:

$$PF = \cos \varphi = \frac{P}{S} \quad (1)$$

To improve the power factor from an initial condition characterized by angle φ_1 to a target condition characterized by angle φ_2 (where $\varphi_1 > \varphi_2$), the inductive reactive power component must be reduced by supplying an equivalent amount of leading reactive power through capacitor compensation [1, 3]. Geometrically, in the power triangle, the installation of a capacitor bank shifts the reactive power vector downward by reducing the lagging reactive power component while maintaining the active power component unchanged. As a result, the phase angle φ decreases and the power factor ($\cos\varphi$) increases.

Power factor correction is therefore achieved by increasing the value of $\cos\phi$ through the reduction of inductive reactive power demand. This reduction is accomplished by injecting capacitive reactive power using capacitor banks. The required capacitor reactive power (Q_c) is calculated using Equation (2):

$$Q_c = P(\tan \varphi_1 - \tan \varphi_2) \quad (2)$$

Where (Qc) is the required capacitor reactive power (kvar), (P) is the active load power (kW), (φ_1) is the initial power factor angle obtained from ($\varphi_1 = \cos^{-1}(PF_1)$), and (φ_2) is the target power factor angle obtained from ($\varphi_2 = \cos^{-1}(PF_2)$).

Equation (2) can also be expressed in the equivalent form:

$$Q_c = P \tan \varphi_1 - P \tan \varphi_2 = Q_1 - Q_2 \quad (3)$$

Which indicates that the capacitor bank must supply the difference between the initial reactive power (Q_1) and the target reactive power (Q_2). This equation has been widely adopted in standard power system analysis literature and validated through numerous industrial applications and case studies both in Indonesia and internationally [1, 7, 8].

In this study, Equation (3) is used to express the required compensation as the difference between the ETAP-reported reactive power before and after compensation at SS-05B. The resulting capacitor rating is then evaluated through load-flow simulation to assess its effect on power factor, voltage profile, feeder current, and upstream system performance.

2.4. Research Methodology

This study was conducted through a systematic approach consisting of data collection, system modelling, reactive power compensation analysis, and performance evaluation. The research methodology began with the collection of electrical system data, including the single-line diagram, transformer ratings, load characteristics, bus voltage levels, and initial power factor values obtained from the base-case load flow simulation. The collected data were then used to develop a distribution system model representing the actual operating conditions of the network.

Subsequently, a base-case load flow analysis was performed to identify buses with low power factor conditions. Based on the simulation results, bus SS-05B was selected as the target bus for reactive power compensation because it supplied an 800-kW induction motor load with an initial power factor of 70%, which was below the minimum requirement specified by PT PLN (Persero).

The capacitor-bank rating was determined from the difference between the base-case and compensated reactive-power values at SS-05B. With $Q_{\text{before}} = 858.14$ kvar and $Q_{\text{after}} = 119.12$ kvar, the required local compensation is $Q_c = 739.02$ kvar. A practical 739 kvar capacitor bank was therefore used in the ETAP model using the individual compensation method.

After capacitor-bank integration, a second load-flow simulation was carried out under the same loading condition. The evaluation focused on changes in power factor, bus voltage, feeder current, and reactive-power flow. A techno-economic framework is also discussed; however, no numerical payback period is calculated because verified CAPEX, tariff, annual operating-hours, and reactive-energy billing data were not available.

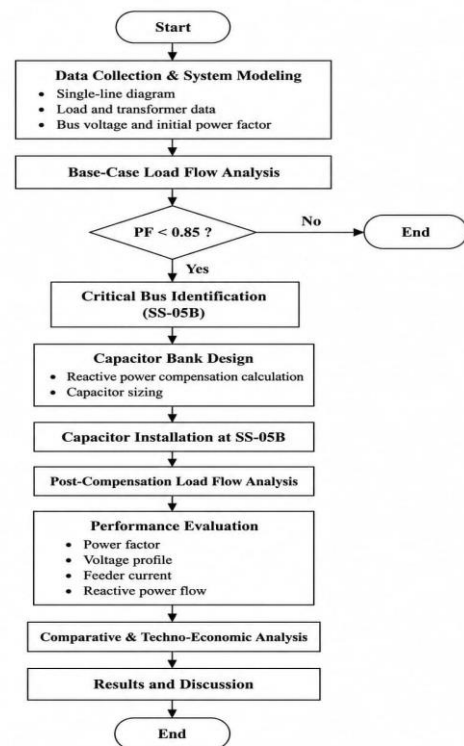


Fig.2. Research methodology for power factor correction analysis using the individual compensation method.

2.5. State of the Art

Reactive power compensation through capacitor bank installation has been extensively studied as an effective solution for improving power factor, reducing power losses, and enhancing voltage regulation in electrical distribution systems. Most recent studies have focused on optimization-based approaches for determining the optimal placement and sizing of capacitor banks using advanced algorithms such as Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). While these approaches have demonstrated significant technical and economic benefits, their primary focus has been on network-wide optimization rather than the practical implementation of individual compensation for specific industrial loads. To highlight the current state of research and identify the gap addressed in this study, a summary of relevant literature is presented in Table 1.

Table 1

State-of-the-Art Review of Capacitor Bank Applications in Distribution Systems.

No	Authors	Year	Research Focus	Method	Main Findings
1	Ruliyanta al[24].	et 2022	Load flow analysis capacitor bank using individual and global compensation methods	ETAP load flow analysis	Improved power factor and reduced power losses
2	Myintzu al[25].	et 2023	Optimal capacitor allocation to minimize energy loss cost under different load conditions	GA optimization and load flow analysis	Capacitor allocation reduced energy losses and improved voltage stability.

No	Authors	Year	Research Focus	Method	Main Findings
3	Jayabarathi al[26].	et 2024	Capacitor bank deployment for distribution system improvement	GWO optimization + simulation	Improved voltage profile and reduced losses
4	Thongsuk al[27].	et 2025	High voltage capacitor bank application for voltage drop improvement in distribution lines	Capacitor bank analysis and power system simulation	Capacitor banks improved voltage regulation and reduced voltage drop.
5	Fakolujo al[28]	et 2023	Reactive power compensation in industrial distribution networks	Reactive power analysis and capacitor sizing	Reactive power compensation improved power factor and reduced system loading.
6	Okeke al[29].	et 2024	Optimal capacitor placement in distribution networks	Convex optimization	Reduced power losses and improved voltage regulation
7	Lakshmi al[30].	et 2024	Load flow analysis for identifying weak buses in distribution systems	Load flow simulation	Weak buses identification supported capacitor placement decisions.

As summarized in Table 1, recent studies on capacitor bank applications have predominantly focused on optimization-based approaches, including Genetic Algorithm (GA), Multi-Objective Genetic Algorithm (MOGA), and Particle Swarm Optimization (PSO), to determine the optimal placement and sizing of capacitor banks in distribution networks. These studies have demonstrated significant improvements in power loss reduction, voltage profile enhancement, and energy efficiency. However, most existing research emphasizes optimization techniques for network-wide capacitor allocation, while limited attention has been given to the practical implementation of individual compensation methods for large induction motor loads in low-voltage industrial distribution systems. Furthermore, the impacts of individual capacitor bank installation on feeder current reduction, upstream bus performance, and voltage profile improvement in dual-source distribution networks remain insufficiently investigated.

Therefore, this study investigates the application of individual capacitor bank compensation in a 0.4 kV industrial distribution system supplying an 800-kW induction motor load. Unlike previous studies that focus primarily on optimization algorithms, this work evaluates the technical effectiveness of analytical capacitor sizing

combined with load flow simulations before and after compensation. The study provides a comprehensive assessment of power factor improvement, voltage profile enhancement, feeder current reduction, and reactive power flow mitigation within a practical industrial distribution network.

3. Results and discussion

3.1. System performance

This subsection presents the analytical calculation results of the required capacitor bank capacity and the load flow simulation results before and after capacitor installation. The input data used in the calculations were obtained from the base-case load flow simulation of the electrical distribution system. The simulation provided detailed information regarding active power demand, reactive power demand, current magnitude, voltage profile, and power factor at each bus within the network. These parameters were used as the basis for determining the most critical load point requiring reactive power compensation and for evaluating the effectiveness of the proposed capacitor bank installation.

Based on the initial load flow analysis, bus SS-05B was identified as the most critical bus in the system due to its low power factor and high reactive power consumption. This bus supplies the MTR_SS-05B induction motor load with a rated capacity of 800 kW. Induction motors are well known as significant consumers of reactive power because they require magnetizing current to establish the magnetic field necessary for operation. Consequently, a large amount of reactive power is drawn from the distribution network, causing the power factor to decrease and increasing the current required to deliver the same active power output.

Under the initial operating condition, bus SS-05B exhibited a power factor of 70.00% and an ETAP-reported reactive power demand of 858.14 kvar. The same base-case simulation reported a feeder current of 1845 A and a bus-voltage magnitude of 94.11% of nominal. These values are used consistently as the base-case data for the compensation analysis.

A capacitor bank of approximately 739 kvar was evaluated at SS-05B using the individual compensation method. After compensation, ETAP reported a power factor of 97.65% and a residual reactive power demand of 119.12 kvar. The compensated power factor is therefore reported directly as a simulation result rather than reconstructed from rounded phase-angle values.

To maintain numerical consistency with Table 2, the reactive-power compensation is calculated using Equation (3) from the ETAP-reported reactive power values before and after compensation:

$$Q_c = 842,1 (\tan 45,57^\circ - \tan 8,11^\circ) = 842,1 (0,877) = 739,025 \text{ kvar}$$

The calculation gives $Q_c = 858.14 - 119.12 = 739.02$ kvar. A practical 739 kvar capacitor-bank rating was therefore used in the ETAP model, and this value is reported consistently throughout the revised manuscript.

The 739 kvar capacitor bank was installed at bus SS-05B (CAP_SS-05B) to provide individual reactive-power compensation for the 800-kW induction motor load.

Connecting the capacitor at the load bus supplies reactive power locally and reduces the reactive-power burden on the upstream feeder.

Local reactive-power support reduces the reactive component carried by the feeder and upstream transformer. This can lower apparent-power loading and current and may reduce I^2R losses when conductor resistance and operating conditions remain unchanged. The loss effect is therefore discussed as a calculated indication rather than as a directly measured energy-loss value.

Following the capacitor bank installation, load flow simulations were performed to evaluate the resulting changes in system performance. The simulations were conducted under identical loading conditions to ensure that any differences observed in the results could be attributed solely to the effect of reactive power compensation. Several electrical parameters were analyzed, including power factor, active and reactive power flow, feeder current, apparent power demand, and bus voltage magnitude.

The simulation results demonstrate a significant impact of reactive power compensation on the electrical characteristics of the distribution system. The most notable improvement was observed in the power factor at bus SS-05B, which increased substantially after capacitor installation. This improvement indicates that the reactive power supplied by the capacitor bank effectively offset a large portion of the inductive reactive power demand of the motor load. As a result, the current required to deliver the same active power decreased, reducing stress on the electrical infrastructure and improving energy utilization efficiency.

In addition to improving the local power factor, the capacitor bank installation also produced beneficial effects on the upstream portions of the distribution network. The reduction in reactive power flow through feeders and transformers contributed to lower current loading and reduced voltage drops along the network. Consequently, the voltage profile at several buses improved, bringing operating voltages closer to their nominal values and enhancing overall system stability.

The simulation results indicate that individual reactive-power compensation is effective in improving power factor and voltage regulation in the studied low-voltage system. Because the network includes power-electronic and photovoltaic equipment, practical application of a 739 kvar capacitor bank at 0.4 kV should include a harmonic-spectrum and frequency-scan assessment to identify possible resonance. Where a resonance risk is identified, detuned reactors (anti-resonance coils) or an appropriately designed harmonic-filter arrangement should be considered before field installation.

The load flow simulation results for the system before and after capacitor bank installation are presented in Figure 3 and Figure 4, respectively. These figures provide a graphical representation of the changes in electrical parameters throughout the network and clearly illustrate the positive impact of the 739 kvar capacitor bank installed at bus SS-05B.

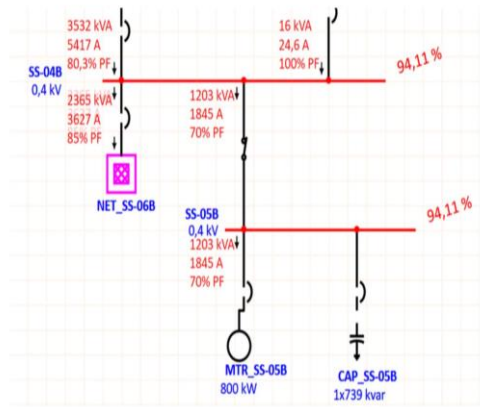


Fig.3. System Operating Condition Before Capacitor Bank Installation (SS-05B Power Factor = 70%; Bus Voltage = 94.11%).

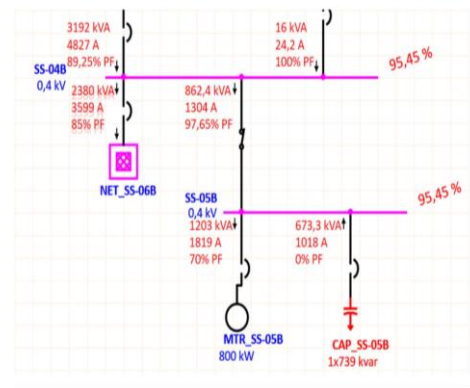


Fig.4. Operating Condition of the Distribution System After Capacitor Bank Installation (SS-05B Power Factor = 97.65%; Bus Voltage = 95.45%).

Before capacitor-bank installation, bus SS-05B exhibited a power factor of 70.00%, a feeder current of 1845 A, a bus-voltage magnitude of 94.11% of nominal, and an ETAP-reported reactive power demand of 858.14 kvar.

$$Q_{\text{before}} = 858.14 \text{ kvar}$$

$$Q_{\text{after}} = 119.12 \text{ kvar}$$

$$Q_c = Q_{\text{before}} - Q_{\text{after}}$$

$$Q_c = 739.02 \text{ kvar}$$

After installation of the 739 kvar capacitor bank at bus SS-05B, ETAP reported a power factor of 97.65%, a feeder current of 1819 A, and a residual reactive power demand of 119.12 kvar. Thus, the reactive-power reduction is 739.02 kvar, consistent with Table 2 and the capacitor-bank rating.

This improvement also produced beneficial upstream effects on the distribution network. At bus SS-04B, the power factor increased from 80.3% to 89.25%, while the total current decreased from 5417 A to 4827 A, corresponding to a reduction of 590 A or approximately 10.9%. Furthermore, the voltage profile improved from 94.11% to 95.45%. Although the voltage increase of 1.34% may appear modest, it has a significant impact on the operational reliability and performance of voltage-sensitive electrical equipment.

The simulation results confirm that individual reactive power compensation effectively reduces reactive power demand and improves overall system performance. These findings are consistent with previous studies reporting that

individual compensation of large induction motor loads can reduce total network current by approximately 8–15% and improve voltage profiles by 1–3%, depending on system characteristics and load conditions [9,11,12].

3.2. Comparative Analysis Before and After Capacitor Bank Installation

A comprehensive comparison of the electrical parameters before and after the installation of the 739 kvar capacitor bank at bus SS-05B reveals significant improvements in all evaluated aspects of the distribution system performance. The implementation of reactive power compensation not only enhanced the electrical conditions at the compensated bus but also produced measurable benefits throughout the upstream and downstream sections of the network. These improvements demonstrate the effectiveness of capacitor bank installation as a practical solution for mitigating low power factor conditions and improving the operational efficiency of low-voltage distribution systems. The comparative results obtained from the load flow simulations are summarized in Table 2.

Table 2
Comparative Analysis of Distribution System Performance Before and After Capacitor Bank Installation.

Performance Indicator	Before Compensation	After Compensation	Improve ment
Power Factor at SS-05B	70.00%	97.65%	+27.65 percentage points
Feeder Current at 1845 A SS-05B		1819 A	−26 A (1.41%)
Reactive Power Demand at SS-05B	858.14 kvar	119.12 kvar	−739.02 kvar
Power Factor at SS-04B	80.30%	89.25%	+8.95 percentage points
Total Current at SS-04B	5417 A	4827 A	−590 A (10.89%)

As shown in Table 2, the installation of the capacitor bank significantly improved the power factor at bus SS-05B from 70% to 97.65%, representing an absolute increase of 27.65 percentage points. Prior to compensation, the low power factor indicated a substantial reactive power demand, requiring a larger apparent power to deliver the same amount of active power to the load. After compensation, most of the reactive power required by the 800-kW induction motor load was supplied locally by the capacitor bank, thereby reducing the burden imposed on the upstream electrical network.

The current flowing through the SS-05B feeder decreased from 1845 A to 1819 A, equivalent to a 1.41% current reduction. Because conductor losses are proportional to I^2R , this current decrease indicates a potential reduction in feeder resistive losses when feeder resistance is assumed unchanged.

Under the simplifying assumption of constant feeder resistance, the relative I^2R loss reduction is estimated from the squared-current ratio:

$$\text{Relative loss reduction} = 1 - (1819/1845)^2 = 0.0280 \approx 2.80\%.$$

The estimated feeder I^2R loss reduction is therefore approximately 2.80%. This value is an engineering estimate and should not be interpreted as a measured energy-loss saving because detailed feeder-resistance and time-series energy data were not available.

In addition to the local improvements observed at bus SS-05B, significant benefits were also recorded at the upstream bus SS-04B. Before compensation, the power factor at SS-04B was 80.3%, which is below the recommended operational target for efficient distribution system performance. Following capacitor bank installation, the power factor increased to 89.25%, representing an improvement of 8.95 percentage points. This enhancement indicates that the reactive power compensation applied at SS-05B effectively reduced the reactive power demand seen by the upstream network, thereby improving the operating conditions of the entire feeder section connected to the distribution transformer.

The effect of compensation on current reduction was even more pronounced at bus SS-04B. The total current decreased from 5417 A to 4827 A, representing a reduction of 590 A or approximately 10.9%. This substantial decrease demonstrates that the capacitor bank successfully supplied a significant portion of the reactive power demand locally, reducing the amount of current that must be delivered from the upstream source. Lower current levels reduce conductor loading, decrease voltage drops, and minimize power losses throughout the feeder. Consequently, the overall efficiency of the distribution system is enhanced while additional capacity becomes available for future load growth.

Another important improvement resulting from the capacitor bank installation is the enhancement of the system voltage profile. Prior to compensation, the voltage magnitude at SS-04B was 94.11% of the nominal value, indicating a noticeable voltage drop due to reactive power flow and feeder impedance. After compensation, the voltage level increased to 95.45%, corresponding to an improvement of 1.34%. Although the numerical increase may appear modest, it is operationally significant because it moves the system voltage closer to the acceptable operating range specified by PLN standards, namely $\pm 5\%$ of the nominal system voltage [6,8]. Improved voltage regulation contributes to better performance of electrical equipment, reduced risk of undervoltage conditions, and enhanced power quality for end users.

The reduction of reactive current by 590 A at bus SS-04B clearly demonstrates that individual compensation applied at bus SS-05B provides benefits extending far beyond the compensated load itself. By supplying reactive power directly at the point of consumption, the capacitor bank reduces the reactive power that must be transmitted through upstream conductors and transformers. This reduction improves the electrical characteristics of the entire downstream network supplied by the distribution transformer, including lower current loading, reduced voltage drops, and decreased network losses.

From a system-wide perspective, the observed improvements confirm the fundamental principle of reactive power compensation in electrical distribution systems. When reactive power is generated locally near the load, the

apparent power demand seen by the source decreases, allowing the distribution network to operate more efficiently. The resulting reduction in current flow decreases copper losses, improves voltage stability, and enhances the utilization of existing electrical infrastructure. These benefits are particularly important in heavily loaded low-voltage distribution systems where poor power factor conditions can significantly affect system performance and operational costs.

Improved power factor may provide economic benefits by reducing reactive-energy charges and releasing transformer or feeder capacity. However, the source dataset does not include verified procurement costs for the 739 kvar capacitor bank, switching/protection equipment, installation and maintenance costs, the applicable PLN reactive-energy tariff, or annual operating data. Therefore, a numerical payback period is not claimed. A defensible calculation would use $\text{Payback Period} = \text{Total Installed CAPEX} / \text{Annual Monetary Saving}$.

The simulation results obtained in this study are consistent with previous studies, which have demonstrated that individual reactive power compensation in 0.4 kV distribution systems can improve the average power factor by 20–30 percentage points while reducing network current by up to 15%. These findings further support the effectiveness of reactive power compensation in enhancing distribution system efficiency and minimizing electrical losses.

Overall, the simulation results verify that the 739 kvar capacitor bank is technically effective under the modeled operating condition. The increase in power factor, reduction in current, and improvement in voltage profile demonstrate the technical benefits of localized reactive-power compensation. Economic feasibility should be evaluated separately using verified CAPEX, tariff, and annual operating data.

3.3. Practical Considerations, Limitations, and Future Work

This study is subject to several limitations. The analysis was conducted under steady-state conditions using a single load-flow scenario and did not consider daily or seasonal load variation. The active and reactive power data were obtained from simulation rather than direct field measurements. The study also did not perform a harmonic-frequency scan or resonance assessment. This is important because connecting a 739 kvar capacitor bank to a 0.4 kV industrial bus containing power-electronic and PV equipment may shift network resonant frequency and amplify harmonic voltage or current. Before field implementation, a harmonic study should therefore be performed, and detuned reactors (anti-resonance coils) or appropriately tuned filtering should be considered where required. Finally, verified CAPEX, PLN tariff, annual operating hours, and reactive-energy billing data were unavailable; consequently, no numerical payback period is reported.

Future work should incorporate time-varying load profiles and multi-scenario load-flow simulations, compare individual, group, and centralized compensation, and validate the model using field power-quality measurements.

Harmonic spectrum and frequency-scan analyses should assess resonance and determine whether detuned reactors are required. A complete techno-economic assessment should quantify capacitor-bank CAPEX, switching/protection and installation costs, maintenance costs, applicable reactive-energy tariffs, annual operating hours, NPV, IRR, payback period, and sensitivity to tariff and load variation.

4. Conclusion

This study analyzed power factor correction at the 0.4 kV SS-05B bus supplying an 800-kW induction motor using individual compensation. The base-case ETAP result reported a power factor of 70.00% and reactive power demand of 858.14 kvar. With a 739 kvar capacitor bank, residual reactive power demand decreased to 119.12 kvar, corresponding to a reduction of 739.02 kvar, while the simulated SS-05B power factor increased to 97.65%. Bus voltage increased from 94.11% to 95.45%, and feeder current decreased from 1845 A to 1819 A. At SS-04B, power factor increased from 80.30% to 89.25% and total current decreased from 5417 A to 4827 A. These results confirm the technical effectiveness of localized reactive-power compensation for the modeled condition. Because harmonic resonance, field validation, and verified economic inputs were not available, practical implementation should include a harmonic/frequency-scan study with consideration of detuned reactors where necessary, and no numerical payback period is claimed until validated CAPEX and annual savings data are available.

CRedit authorship contribution statement

Alqadri Prasetya Dwiputra: Conceptualization, Methodology, Writing - original draft, Data curation, Software, Formal analysis. **Resky Winanda:** Validation, Visualization. **Muhammad Zaki Dhiaulhaq:** Supervision, Writing - review and editing.

Declaration of competing interest

No Conflict of interest.

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Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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