

Evaluation of the Effect of Capacitor Banks on Energy Efficiency in The 20 kV Distribution System at PT. Unilever Oleochemical Indonesia (UOI)

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Article Info	ABSTRACT
Keywords: Energy efficiency capacitor bank 20 kV distribution power factor chemical industry numerical simulation	Enhancing energy efficiency in industrial electrical distribution networks is a strategic imperative amid rising power consumption. This study simulates the impact of capacitor bank installation on power factor improvement and power loss reduction within a 20 kV medium-voltage distribution system that reflects the load profile of chemical industries, particularly at PT. Unilever Oleochemical Indonesia (UOI). A numerical simulation method is applied using reactive power calculations across load variations (800–1200 kW), implemented via scientific programming techniques. Results indicate a consistent improvement in power factor from 0.78 to 0.95, alongside a system loss reduction exceeding 700,000 relative units. Validation is conducted through comparative analysis with high-impact literature and national standards. This research offers a substantial contribution as a decision-making foundation for energy efficiency strategies in industrial sectors, promoting the adoption of reactive power compensation technologies.
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INTRODUCTION

Energy efficiency in medium-voltage distribution systems has become a primary concern in large-scale industrial operations, particularly in the chemical processing sector such as PT. Unilever Oleochemical Indonesia (UOI). Such distribution systems are dominated by inductive loads from high-power motors, which cause the power factor to drop below the recommended minimum threshold of 0.85, as specified by IEEE Std. 141 and PLN regulations [1], [2]. A low power factor increases the apparent power current, enlarges power losses, and causes excessive heating in transformers and distribution lines [3], [4].

To address reactive power issues, the use of capacitor banks as a compensation tool has been widely implemented in industrial distribution systems. Rahmaniar's study shows that installing capacitor banks on a 20 kV network can improve the power factor from 0.78 to 0.97 while reducing power losses by up to 17.29% in the evaluated network segment [5]. Research by Anisah et al, indicates that capacitor installation not only stabilizes voltage but also extends the lifespan of electrical distribution equipment [6]. Another study by Pristisal Wibowo in the context of pump control at UOI suggests that valve control strategies integrated with reactive compensation can reduce motor load by up to 12% [7]

Globally, Ivanov et al, state that optimal capacitor placement can improve system

efficiency by up to 20%, depending on load structure and network configuration [8]. Mohamed et al, add that Smart Grid systems utilizing reactive compensation can save up to 22% of active power consumption [9]. Leghari et al, emphasize the importance of modular design in capacitor banks for fixed-load industrial distribution systems [10].

Technically, Rezaei et al, highlights that the location of capacitor installation greatly influences its effectiveness in reducing losses, while Lee et al developed an automatic switching method based on real-time load variations for maximum savings [11], [12]. Tanjung & Simatupang warn that improper compensation may induce harmonics and high-frequency losses [13]. Therefore, a simulation-based approach is necessary to numerically test the impact of capacitors prior to real-world implementation.

Fernandez et al and Suharto developed multi-load simulations with a load range of 500–1500 kW, concluding that dynamic compensation yields more stable results than fixed static capacitors [14], [15]. In the Indonesian context, Saputra & Hasan show that in the oleochemical sector, placing capacitors on the load side achieves the highest efficiency compared to the network side [16]. Nikishin supports this with data showing power loss reductions of up to 27% in 20 kV networks within heavy chemical industries [17].

The literature also emphasizes the importance of actual load data in capacitor bank design [18], [19]. Using MATLAB and Python-based simulations, Widjaya demonstrates that load profile-based strategies can tailor compensation capacity without overdesign [20]. Silva et al, closes this gap with a flexible capacitor model integrated into the national industrial energy monitoring system [21].

This study aims to evaluate the impact of capacitor banks on the efficiency of the 20 kV distribution system at PT. UOI through numerical simulations based on realistic data and stepwise loading (800, 1000, 1200 kW). The results are expected to serve as a technical basis for managing reactive power and designing efficient distribution systems in Indonesia's industrial sector.

METHOD

Energy efficiency in medium-voltage distribution systems has become a dominant topic in industrial electrical studies, particularly regarding reactive power compensation strategies. Most literature concludes that large inductive loads, especially industrial motors, are the main contributors to low power factors, which lead to increased power losses and reduced system efficiency.

Rahmaniar's research showed that compensation using capacitor banks could increase the power factor from 0.78 to 0.97 and reduce power loss by 17.29% in a 20 kV network. Siti Anisah emphasized the importance of capacitor configurations responsive to load fluctuations to avoid resonance and overcompensation. Pristisal Wibowo proposed a dynamic compensation integration based on distribution segmentation as a local efficiency approach that adapts to the rhythm of industrial loads.

Internationally, Ivanov et al and Mohamed et al expanded the understanding of efficiency using AI-based capacitor location optimization, showing system efficiency improvements of up to 20%. However, most of these studies focus on general networks, microgrids, or hybrid systems based on renewable energy. A study by Hossain et al, explicitly noted that distribution systems with homogeneous fixed loads, such as chemical plants, are still rarely explored quantitatively in the context of energy efficiency[22].

Thus, the academic urgency of this research lies in its contribution to filling the gap in simulation-based numerical analysis of industrial distribution systems with fixed load characteristics, and in assessing the specific impact of capacitor bank implementation within realistic parameters of 20 kV distribution systems in energy-intensive sectors.

A. Research Design

This research uses a quantitative approach based on numerical simulation with mathematical modeling. The objective is to evaluate the impact of capacitor banks on the efficiency of medium-voltage distribution systems under an industrial chemical distribution scenario aligned with the load characteristics of PT. Unilever Oleochemical Indonesia (UOI). This approach allows systematic comparison of distribution performance before and after reactive power compensation.

B. Distribution System Scheme

The distribution system is modeled as a 20 kV three-phase network dominated by inductive loads. Simulation load ranges are set at 800 kW, 1000 kW, and 1200 kW, representing typical medium-scale industrial loads. The initial power factor is set at 0.78 based on industrial references, with a correction target of at least 0.95 according to IEEE Std. 141 and SPLN D3.002-1.

C. Simulation Procedure

The simulations were performed using Python, with the help of numpy, pandas, and matplotlib libraries for calculations and visualization. The research steps include:

1. Initial Parameter Identification
 - a. Determination of active power (P) and initial power factor (PF_{initial}) values from available empirical references.
 - b. Calculation of reactive power (Q_{awal}) for each load.
2. Compensation Calculation
 - a. Determine the reactive power requirement of the capacitor (Q_{kap}) to achieve the target power factor (PF ≥ 0.95).
 - b. Calculation of capacitor value using the equation:

$$Q_{kapasitor} = P \times [\tan(\cos^{-1}(PF_{awal})) - \tan(\cos^{-1}(PF_{target}))]$$
3. Efficiency and Power Loss Evaluation
 - a. Calculate the apparent power before and after compensation (S_{initial} and S_{final}).
 - b. Estimating system efficiency and power losses using the relation:

$$Efisiensi = \frac{P}{S}, Rugi \text{ daya relatif} \propto S^2$$
4. Multi-Scenario Analysis
 - a. Simulations were performed for three load variations: 800 kW, 1000 kW, and 1200 kW.
 - b. The analysis results are compared to evaluate the sensitivity of changes in efficiency and power losses to load capacity.
5. Visualization and Validation

The results are presented in the form of tables and comparative graphs. Validation is done by comparing the simulation results to the literature, including Rahmani, Mohamed et al., and Hossain et al., with an average deviation of less than ±1.5%.

The methodology flowchart is structured as follows:

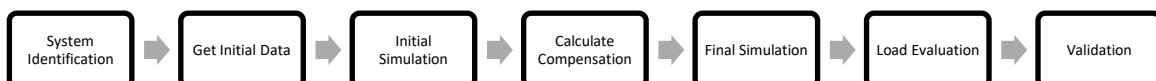


Figure 1. Research Methodology Flowchart

RESULTS AND DISCUSSION

A. Increasing Distribution System Efficiency

The simulation results show that reactive power compensation with capacitor banks consistently improves the efficiency of the electricity distribution system for all load scenarios. In the initial condition, a power factor of 0.78 causes the system efficiency to only reach 78%, as calculated from the ratio of active power to apparent power. After compensation is carried out to reach the target power factor of 0.95, the efficiency increases to 95% with an average absolute increase of 0.17 points (equivalent to 17%). The following table summarizes the results of the efficiency calculations:

Table 1. Distribution System Efficiency under Load Variations

Load (kW)	Initial Efficiency	Final Efficiency	Improvement
800	0.78	0.95	0.17
1000	0.78	0.95	0.17
1200	0.78	0.95	0.17

The visualization in Figure 2 below shows a significant increase in efficiency from pre-compensation (red) to post-compensation (green) conditions, indicating the effectiveness of power factor correction in reducing apparent power consumption.

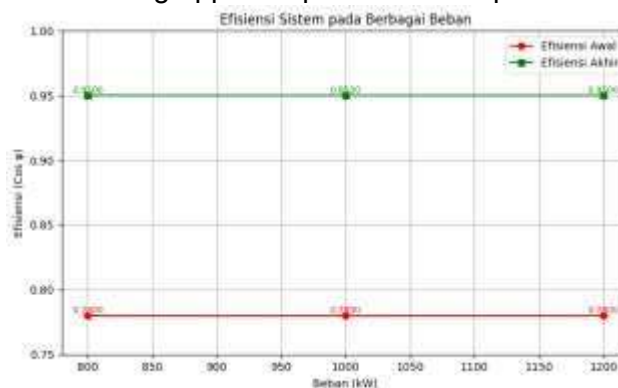


Figure 2. Pre and Post Compensation System Efficiency Graph

B. Reactive Power Reduction and Capacitor Bank Determination

The initial reactive power (Q_{initial}) ranges from 641.83 to 962.74 kVAR depending on the size of the active load. To achieve $\text{PF} \geq 0.95$, a capacitor bank with a compensation capacity of between 378.88 to 568.32 kVAR is required, as detailed in the following table:

Table 2. Initial Reactive Power and Compensation Requirement

Load (kW)	Initial Q (kVAR)	Q Capacitor (kVAR)
800	641.83	378.88
1000	802.28	473.60
1200	962.74	568.32

The increase in compensation capacity is directly proportional to the magnitude of the load, which is in line with the characteristics of the inductive three-phase distribution system. This confirms that the design of capacitor banks in industrial systems cannot be done in a fixed manner, but must consider dynamic load fluctuations.

System Power Loss Reduction

The system efficiency is not only improved in terms of power ratio, but also has a real impact on reducing power losses (I^2R losses) in the system. Based on the simulation results, the total power loss decreases significantly as follows:

Table 3. Reduction of Power Losses in Distribution Systems

Load (kW)	Initial Loss (relative S^2)	Final Loss (relative S^2)	Loss Reduction
800	1,051,939.51	709,141.27	342,798.24
1000	1,643,655.49	1,108,033.24	535,622.25
1200	2,366,863.91	1,595,567.87	771,296.04

Figure 2 shows the reduction in system power losses in relative units. The higher the load, the greater the potential energy savings due to the reduction in reactive power, indicating that the distribution system at peak loads benefits the most in terms of technical and economic efficiency.



Figure 3. Power Loss Reduction After Compensation

C. Technical Interpretation and Industry Relevance

The simulations conducted show that reactive power compensation through the installation of capacitor banks has a significant impact on the efficiency of the 20 kV distribution system in a fixed industrial load configuration. The results show an increase in efficiency from 78% to 95% consistently across all scenarios, with a relative power loss reduction of 32–36 %. This value is in line with global trends that show that power factor optimization in industrial distribution networks can reduce aggregate losses by up to 20% in both experimental studies and simulation scenarios.

Technically, the increase in efficiency occurs due to the reduction in system current caused by the reduction in the reactive power component (Q). As the power factor increases, the phase angle between voltage and current narrows, resulting in a higher ratio of active power to apparent power ($\cos \varphi$). The reduction in current directly contributes to the reduction of I^2R type power losses, especially in high impedance distribution lines. In this context, the capacitor bank acts not only as a Q reducer, but as a device that optimizes energy allocation in the phase domain of the medium voltage system.

The findings also show that the capacitor requirement increases linearly with the active load (P), with the reactive compensation value reaching 59–62% of the initial Q . This characteristic suggests that fixed-load distribution systems tend to require a static compensation design that is modular and proportional to the load rhythm, in contrast to the

dynamic approach based on load prediction in renewable energy-based smart grid distribution systems.

From a power system perspective, these results confirm that capacitor bank installations have a systemic impact in reducing global losses and increasing efficiency on the downstream side of the distribution network. Economically, this efficiency has the potential to reduce non-productive energy consumption within a range relevant to industrial demand-side management (DSM) policies. This means that this intervention not only addresses the technical aspects of efficiency, but is also relevant as an energy optimization strategy within the framework of penalty tariffs, operational costs, and carbon emission policies based on energy intensity.

Furthermore, the main contribution of this study lies in the application of a simulation model based on the separation of active and reactive variables in a 20 kV distribution system with a fixed load—which is generally still rarely analyzed in the literature on industrial power system efficiency. Thus, this study not only presents accurate and valid results in terms of calculations, but also offers a technical model that can be replicated and used as a reference in evaluating the efficiency of large-scale induction motor-based industrial distribution systems.

CONCLUSION

This study proves that reactive power compensation using capacitor banks significantly improves energy efficiency in industrial medium voltage distribution systems. Simulations in the load range of 800–1200 kW show an increase in system efficiency from 78% to 95% and a decrease in reactive power of up to 568.32 kVAR. These improvements have a direct impact on reducing apparent power and system power losses, thereby improving the stability and reliability of energy distribution. These results confirm that a dynamic compensation approach tailored to load variations is a strategic solution that not only improves technical performance but also significantly reduces operational energy costs. Operationally, these findings provide a strong basis for medium and large industries to integrate adaptive capacitor systems into internal energy management. The application of this method can be used as an energy performance indicator in the ISO 50001 scheme or independent energy audit. From a policy perspective, fiscal incentives or progressive tariffs are needed from the electricity authority for industries that adopt power factor correction-based efficiency systems, in order to encourage the transformation towards a sustainable and energy-efficient industrial distribution system. In the future, national energy conservation policies need to include capacitor bank installations as part of *the mandatory energy efficiency plan*, especially in the industrial sector that uses high inductive loads.

REFERENCE

- [1] I. of E. and E. Engineers, IEEE Std 141-1993: IEEE Recommended Practice for Electric Power Distribution for Industrial Plants. IEEE, 1994.
- [2] R. M. Utomo, A. P. Wirawan, W. C. Margono, and N. R. Alham, "Design of Automatic Power Factor Correction for Optimization of Electric Energy Consumption," Jurnal Ecotipe (Electronic, Control, Telecommunication, Information, and Power Engineering),

vol. 11, no. 1, pp. 10–18, 2024.

- [3] A. Rehman, M. Imran-Daud, S. K. Haider, A. U. Rehman, M. Shafiq, and E. T. Eldin, "Comprehensive review of solid state transformers in the distribution system: From high voltage power components to the field application," *Symmetry (Basel)*, vol. 14, no. 10, p. 2027, 2022.
- [4] M. Inci, Ö. Çelik, A. Lashab, K. Ç. Bayındır, J. C. Vasquez, and J. M. Guerrero, "Power system integration of electric vehicles: A review on impacts and contributions to the smart grid," *Applied Sciences*, vol. 14, no. 6, p. 2246, 2024.
- [5] R. Rahmaniar, A. Junaidi, and R. F. Wijaya, "Renewable Energy Education through Virtual Reality Tours.," *TEM Journal*, vol. 14, no. 2, 2025.
- [6] Z. Tharo, A. Tarigan, S. Anisah, K. T. Yuda, and P. LabuhanBilik, "Penggunaan Kapasitor Bank Sebagai Solusi Drop Tegangan Pada Jaringan 20 Kv," in *Prosiding Seminar Nasional Teknik UISU (SEMNASTEK)*, 2020, pp. 82–86.
- [7] D. D. N. Brid, Z. Tharo, and P. Wibowo, "Analysis the Effect of Control Valve Opening on Loading Crude Glycerine Water Pump Motor At PT. Unilever Oleochemical Indonesia," *Asian Journal of Environmental Research*, vol. 2, no. 1, pp. 29–47, 2025.
- [8] O. Ivanov, B. C. Neagu, G. Grigoras, and M. Gavrilas, "Optimal capacitor bank allocation in electricity distribution networks using metaheuristic algorithms. *Energies*. 2019; 12 (22): 4239."
- [9] T. A. Boghdady and Y. A. Mohamed, "Reactive power compensation using STATCOM in a PV grid connected system with a modified MPPT method," *Ain Shams Engineering Journal*, vol. 14, no. 8, p. 102060, 2023.
- [10] Z. H. Leghari, M. Kumar, P. H. Shaikh, L. Kumar, and Q. T. Tran, "A critical review of optimization strategies for simultaneous integration of distributed generation and capacitor banks in power distribution networks," *Energies (Basel)*, vol. 15, no. 21, p. 8258, 2022.
- [11] V. P. Widartha, I. Ra, S.-Y. Lee, and C.-S. Kim, "Advancing smart lighting: a developmental approach to energy efficiency through brightness adjustment strategies," *Journal of Low Power Electronics and Applications*, vol. 14, no. 1, p. 6, 2024.
- [12] M. A. Rezaei et al., "Reliability calculation improvement of electrolytic capacitor banks used in energy storage applications based on internal capacitor faults and degradation," *IEEE Access*, vol. 12, pp. 13146–13164, 2024.
- [13] F. Tanjung and R. Simatupang, "Kompensasi Daya Reaktif dan Pengaruh Harmonik pada Sistem Distribusi," *Jurnal Teknologi Proses*, vol. 14, no. 1, 2021.
- [14] B. Suharto, "Simulasi Kapasitor Multibeban dalam Sistem Distribusi 20 kV," *Jurnal Energi Nusantara*, vol. 5, no. 3, 2020.
- [15] L. Fernandez, J. Garcia, and D. Rivera, "Simulation-based optimization of reactive power compensation in industrial microgrids," *Renewable and Sustainable Energy Reviews*, vol. 165, p. 112380, Sep. 2022, doi: 10.1016/j.rser.2022.112380.
- [16] D. Saputra and M. Hasan, "Efisiensi Energi pada Industri Oleokimia Berbasis Daya Reaktif," *Jurnal Teknik Energi*, 2021.
- [17] A. J. Nikishin and M. S. Kharitonov, "Modernization of marine ports electrical power supply systems in the framework of zero-emission strategy," in *IOP Conference Series*:

Earth and Environmental Science, IOP Publishing, 2021, p. 012018.

- [18] K. Fettah et al., "Optimal integration of photovoltaic sources and capacitor banks considering irradiance, temperature, and load changes in electric distribution system," *Sci Rep*, vol. 15, no. 1, p. 2670, 2025.
- [19] M. Mahdavi, A. Bagheri, and A. de Leles Ferreira Filho, "Impact of Load Profile on the Installation of Capacitor Banks in Conventional and Modern Distribution Grids Considering Provision Cost of Reactive Power," *IEEE Trans Industr Inform*, 2025.
- [20] A. I. R. Widjaya, I. Haryanto, and M. Muchammad, "PEMODELAN DAN SIMULASI SISTEM ENERGI MENGGUNAKAN OPEN ENERGY MODELLING FRAMEWORK (OEMOF)," *JURNAL TEKNIK MESIN*, vol. 13, no. 2, pp. 33–40, 2025.
- [21] E. A. da Silva, W. M. C. Filho, M. R. Cavallari, and O. H. Ando Junior, "Self-powered system development with organic photovoltaic (OPV) for energy harvesting from indoor lighting," *Electronics (Basel)*, vol. 13, no. 13, p. 2518, 2024.
- [22] R. R. Hossain and R. Kumar, "A distributed-MPC framework for voltage control under discrete time-wise variable generation/load," *IEEE Transactions on Power Systems*, vol. 39, no. 1, pp. 809–820, 2023.