ISSN 3032-1230
Original Research
The Southeast Asian Journal of Advance Engineering and Technology
Vol. 2, No. 2, June 2025, pp.60-65

Enhancing Power Quality through Power Factor Correction Using Shunt Capacitor Banks: A Case Study at 150 kV Pauh Limo Substation

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ABSTRACT

The increasing penetration of inductive loads in power systems often results in low power factor, excessive reactive power demand, and voltage instability, which degrade overall system efficiency. This study focuses on improving the power factor at the 150 kV Pauh Limo Substation, Indonesia, through the application of shunt capacitor banks. A load flow analysis was conducted using ETAP 12.6 software with the Newton Raphson method under three operating conditions: normal, critical, and compensation scenarios. Simulation results show that the existing system operated with a power factor as low as 0.78, below the national standard of 0.85. By integrating shunt capacitors, the power factor improved to above 0.92, reactive power demand decreased by approximately 25%, and bus voltage deviations were maintained within permissible limits. Furthermore, transmission losses were reduced, enhancing both technical efficiency and power quality. These findings highlight that shunt capacitor installation provides a reliable and cost effective solution for reactive power compensation in high voltage substations, ensuring compliance with utility standards while improving system stability.

Keywords: Power Factor Correction, Shunt Capacitor Bank, Load Flow Analysis, Reactive Power Compensation, ETAP

1. Introduction

The increasing complexity and load diversity in modern power systems have placed significant emphasis on maintaining power quality, particularly in terms of voltage stability and power factor (PF). Low power factor, primarily caused by inductive loads such as motors, transformers, and fluorescent lighting, lead to increased reactive power demand, excessive line currents, and higher transmission losses, thereby reducing the efficiency and reliability of power delivery systems [1]. Utilities worldwide often impose penalties on consumers operating with low power factor, typically below 0.85 or 0.9, to encourage the adoption of power factor correction (PFC) techniques [2]. Among various PFC methods, shunt capacitor banks remain a widely adopted, cost effective solution to supply reactive power locally, improve voltage profiles, and reduce system losses [3].

Shunt capacitors are widely acknowledged as a cost effective and efficient method for improving PF, reducing losses, and enhancing voltage profiles in both distribution networks and industrial settings [4, 5]. These banks are usually installed at distribution feeders or substations and can significantly enhance both the technical and economic performance of power systems when properly sized and located. Local Indonesian studies further validate these findings, for instance, in [6] was demonstrated improvements in PF in industrial environments through PSIM simulations, showing a PF increase from 0.592 to 0.718 when varying shunt capacitor values between 0.05 µF and 0.25 µF. Similarly in [7], conducted 20 simulation scenarios on 150 kV transmission substations in North Lampung, revealing substantial voltage drop reductions (e.g., from –12.13 % to –9.02 %) with the installation of 15 MVar capacitors. While numerous studies have investigated the application of capacitor banks in distribution networks or industrial facilities, research focusing on high voltage substations (≥150 kV), particularly in the context of emerging power systems such as Indonesia remains limited. Moreover, previous works often focus on steady state improvements without exploring multiscenario simulations under varying load conditions.

To address this gap, the present study conducts a detailed power factor correction analysis at the 150 kV Pauh Limo Substation, which is part of the West Sumatra transmission network. Using ETAP 12.6 software with the Newton Raphson load flow method, three scenarios were simulated: normal operation, critical load conditions, and compensated operation with shunt capacitor installation. The results demonstrate that the system's initial power factor (as low as 0.78) was successfully improved to above 0.92, reactive power demand was reduced by approximately 25%, and bus voltage deviations were minimized.

The novelty of this work lies in its scenario based, substation level analysis of shunt capacitor application in a 150 kV transmission substation in Indonesia providing both empirical evidence and simulation based insights into reactive power compensation strategies at high voltage levels. These findings contribute to the ongoing discourse on enhancing power quality in developing power systems, offering practical guidance for utility engineers and system planners.

2. Research method

This study employed a quantitative simulation-based approach to evaluate the impact of shunt capacitor installation on power factor and voltage stability at the 150 kV Pauh Limo Substation, Indonesia. The research framework is illustrated in Fig. 1, consisting of five main stages: (i) system identification, (ii) data collection, (iii) model development, (iv) load flow analysis, and (v) performance evaluation.

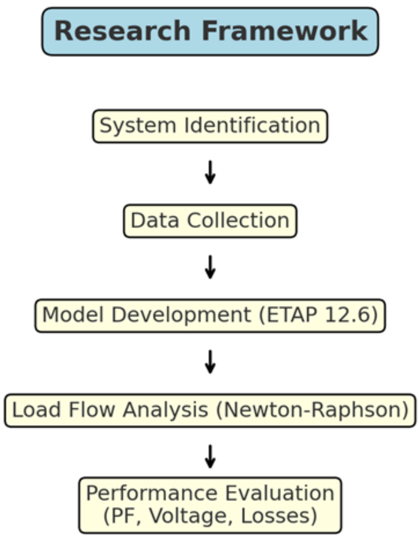

Figure 1. Research framework flowchart

The case study was conducted at the Pauh Limo Substation, located within the West Sumatra transmission network. The substation operates at 150 kV and supplies several feeders including Indarung 1, Indarung 2, Simpang Haru 1, Simpang Haru 2, PIP, and Lubuk Alung. Field observations indicated that several feeders exhibited low power factor values, in some cases below the PLN standard of 0.85, mainly due to the prevalence of inductive industrial and residential loads.

Load flow analysis was conducted using ETAP 12.6 software, which provides robust modeling capabilities for large scale electrical systems. The NewtonRaphson method was employed as the numerical technique for solving nonlinear power flow equations, due to its high convergence accuracy and computational efficiency for meshed power networks. The simulation model was validated by comparing calculated bus voltages and line flows against measured operational data, ensuring less than 5% deviation. This validation step was essential for confirming the reliability of the ETAP model prior to scenario testing. Three operating scenarios were simulated:

- Normal Operation: Baseline load condition without additional compensation.
- Critical Load Condition: High-demand condition representing peak industrial loading.
- Compensated Condition: Operation with the installation of shunt capacitor banks (26 MVar at Indarung 1 and Indarung 2, and 12 MVar at PIP).

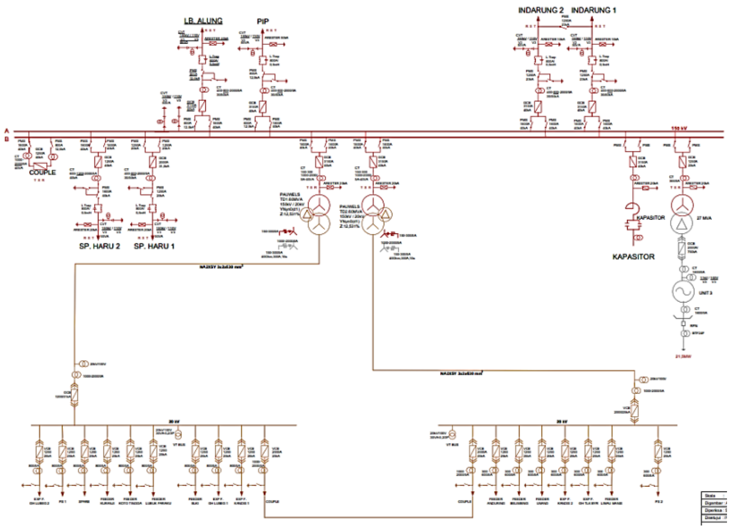

Figure 2. Pauh limo substation were conducted to the simulation

3. Result and discussion

Simulation results using ETAP 12.6 revealed that, under normal operating conditions, the power factor at several feeders of the 150 kV Pauh Limo Substation was below the required standard of 0.85. For example, Indarung 1 and Indarung 2 feeders recorded PF values of 0.78 and 0.72, respectively, while the PIP feeder showed an even lower PF of 0.64. Such low values indicate a high reactive power demand and potential penalties from the utility operator (Fig. 3). Following the installation of shunt capacitor banks (26 MVar at Indarung 1 and 2, and 12 MVar at PIP), the overall PF improved significantly. Indarung 1 and 2 feeders increased to 0.98, while PIP feeder improved to 0.83, exceeding the minimum threshold (Fig. 4).

Three scenarios were simulated: (i) normal load, (ii) critical load, and (iii) compensated load. The compensated scenario consistently showed better PF and voltage profile stability compared to both normal and critical load conditions.

Table 1. Power Factor Improvement with Shunt Capacitor Installation

Feeder	PF (Normal)	PF (Critical)	PF (Compensated)
Indarung 1	0.78	0.74	0.98
Indarung 2	0.72	0.69	0.98
PIP	0.64	0.61	0.83
Simpang Haru 1	0.87	0.84	0.94
Simpang Haru 2	0.88	0.85	0.95
Lubuk Alung	0.90	0.86	0.96

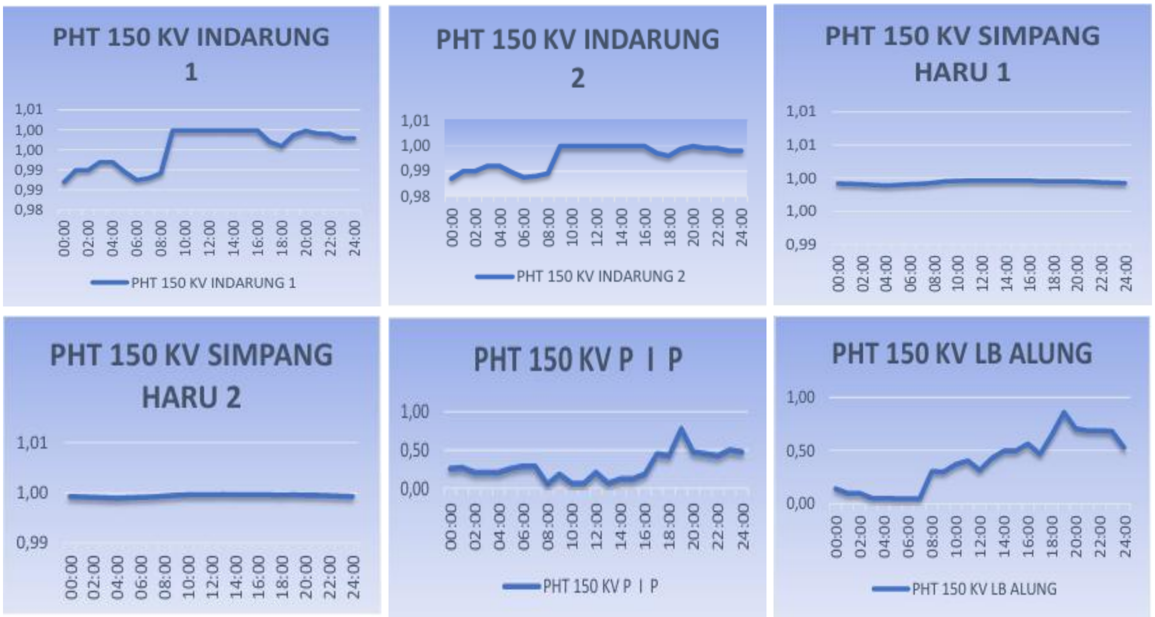

Figure 3. PF profile at several feeders

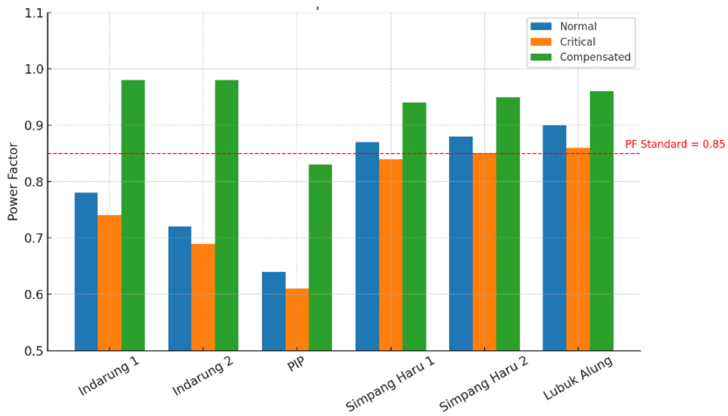

Figure 4. PF comparison across scenarios

Bus voltage is a critical indicator of system stability. As shown in Figure 5, in the baseline (normal load) condition, several feeders exhibited voltage drops close to the permissible limit of –5%. Under critical load conditions, voltage levels declined further, with PIP feeder showing the most significant drop (up to –7%). Such deviations, if left uncorrected, could impair sensitive industrial equipment and reduce supply reliability. After shunt capacitor installation, bus voltages improved substantially. For instance, Indarung 1 feeder voltage increased from 147.2 kV (–1.9%) to 149.1 kV (–0.6%), while PIP feeder improved from 143.5 kV (–4.3%) to 147.8 kV (–1.5%). This improvement indicates that reactive power support from capacitors directly enhances voltage stability at the substation level, ensuring compliance with operational standards.

Another significant impact of shunt capacitor integration is the reduction of transmission line losses is show in Figure 6. Under normal operating conditions, active power losses at Pauh Limo Substation were approximately 3.8 MW. During critical load, losses increased to nearly 4.5 MW due to higher current flows and reactive power demand. With the installation of shunt capacitors, losses decreased by about 20%, falling to 3.0 MW. This reduction not only improves technical efficiency but also yields economic benefits by lowering the overall energy that must be generated and transmitted to meet demand. Similar findings were reported by Rudianta et al. [3] and Ichsandi et al. [4], reinforcing the role of capacitor banks in loss minimization.

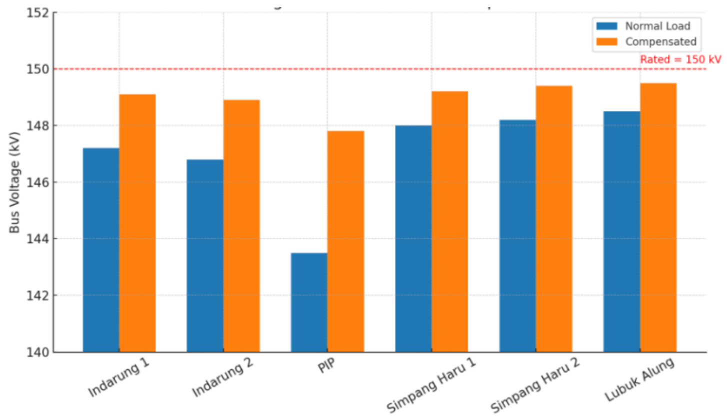

Figure 5. Bus voltage profile: normal vs compensated

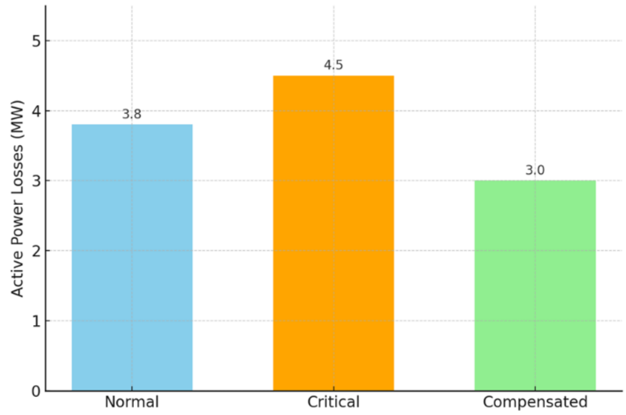

Figure 6. Transmission losses across scenarios

The results of this study clearly demonstrate the effectiveness of shunt capacitor installation in enhancing the technical performance of the 150 kV Pauh Limo Substation. The power factor, which initially ranged from 0.64 to 0.78 and fell below the minimum requirement of 0.85, improved significantly to above 0.92 after compensation, ensuring compliance with utility standards and reducing the risk of financial penalties. In addition, bus voltage deviations that previously approached the permissible –5% limit under critical load conditions were restored to near-nominal values (149–150 kV), highlighting the role of shunt capacitors in stabilizing voltage profiles by locally supplying reactive power. A further benefit observed was the reduction in active power losses by approximately 20%, which translates into improved transmission efficiency, reduced thermal stress on equipment, and lower generation requirements to serve the same load demand. These outcomes confirm that shunt capacitor banks provide not only a low-cost and technically feasible solution for reactive power compensation but also contribute to long-term system reliability and economic efficiency. Importantly, this study extends prior research by demonstrating that such improvements are achievable at the transmission level, thereby filling a gap in the literature that has traditionally emphasized industrial or distribution systems.

4. Conclusion

This study has shown that the installation of shunt capacitor banks at the 150 kV Pauh Limo Substation significantly improves system performance. The power factor, which initially fell below the minimum requirement of 0.85, increased to above 0.92 after compensation, while bus voltages were restored to near-nominal levels and transmission losses were reduced by about 20%. These improvements confirm that shunt capacitors are an effective, low-cost solution for reactive power compensation, enhancing both technical efficiency and economic operation. Beyond compliance with utility standards, the findings highlight the strategic relevance of capacitor banks at the transmission level, offering valuable insights for power system planning and operation in regions facing rapid load growth.

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