3-Phase Electrical Power Factor Improvement Simulator System Design Based on Automatic Control

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Abstract

This research aims to design and test a three-phase power factor improvement simulator based on Power Factor Controller (PFC) to improve power efficiency in industrial electrical systems. This simulator is equipped with two modes of operation, namely manual and automatic, and uses a capacitor bank to improve the power factor. Tests were conducted with two types of loads, namely resistive loads (light bulbs) and inductive loads (three-phase induction motors). The test results showed that in manual mode, the gradual addition of capacitors succeeded in increasing the power factor from 0.22 to 0.71. While in automatic mode, the power factor reached 0.73, although slightly lower than the desired set point value (0.85). This improvement in power factor has the effect of reducing reactive power consumption and operating costs. This research proves that the use of a Power Factor Controller can improve energy efficiency and reduce operational costs in three-phase induction motor-based electrical systems. Further development can involve the use of capacitors with smaller capacities and the integration of IoT-based monitoring systems for performance optimization.

Keywords: Power Factor Improvement Simulator, Power Factor Controller, Capacitor Bank, Power Efficiency, 3 Phase.

Introduction

Electrical power quality is one of the crucial aspects that affect the performance and efficiency of electrical systems, especially in increasingly complex distribution networks. Along with technological developments and increasing energy demand, issues related to electrical power quality are becoming an increasingly significant concern. The increasingly widespread use of electrical energy, both in the household and industrial sectors, makes power quality a major challenge in meeting the energy needs of the community.

One of the main parameters in assessing the quality of electrical power is the power factor, which reflects the efficiency of active power utilization in an electrical system. Power factor values are in the range of 0 to 1, where values close to 1 indicate high efficiency in power utilization. Conversely, a low power factor value indicates high reactive power consumption, which can lead to energy losses and lower system efficiency. Poor power factor is generally caused by high inductive loads, such as electric motors and various electronic equipment, or by unbalanced load conditions.

Low power factor not only impacts energy efficiency, but also affects the stability of the electrical system, increases operational costs, and potentially causes damage to electrical equipment. Therefore, optimal power factor management is very important to improve energy use efficiency, reduce power losses, and reduce distribution network maintenance costs. In addition, poor power factor can cause the distribution of active power to be uneven, thus disrupting the quality of energy services to consumers.

Various efforts have been made to improve the power factor, one of which is the installation of capacitor banks in the electricity system. Capacitor banks function to supply the reactive power needed by the system, so as to offset the reactive power requirements of inductive loads. Some previous studies have shown that the use of capacitor banks, for example in the cement industry, can increase the efficiency of active power utilization and reduce line losses in the distribution network. In addition, on a laboratory scale, a microcontroller-based power factor improvement simulator for single-phase systems has also been developed, which can be used as a test tool for the effectiveness of power factor improvement.

However, challenges still arise in power factor improvement in three-phase systems, which have higher complexity than single-phase systems. Three-phase systems are widely used in industrial and commercial applications due to their ability to supply greater and more stable power. Therefore, the design of a three-phase electrical power factor improvement simulator system with automatic control is very relevant and needed. This system is designed to be able to monitor and improve the power factor in real-time by utilizing automatic control technology that is efficient and easy to implement.

Through the development of this simulator system, it is hoped that a deeper understanding of power factor improvement in three-phase systems can be obtained, as well as a reference in developing similar solutions in the future. This research aims to produce an automatic control-based three-phase power factor improvement simulator system that is able to increase the efficiency of electric power usage. In addition, this research is also expected to make a real contribution to the development of electricity technology, especially in terms of efficiency and sustainability of energy utilization.

Literature Review

A. Three Phase Electrical Power

In an alternating current (AC) electrical system, three types of power are known: active power, reactive power, and apparent power. The utilization of electrical power is highly dependent on the nature of the installed electrical load. Electrical loads can be classified into active loads, passive loads, and mixed loads.

a. **Active loads** generally consist of semiconductor components that use active power to convert into other forms of energy such as light or heat.
b. **Passive loads** consist of resistive, inductive, and capacitive loads. Resistive loads consume active power, while inductive loads require reactive power to generate electromagnetic fields.

The relationship between these three types of electrical power can be described using a *power triangle*, which shows the vector relationship between active power (P), reactive power (Q), and apparent power (S).

The basic formula for power in a balanced three-phase system with phase voltage to neutral (VL-N) is as follows:

$$S = 3 \times V_{L-N} \times I_L \tag{1}$$

$$P_{3\phi} = 3 \times V_{L-N} \times I_L \times \cos\phi \tag{2}$$

$$Q_{3\phi} = 3 \times V_{L-N} \times I_L \times \sin\phi \tag{3}$$

If using the voltage parameter between phases (VL-L), the equation becomes:

$$S = \sqrt{3} \times V_{L-L} \times I_L \tag{4}$$

$$P_{3\phi} = \sqrt{3} \times V_{L-L} \times I_L \times \cos\phi \tag{5}$$

$$Q_{3\phi} = \sqrt{3} \times V_{L-L} \times I_L \times \sin\phi \tag{6}$$

Description:

- *S* = Apparent power (Volt-Ampere)
- *P* = Active power (Watt)
- *Q* = Reactive power (VAR)
- *VL-N* = Phase to neutral voltage (Volt)
- *VL-L* = Voltage between phases (Volt)
- *IL* = Phase current (Ampere)
- *φ* = Phase angle between voltage and current

B. Power Factor

Power factor is the ratio between the active power (kW) and apparent power (kVA) of an electrical load. Mathematically, the power factor is expressed as **cos φ**, where φ is the phase angle between current and voltage.

- kW (kilowatt) is a unit of active power, which is power that is actually used to do work.
- kVA (kilovolt-ampere) is a unit of apparent power, which is a combination of active power and reactive power.
- kVAR (kilovolt-ampere reactive) is a unit of reactive power, which is the power used to form an electromagnetic field in an inductive load.

The power factor indicates the efficiency of electrical energy utilization in converting electrical energy into other forms of energy (e.g. mechanical energy or heat). The power factor value ranges from 0 to 1. The closer to 1, the more efficient the use of electrical energy.

Inductive loads such as induction motors and transformers cause low power factor because these devices require current to generate magnetic fields in order to operate. When the power factor is less than one, the apparent power supplied to the load will be greater than the active power actually used.

In alternating current (AC) systems, there is often a phase difference between voltage and current. This is known as the power factor of a circuit. If the circuit is inductive, then the current is lagging behind the voltage so the power factor is called lagging power factor. Conversely, if the circuit is capacitive, then the current is leading the voltage and the power factor is called leading power factor.

Efforts to increase the power factor value can be made by installing a series of capacitors. Some household consumers have started using capacitors, although the number is still limited. However, the installation of capacitors has limitations because the capacitance value of capacitors is generally fixed, while inductive loads in households can change. This causes the capacitor to only be able to optimally improve the power factor according to its capacitance value. As the inductive load increases, the effectiveness of the capacitor in improving the power factor will decrease.

This power factor analysis can be visualized through a **power triangle**, as shown in Figure 2.

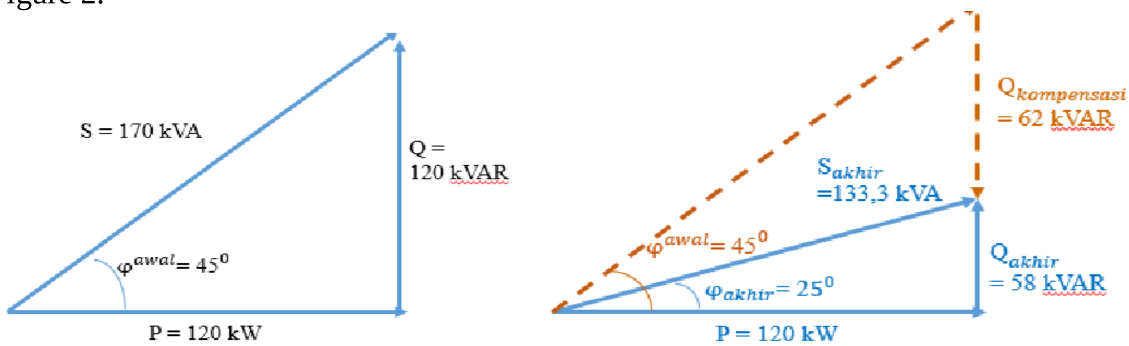


Figure 2. Reactive Power Compensation Analysis
(a) Power triangle condition when power factor (Pf) = 0.7 lagging
(b) Power triangle condition when power factor (Pf) = 0.9 lagging.

Description:

- S: Apparent power before capacitor usage (VA)
- S_{end}: Apparent power after capacitor usage (VA)
- φ_{initial}: Phase angle between current and voltage before capacitor installation
- φ_{end}: Phase angle between current and voltage after capacitor installation
- Q: Reactive power before capacitor installation (VAR)
- Q_{compensation}: Reduction of reactive power as a result of capacitor installation (VAR).
- Q_{end}: Reactive power after capacitor installation (VAR)

The power triangle is used to visualize the relationship between active power (P), reactive power (Q), and apparent power (S). With the installation of capacitors, the value of Q decreases, so φ decreases and the power factor increases, approaching 1.

Research Methods

1. Problem Identification
   a. Identify the problem of low power factor in three-phase electrical systems, which results in inefficient use of power and cost penalties from electricity providers.
2. Literature Study
   a. Conduct literature review to understand basic concepts and related technicalities:
      1). Power factor and its correction.
      2). Use of capacitor banks.
      3). Power Factor Controller (PFC) function.
      4). Three-phase power distribution system.
3. Formulation of System Objectives and Specifications
   a. Set research objectives, namely designing and building a PFC-based 3-phase power factor improvement simulator.
   b. Develop system technical specifications, including capacitor bank, CT (Current Transformer), PFC controller, relays, contactors, 3-phase load, and control mode.
4. System Design
   a. Develop a system block diagram.
   b. Design electrical circuits (wiring diagrams).
   c. Design manual and automatic control mode configurations.
   d. Determine the setting parameters of the PFC, such as voltage, current, active/reactive/semi power, THD, and temperature.
5. Component Selection and Compilation
   a. Determine and select components based on technical requirements (refer to Table 1 and Table 2).
   b. Systematically and safely assemble and arrange components on the simulator panel.
6. System Implementation and Testing
   a. Assemble the entire system according to the planned design.
   b. Set up a measurement system to monitor electrical parameters.
   c. Conducting tests on manual and automatic modes to evaluate the performance of PFC in improving power factor.
7. Data Analysis
   a. Analyze the results of power factor measurements before and after capacitor installation.
   b. Evaluate the effectiveness of automatic and manual capacitor selection based on measurement results (kVAR, kW, THD, etc.).
8. Conclusions and Suggestions
   a. Draw conclusions from the implementation results of the power factor improvement simulator.
   b. Provide suggestions for future development, such as the addition of an IoT-based monitoring system, integration of harmonic protection, or increasing the efficiency of adaptive capacitor selection.

Results and Discussion

System design

Basically, this system is a capacitor switching system that is installed in parallel on the power grid. For three-phase systems, the capacitor bank used is also a three-phase capacitor. The selection of the capacitor value is based on the measurement of the phase angle between current and voltage. Current measurements are taken using a CT (Current Transformer) and voltage measurements are taken with a voltage meter.

After that, the current and voltage values will be compared with the set points set on the PFC (Power Factor Controller). Thus, some of the measurement parameters that will be displayed on the PFC are as follows:

a. Line voltage (Volt)
b. Rated current (Ampere)
c. Reactive power (kVAR)
d. Active power (kW)
e. Apparent power (kVA)
f. Difference between reactive power and setting (kVAR)
g. Frequency (Hz)
h. Temperature (°C)
i. Harmonics of voltage (V) and current (I)
j. THD (Total Harmonic Distortion) on voltage (V) and current (I) (%)

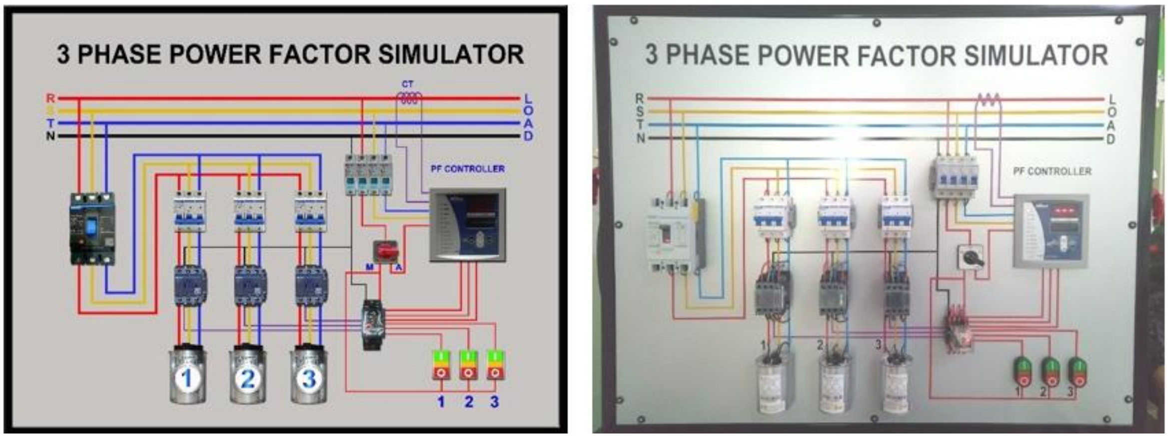
As a result, the PFC will calculate how many capacitors need to be installed to achieve the desired power factor.

The block diagram of the three-phase power factor improvement simulator is shown in Figure 1, while the PFC control concept is shown in Figure 3.

The simulator is designed with a three-phase input terminal equipped with protection. There is also one terminal for a three-phase load and three step capacitors assembled in a triangular (delta) configuration. The system is equipped with three buttons to select the manual operation mode, as well as a power factor controller whose wiring diagram is shown in Figure 4. The simulator design display can also be seen in Figure 5. The simulator design is based on the component specifications listed in Table 1, as well as the load specifications listed in Table 2.

The principle of power factor improvement in single-phase and three-phase circuits is the same, namely by using capacitor variations. However, the three-phase simulator is equipped with a PFC (Power Factor Controller), which allows the selection of the most suitable capacitor to be done automatically with the help of a microcontroller. The researcher can still select the two modes of operation provided, namely manual mode and automatic mode, which are selected by adjusting the selector switch.

The controller is supplied with a standard voltage of 230 VAC (L-N) and can measure voltages between 30-300 VAC (L-N) at a frequency of 50/60 Hz. The current setting is sized according to the plan. This simulator allows setting the operating mode to Automatic, Programming, and Manual.



Design of 3-phase power factor improvement simulator and Implementation of simulator manufacturing

Table 1. Component Specifications

Component Name	**Specifications**
3 Phase Capacitor	SYC brand; 3 x 9.3 uF; 1.5 Kvar; 415V; 2.1A
3 Phase MCB	Brand: CHNT; 6 A; 3 Phase
Contactor Relay	CHNT, NXB-63, C40
Multi Contact Relay	11 Contact Terminals, 250VAC/28VDC 10A
3 Phase MCCB	Brand: CHNT; 25 A; 3 Phase
Selector Switch	Manual/Auto
Push Button On/Off	-
CT 50/5 A	-
Micro PFC, PFR60	-

Table 2. Load Specifications

Component Name	**Specifications**
3 Phase Motor	7.5 kW; 380/660V; 15.6/9A; 50 Hz; cos φ 0.84
Lamp bulbs	3 x 100 W

Results and Discussion

The designed and built power factor improvement simulator was tested with two operating modes, namely manual mode and automatic mode, and using two types of loads: resistive load (light bulb) and inductive load (three-phase induction motor without load). The energy source is obtained from the three-phase power grid. The system implementation can be seen in Figure 6.

1. Manual Mode Testing

In this mode, the capacitor addition is done gradually by the operator. Table 3 shows the test results:

a. Without capacitors and using a no-load induction motor load, the initial power factor was only 0.22, indicating the dominance of reactive power due to the inductive characteristics of the motor and the absence of mechanical loads.
b. The addition of 1 unit capacitor bank (3x9.3 µF) improved the power factor to 0.26, with a decrease in current and active power to 0.49 A and 86.94 W, respectively.
c. With 2 units of capacitor bank (2x3x9.3 µF), the power factor rose to 0.37, and the current consumption dropped significantly to 0.31 A.
d. When using 3 capacitor bank units (3x3x9.3 µF), there was an increase in power factor to 0.71, with a current of only 0.12 A and an active power of 58.14 W.

The decrease in current indicates that the system load becomes more efficient, so the capacitor is able to reduce the reactive power load, and potentially reduce the cost of energy consumption on inductive equipment.

Meanwhile, when tested with a light bulb load (resistive load) without capacitors, the direct power factor was 1.00, indicating that there was no need for reactive power compensation in this type of load.

2. Auto Mode Testing

The next test uses automatic mode, where the Power Factor Controller (PFC) will automatically adjust the number of capacitors connected to the system. The specified power factor target or set point is 0.85.

However, from the measurement results shown in Table 4, the final value of the power factor only reached about 0.73. This is due to several factors:

a. The number of capacitor banks available is limited.
b. The capacitor step is large, so the adjustment is less precise to the reactive power requirements of the load.
c. The reactive power requirement of the motor is quite large, while the total capacitor capacity is insufficient to achieve the desired set point.

Although the target was not fully achieved, the system still demonstrated the ability to gradually and adaptively improve the power factor according to load conditions. This shows the potential of using the automatic mode for more practical operational efficiency on a distribution system scale.

Table 3. Tool Testing Results During Manual Operation Mode

No.	Load	Voltage (V)	Current (A)	Power Factor (Cosφ)	Power (P) (W)	Description
1	Motor without load	394	0,69	0,22	103,5	Without capacitor
2	Motor without load	394	0,49	0,26	86,94	+ 3x9.3 µF capacitor
3	Motor without load	394	0,31	0,37	78,2	+ 2x3x9.3 µF capacitor
4	Motor without load	394	0,12	0,71	58,14	+ 3x3x9.3 µF capacitor
5	Lamp (resistive load)	394	0,26	1	312	Without capacitor

This table presents the power measurement data in the manual mode test, with induction motor and light bulb loads. The data shows the changes in power factor (Cosφ), current (A), and power (P) that occur after the addition of capacitor banks. These changes in power factor values illustrate the effectiveness of capacitors in gradually improving the system power factor.

Table 4. Tool Testing Results During Automatic Operation Mode

No.	Load	Voltage (V)	Current (A)	Power Factor (Cosφ)	Power (P) (W)	Description
1	Motor	394	0,12	0,71	58,1	Capacitor position at 3x3x9.3 µF
2	Light bulb 3	394	0,26	1	312	No capacitors connected

This table presents the measurement data in the automatic operation mode, showing the changes in power factor (Cosφ), current (A), and power (P) during the test. In the first test, with the capacitors positioned at 3x3x9.3 µF, the power factor value was 0.71, while at the light bulb load, no capacitors were connected.

Discussion of Test Results

1. Manual Operation Mode Testing

In the manual operation mode test, the capacitor was gradually adjusted to improve the power factor of the system connected to the three-phase induction motor load. Before the installation of the capacitors, with the motor load without load, the power factor value was at a very low number of 0.22. This indicates that the motor load is not working optimally in using the available power, and most of the energy is used to generate the magnetic field in the motor (reactive power). After the addition of the capacitor bank, the power factor value began to increase. At the addition of the first capacitor (1 unit capacitor), the power factor increased to 0.26, at the addition of the second capacitor (2 units capacitor) to 0.37, and at the addition of the third capacitor (3 units capacitor), the power factor increased significantly to 0.71. This improvement in power factor indicates that the capacitors successfully compensate for the reactive power generated by the motor, reducing the required current, and thus reducing the consumption of useless reactive power. This result contributes to the reduction of the operating costs of the three-phase induction motor, as the power used is more efficient. In addition, the reduction in current that occurs in the system after the installation of capacitors also indicates a decrease in power consumption, which indicates that the system becomes more efficient in energy use.

2. Auto Operation Mode Testing

In the automatic operation mode test, the main objective is to compare the system performance when the capacitor is automatically selected by the **Power Factor Controller (PFC)**. In this experiment, the test results show that the power factor value gradually approaches the predetermined set point value of 0.85. However, the final value obtained in this experiment was 0.73, slightly lower than the desired set point value. This is due to several factors, such as the limited number of capacitor banks and the capacitor bank step capacity being too large. The motor loads used in the experiments have a greater reactive power demand than the capacity of the connected capacitors, so even though the system is trying to improve the power factor, there are not enough capacitors to achieve the optimal power factor (0.85). In addition, in the test with a resistive light bulb load, no capacitors were connected, and the power factor was at the ideal value of 1, indicating that the system did not require reactive power correction for this type of load.

3. Effectiveness Analysis of Manual vs Automatic Mode

a. **Manual mode** provides the flexibility of selecting capacitors directly according to needs, allowing for more optimized results (power factor reaches 0.71 at motor load).
b. **Automatic Mode**, although successful in gradually improving the power factor, is limited by the number of capacitors available and the large capacitor step size, which limits the system's ability to achieve the ideal power factor value. The system can be further improved by adding smaller capacitors or more capacitor steps to match more variable loads.

4. Implications for Operating Costs

With power factor improvement, either through manual or automatic settings, the system becomes more efficient in power usage. Reduced reactive power consumption leads to operational cost savings, especially in industries that use three-phase induction motors, which typically require considerable reactive power. Proper use of capacitor banks can reduce reactive power requirements and optimize active power consumption, which contributes to reduced electricity bills as well as increased longevity of electrical equipment.

Testing in manual mode showed better results in correcting the power factor, with a higher power factor value (0.71). Meanwhile, the automatic mode can improve the power factor gradually, but needs to be improved by adding capacitors that are more suitable for the capacity and load used to achieve a more optimal power factor. The results of this test illustrate that a capacitor-based Power Factor Correction (PFC) system can help improve power usage efficiency and reduce operating costs on inductive loads, especially three-phase induction motors.

Conclusion

Based on the research results, the Power Factor Controller (PFC)-based 3-phase power factor improvement simulator successfully improves the power factor and power usage efficiency of three-phase induction motor loads. In manual mode, the gradual addition of capacitor banks succeeded in increasing the power factor from 0.22 to 0.71. However, in the automatic mode, the power factor reached 0.73, which is still slightly lower than the desired set point value (0.85), due to the limited capacitor capacity. This improvement in power factor has the effect of reducing reactive power consumption and operating costs. Nonetheless, capacitors with smaller capacities and more in automatic mode are needed for the system to better adjust reactive power requirements. The use of an IoT-based monitoring system and harmonic management can also be a further development step to improve system performance and efficiency. Overall, this research shows that the PFC system can improve energy efficiency and reduce operational costs in three-phase induction motor applications.

References

[1] Anisah, S., Tarigan, A. D., & Wardhani, D. P. (2022, November). Study And Potential Utilization Of Solar Power Plant As A Source Of Energy At University Of Pembangunan Panca Budi. In Proceeding International Conference of Science Technology and Social Humanities (Vol. 1, pp. 106-114).

[2] Tharo, Z., Kusuma, B. S., Anisah, S., & Dhalimunte, M. E. (2021). Analisis Perbandingan Kinerja Kwh Meter Prabayar Dan Pascabayar. *Prosiding Konferensi Nasional Social & Engineering Polmed (KONSEP)*, *2*(1), 358-365.

[3] Tharo, Z., Hamdani, H., Andriana, M., & Anisah, S. (2022). Perancangan Dan Implementasi Genset 450 Va Berbasis Panel Surya. *Journal of Electrical and System Control Engineering*, *6*(1), 50-58.

[4] Barus, S., Aryza, S., Wibowo, P., Anisah, S., & Hamdani, H. (2020). Rancang bangun pemanfaatan aliran tandon air gedung bertingkat sebagai pembangkit listrik mikro hidro. In *Scenario (Seminar of Social Sciences Engineering and Humaniora)* (pp. 545-557).

[5] Yusup, M. (2022). Teknologi Radio Frequency Identification (RFID) sebagai tools system pembuka pintu outomatis pada smart house. *Jurnal Media Infotama*, *18*(2), 367-373.

[6] S. Khan, B. Singh, and P. Makhija, "A review on power quality problems and its improvement techniques," in 2017 Innovations in Power and Advanced Computing Technologies (i-PACT), Apr. 2017, pp. 1–7. doi: 10.1109/IPACT.2017.8244882.

[7] A. Arranz-Gimon, A. Zorita-Lamadrid, D. Morinigo-Sotelo, and O. Duque-Perez, "A Review of Total Harmonic Distortion Factors for the Measurement of Harmonic and Interharmonic Pollution in Modern Power Systems," Energies, vol. 14, no. 20, Art. no. 20, Jan. 2021. doi: 10.3390/en14206467.

[8] F. B. Aldousari, "Power Factor in Electrical Networks," Eng. Technol., vol. 8, no. 2, pp. 41–44, 2018. doi: 10.9790/9622-0802034144.

[9] A. Ojo, K. Awodele, and A. Sebitosi, "Power Quality Monitoring and Assessment of a Typical Commercial Building," in 2019 IEEE AFRICON, Sep. 2019, pp. 1–6. doi: 10.1109/AFRICON46755.2019.9133970.

[10] A. B. Setyarso, O. Penangsang, and R. S. Wibowo, "Penentuan Daya Reaktif Untuk Perbaikan Kualitas Daya Berdasarkan Voltage State Estimation Pada Jaringan Distribusi Radial 20 KV Di Surabaya," J. Tek. ITS, vol. 2, no. 2, Art. no. 2, Sep. 2013. doi: 10.12962/j23373539.v2i2.3378.

[11] A. H. Rahman, A. Hidayahtullah, A. N. Ulfa, R. Z. Ahmad, and J. T. Putra, "Improvement of the power factor on the distribution line feeder Sutami 23 Lampung using capacitor bank and SVC with ETAP 12.6 simulation," Tek. J. Sains Dan Teknol., vol. 17, no. 2, Art. no. 2, Oct. 2021. doi: 10.36055/tjst.v17i2.11729.

[12] H. Umran, "Study and analysis for the effects of power factor correction in Al-Najaf Cement Plant," vol. 8, pp. 59–72, Jan. 2015.

[13] A. Aripriharta, N. Mardianto, H. Amri, and M. Muharnis, "Rancang Bangun Simulator Perbaikan Faktor Daya Listrik Sebagai Modul Praktikum di Laboratorium Elektronika Daya," INOVTEK - Seri Elektro, vol. 2, p. 56, May 2020. doi: 10.35314/ise.v2i1.1274.

[14] M. Butarbutar and M. Riyanto, "Manajemen Sisi Beban dan Optimalisasi Tingkat Konsumsi Energi Di SMK Negeri 2 Pontianak," Elkha, vol. 10, no. 1, p. 41, 2019. doi: 10.26418/elkha.v10i1.25331.

[15] V. K. G. Sapna Khanchi, "Online power factor improvement of induction motors," Int. J. Eng. Trends Technol. IJETT, vol. 4, no. 7, pp. 1509–1513, 2013. doi: 10.1109/ias.1988.25257.