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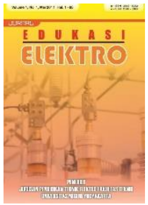

Power Factor Improvement using Capacitor Controlled Based on Dimmers

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Abstract— The utilization of electric power predominantly involves inductive loads, which result in lagging voltage waves that increase power consumption beyond what is effectively utilized, thereby reducing power factors and causing energy losses. To mitigate reactive power from inductive loads, capacitors are commonly installed in parallel. However, conventional fixed capacitor banks often lead to suboptimal results due to improper sizing. This study presents an innovative power factor correction device utilizing dimmer-controlled capacitors for dynamic capacitance adjustment. The research offers a cost-effective alternative to microcontroller-based systems while providing real-time adaptability for varying loads. The system enables precise control of capacitance without complex programming. The experimental approach uses six parallel-connected capacitors (2.5μF each), controlled by a dimmer circuit with TRIAC, DIAC, and potentiometer components. Testing is conducted with variable inductive loads ranging from 1.7 H to 6.8 H, simulating laboratory conditions with potential for scaling to real-world applications. The methodology includes baseline measurements, capacitor compensation, load variation analysis, and performance evaluation. Results demonstrate power factor improvement from 0.55 to 0.85 using a capacitance range of 0.6299μF to 15μF. The dimmer-controlled approach effectively increases active power while reducing reactive power from 56.198 VAR to 33.773 VAR, significantly improving voltage stability under varying load conditions.

Keywords: power factor, dimmer, capacitor.

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1 Introduction

Electrical energy is a crucial resource for both society and industry, supporting various activities in urban and rural areas alike. Dependence on electrical energy continues to increase with population growth and technological advancements. However, inefficient use of electrical energy can lead to unnecessary power consumption and significant energy losses. One of the main factors contributing to this inefficiency is the use of inductive loads, which are commonly found in household and industrial equipment.

Inductive loads are types of loads that contain coil elements, such as electric motors, transformers, and fluorescent lamps. These loads cause a phase shift between voltage and current, resulting in a decrease in the system's power factor. A low power factor leads to higher apparent power compared to the active power used by the load. This condition increases energy consumption and raises electricity costs for both household and industrial consumers [1-6].

In electrical power systems, a decrease in power factors (PF, represented as Cos φ) poses a challenge that must be addressed. A low power factor not only burdens electricity providers with increased reactive power demand but also causes power losses in the distribution system. Therefore, effective methods are required to improve the power factor, optimize electrical energy usage, and reduce power wastage [5].

A commonly used method to improve the power factor is installing capacitors in parallel with inductive loads. Capacitors function as reactive power compensators that reduce the phase shift effects caused by inductive loads. However, improper capacitor selection can lead to suboptimal results. A capacitor that is too small may not provide significant improvement, while an oversized capacitor can cause undesirable voltage increases and system imbalance [5-9].

This study aims to design and develop a power factor correction device using dimmer-controlled capacitors. By utilizing a dimmer as a capacitance controller, this system can dynamically adjust capacitor values based on the requirements of the connected inductive loads. The use of a dimmer allows for more flexible and adaptive power factor adjustment, optimizing the performance of electrical power systems under various operational conditions [10-15].

The urgency of this research is further heightened by modern industrial trends demanding energy efficiency and carbon emission reduction. Many countries have implemented strict regulations regarding energy efficiency in electrical systems, encouraging the widespread adoption of power factor correction technologies. Furthermore, in the context of Industry 4.0, where electrical power systems are increasingly digitized and automation continues to evolve, the use of adaptive and electronically controlled power factor correction methods is becoming more relevant [15-20].

Thus, this research contributes not only to the technical aspects of power factor improvement but also has a broader impact on supporting energy sustainability and electrical system efficiency. The findings of this study are expected to be applicable in various usage scenarios, both for household and industrial needs, to achieve a more efficient and reliable electrical power system.

2 Method

2.1 System design

This study employs an experimental approach to design and evaluate a power factor correction system using dimmer-controlled capacitors. The system is designed to dynamically adjust the capacitance in response to changes in the inductive load, optimizing power factor improvement. The research framework includes system modelling, component selection, circuit design, prototype fabrication, and performance evaluation.

2.2 Experimental Setup

The experimental setup consists of an inductive load represented by a set of variable inductors ranging from 1.7 H to 6.8 H. A capacitor bank, comprising six capacitors of 2.5μF each, is connected in parallel and controlled by a dimmer circuit to regulate capacitance dynamically. The dimmer circuit is employed to modulate the applied capacitance in response to system demands. Measurement instruments, including a digital oscilloscope, power meter, and multimeter, are utilized to capture key electrical parameters such as voltage, current, power factor, and waveform characteristics.

This setup enables systematic evaluation of power factor improvement and system efficiency under varying load conditions.

The dimmer circuit serves as a controller for adjusting the capacitance input from the capacitor bank. It is designed to regulate the amount of capacitance required by the system dynamically. The dimmer circuit incorporates three key components to control its operation, as shown in Figure 1, the TRIAC, DIAC, and a variable resistor (potentiometer). TRIAC regulates the AC voltage supplied to the capacitor bank, determining the effective capacitance value. DIAC and potentiometer work together to control the TRIAC's bias, setting the points on and off points of the TRIAC. The voltage at the TRIAC gate determines the amount of capacitance delivered to the system; higher gate voltages result in higher capacitance values. The dimmer circuit operates based on the principle of a low-pass filter (LPF). An LPF selectively passes low-frequency signals while attenuating high-frequency signals, making it useful for signal shaping and modification. In this study, a passive LPF is employed, consisting of a capacitor and a resistor connected in series. This configuration ensures that only the desired signal is allowed through, enabling precise control of the capacitance input from the capacitor bank.

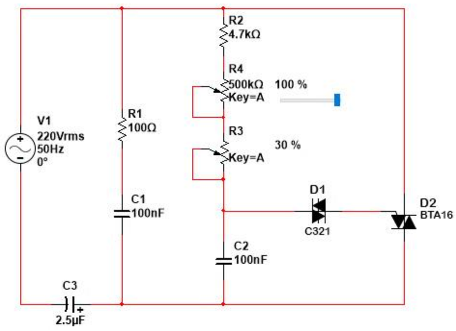

Figure 1. Dimmers range

This section discusses the system design utilized in the research. The primary components of the system include dimmers, capacitor banks, and various types of loads (inductive, capacitive, or resistive). The electrical power source for the system is a single-phase synchronous motor generator, supplying an AC voltage of 220 V.

The design of the power factor improvement system, incorporating controlled capacitors, is illustrated in Figure 2. The primary objective of the design is to enhance the power factor of the electrical load by dynamically regulating the capacitance provided by the capacitor bank. The capacitor bank is integrated into the system with precise control to ensure optimal performance.

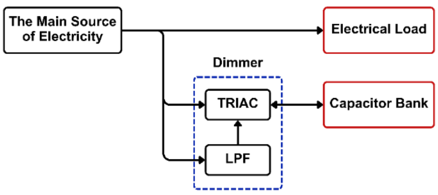

Figure 2. Tool design block diagram

2.3 Testing procedure

The testing process begins with baseline measurements, where the power factor of the system is recorded without any capacitive compensation. Key parameters such as voltage, current, and reactive power are measured to establish a reference point. The experimental setup, as illustrated in Figure 3, consists of three main circuit blocks: the dimmer circuit, the capacitor bank circuit, and the inductor circuit.

After the baseline measurements, capacitor compensation testing is conducted by adjusting the dimmer potentiometer to vary the TRIAC firing angle, effectively controlling the RMS voltage applied to the capacitor bank. The RC network in the dimmer circuit (R5, R6, C1, C2) determines the phase-shift characteristics, which in turn affect the capacitive reactance delivered to the system.

Switches S(n/o)1–6 in the capacitor circuit enable the selective engagement of individual capacitors to achieve the desired total capacitance, while switches S(n/o)7–12 in the inductor circuit allow for precise adjustment of the inductive load. The resulting changes in power factors and other electrical parameters are recorded to analyze the relationship between the dimmer setting, effective capacitance, and the improvement in power factors.

Subsequently, load variation testing is performed by systematically altering the inductive load using switches S(n/o)7–12 to engage different combinations of inductors (L1–L6), allowing evaluation of the system's adaptability across the full range of 1.7 H to 6.8 H. The system's response under different inductive conditions is observed and analyzed while maintaining the optimal dimmer settings identified in the previous phase.

Finally, performance evaluation is conducted by comparing the experimental results with theoretical calculations. This step assesses the overall effectiveness of the dimmer-controlled capacitor system in improving power factors and optimizing energy efficiency.

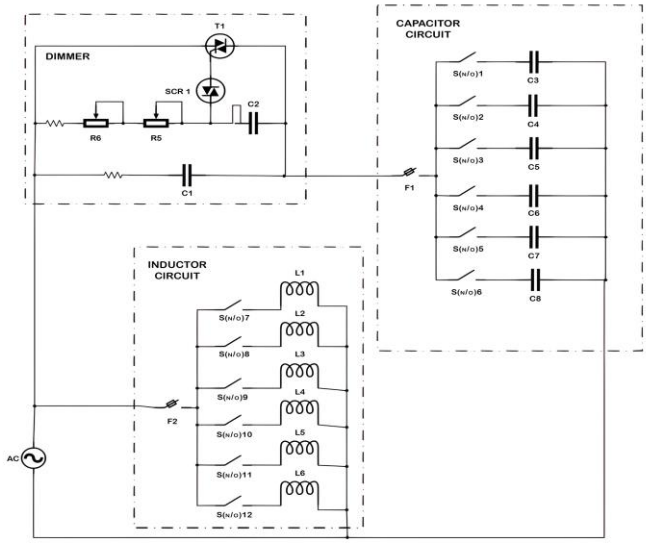

Figure 3. Tool design block diagram

2.4 Data analysis

The collected data is analyzed using statistical and graphical methods. The power factor before and after compensation is compared to determining the improvement achieved. Additionally, system efficiency is evaluated by analyzing reductions in reactive power and improvements in real power utilization. By implementing this methodology, the study aims to provide a comprehensive understanding of how dimmer-controlled capacitors can enhance power factor correction dynamically, contributing to more efficient electrical power usage in various applications.

3 Results and Discussion

The dimmer utilized in this study is an analog type controlled via a potentiometer. The test aims to evaluate the dimmer's performance and verify that its output waveform aligns with the design specifications.

Before advancing to further stages, the dimmer is calibrated by setting reference values to facilitate adjustments. These reference values are voltage increments, ranging from 20 V to 220 V. As part of the testing process, measurements were recorded with a value of V_{rms} = 120V and I_{rms} = 0.201A. Based on the measurements and calculations presented in Table 1, it was observed that as the duty cycle percentage increases, the resistance value also increases. This behavior is attributed to the concurrent rise in V_{rms} and I_{rms} values as the duty cycle percentage is adjusted.

Table 1. Dimmer test

I_{rms} (A)	V_{rms} (V)	Percentage (%)	Frequency (Hz)	R (Ω)
0,114	30	13.69	50	260,87
0,127	40	18.25	50	314,97
0,161	60	27.37	50	372,67
0,165	80	36.5	50	485,46
0,184	100	45.62	50	546,99
0,201	120	54.74	50	597,01
0,216	140,1	63.91	50	649,07
0,232	160	72.99	50	690,09
0,247	180	82.12	50	729,15
0,262	200	91.24	50	763,36
0,275	219,2	100	50	797,1

After calibrating the dimmer, the next step involves testing its output waveform and calculating the duty cycle values. This test is performed using a resistive load. Adjusting the potentiometer modifies the duty cycle by altering the on and off durations. The results confirm that the dimmer effectively regulates the output value, enabling its integration into the system.

Figure 4 illustrates that, at a 100% duty cycle, the output waveform measured by the oscilloscope still exhibits minor deviations from an ideal sinusoidal shape. These distortions arise due to the frequency dependent impedance introduced by the RC circuit within the dimmer, which impedes ideal voltage transfer. The RC time constant (τ = RC) induces phase shifts and filtering effects, resulting in waveform distortion even under full conduction. This behavior underscores the inherent limitation of the system in achieving ideal power factor correction and highlights the trade-off between dimmer control precision and waveform fidelity.

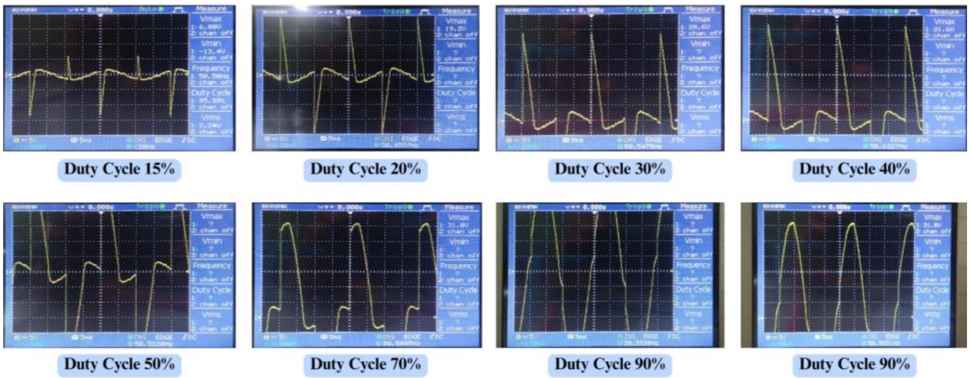

Figure 4. Testing the dimmer output using a digital oscilloscope

The results of the measurements with an RLC load, as shown in Table 2, demonstrate that the inductive load significantly influences changes in the values of Cos *φ, V*, and *I.* When an inductive load of L=1.7 H is introduced into the system without any capacitive compensation C=0μF, the power factor (*Cos φ* (*β*)) decreases to 0.633. This reduction in power factor results in mechanical vibrations in the generator, adversely affecting system stability. By adding a capacitive load of C=2.5μF the power factor improves significantly, reaching *Cos φ* (*α*) = 0.830.

Table 2. RLC load testing without dimmers

R (Ω)	L (H)	C β (μF)	C α (μF)	Cos φ (β)	Cos φ (α)	V β (V)	I β (A)
920	1.7	0	0	0.996	0.996	213.4	0.231
	1.7	0	2.5	0.633	0.830	194.1	0.374
	3.4	2.5	5	0.566	0.693	184.5	0.444
	5.1	5	7.5	0.522	0.621	179.7	0.495
	6.8	7.5	10	0.489	0.563	172.6	0.565
	8.5	10	12.5	0.418	0.468	167	0.688
	10.2	12.5	15	0.394	0.471	163.3	0.776

The analysis of the experimental results indicates a significant improvement in power factors after implementing the dimmer-controlled capacitor bank. Initially, the system exhibited a power factor of 0.633, leading to inefficient power usage and increased reactive power losses. After compensation, the power factor improved to 0.830, demonstrating a more efficient utilization of active power. This improvement resulted in a reduction of reactive power from 56.198VAR to 33.773VAR, minimizing unnecessary energy consumption and enhancing overall system performance.

The increase in power factor was accompanied by a noticeable enhancement in voltage stability and current efficiency. Before correction, the system operated at 194.1V and 0.374A, delivering an active power of 45.95W. After implementing the dimmer-controlled capacitor bank, the voltage increased to 200.5V with a current of 0.302A, resulting in an improved active power of 50.26W. The reduction in reactive power not only optimized energy consumption but also contributed to lowering losses in the electrical system. This effect is particularly beneficial for industrial and household applications, where maintaining a high-power factor helps reduce electricity costs and extend the lifespan of electrical components.

Table 3. Frequency and reactive power data for RLC load testing without dimmer

R (Ω)	L (H)	C β (μF)	C α (μF)	F β (Hz)	F α (Hz)	Q β (KVAR)
920	1.7	0	0	50.3	50.3	0.004
	1.7	0	2.5	50.4	50.5	0.056
	3.4	2.5	5	50.6	50.5	0.067
	5.1	5	7.5	50.6	50.5	0.076
	6.8	7.5	10	50.5	50.5	0.085
	8.5	10	12.5	50.5	50.2	0.098
	10.2	12.5	15	50.1	50.2	0.119

The measured data in Table 4 demonstrates that, despite the correction of the power factor (*Cos φ*), the achieved value remains suboptimal. This limitation is attributed to the maximum capacitance of the capacitor bank employed in this study, which is 15µF. Consequently, the highest corrected *Cos φ* value was 0.471 when the inductive load was 10.2 H, with corresponding voltage and current values of 172V and 0.679A, respectively. This threshold serves as a reference point for subsequent power correction measurements using a dimmer.

Table 4. Calculation results of RLC load active power without dimmers

V (V)	I (A)	Cos φ	P (W)
213.4	0.231	0.996	49.09
194.1	0.374	0.633	45.95
200.5	0.302	0.830	50.26
184.5	0.444	0.566	46.37
192.5	0.373	0.693	49.76
179.7	0.495	0.522	46.43
182.7	0.448	0.621	50.83
172.6	0.565	0.489	47.69
178.3	0.513	0.563	51.49
167	0.688	0.418	48.03
174.4	0.652	0.468	53.22
163.3	0.776	0.394	49.93
172	0.679	0.471	55.01

To enhance the power factor, the required capacitance of the corrective capacitor is determined based on the system's active and reactive power. The reactive power of the system before and after power factor correction was analyzed, showing a reduction in reactive power from 56.198VAR to 33.79VAR based on the data **Table 4**. This reduction indicates a more efficient use of energy and a decrease in power losses.

The test results confirm that the system's reactive power after compensation is 33.79VAR. To achieve this improvement, the capacitive reactance (Xc) of the capacitor was calculated, yielding a value of 1260Ω. Based on this, the reactive power contribution of the capacitor (Qc) was found to be 31.905VAR, which supports the overall improvement in system efficiency. The corresponding capacitance required to achieve the desired power factor was determined to be approximately 0.6299µF.

These findings highlight the effectiveness of using a dimmer-controlled capacitor bank for dynamic power factor correction. Unlike fixed capacitor banks, this approach enables real-time adjustments in capacitance, ensuring optimal performance under varying load conditions. By preventing overcompensation and maintaining system stability, the dimmer-based control method proves to be a viable and efficient solution for improving power quality in residential and industrial applications.

Table 5 presents the real power (*P*) and reactive power (*Q*) measured before (*β*) and after (*α*) power factor correction. The results indicate that an improved power factor (*Cos φ*) leads to an increase in real power, confirming the relationship between these parameters. Table 6 illustrates the results of an RL load test using a dimmer-controlled capacitor bank. The data highlights change in power factors (*Cos φ*) with and without dimmer activation. These results confirm that the dimmer effectively contributes to power factor correction.

Table 5. Comparison of P and Q before and after repair *Cos φ*

Cos φ (β)	Cos φ (α)	P β (W)	P α (W)	Q β (VAR)	Q α (VAR)
0.996		49.09		4.405	
0.633	0.830	45.95	50.26	56.198	33.773
0.566	0.693	46.37	49.76	67.534	51.765
0.522	0.621	46.43	50.83	75.871	64.155
0.489	0.563	47.69	51.49	85.064	75.594
0.418	0.468	48.03	53.22	104.377	100.488
0.394	0.471	49.93	55.01	116.471	103.023

Table 6. RL load testing with dimmers

R (Ω)	L	*Dimmer*	Cos φ (β)	Cos φ (α)	V (β)
920	0	0 %	0.99	0.99	220
	1.7 H	81.8 %	0.71	0.83	194
	3.4 H	68.2 %	0.49	0.86	179
	5.1 H	63.6 %	0.56	0.75	167
	6.8 H	45.4 %	0.55	0.75	155

Initially, a resistive load of 920 Ω was applied, yielding *Cos φ* = 0.99 and a voltage of 220 V, as measured by the instrumentation. This indicates that resistive loads do not significantly affect the power factor. However, when an inductive load of 1.7 H was introduced, the power factor decreased to *Cos φ* = 0.71, accompanied by a voltage drop to 194 V. Upon rotating the dimmer to 81.8%, *Cos φ* improved to 0.86 with a voltage of 213 V, as shown in Table 7. Subsequent testing was conducted with an inductive load value of *L* = 6.8. However, further increases in *L* caused the generator to become unstable, limiting the scope of testing to this value.

To validate the improvement in Cos φ, calculations were performed for the active power before and after correction. Initially, the system operated with a power factor of 0.49, which increased to 0.78 after correction. As a result, the active power also showed a significant improvement, increasing from 16.98 W to 33.59 W. This enhancement indicates a more efficient utilization of electrical energy, reducing losses and optimizing power delivery.

The increase in active power confirms the effectiveness of power factor correction using a dimmer-controlled capacitor bank. The improved power factor not only reduces the reactive power component but also enhances the overall performance of the electrical system. These findings reinforce the importance of dynamic power factor correction in achieving energy efficiency and cost savings in various applications.

Table 7. Calculation of active power using a dimmer

R (Ω)	Cos φ (β)	Cos φ (α)	V (β)	V (α)	P (β)	P (α)
920	0.99	0.99	220 V	220 V	52.08 W	52.08 W
	0.71	0.86	194 V	213 V	29.05 W	40.93 W
	0.49	0.78	179 V	208 V	17.07 W	40.44 W
	0.38	0.73	167 V	203 V	16.98 W	33.59 W
	0.32	0.68	155 V	200 V	14.36 W	32.61 W

The analysis of reactive power before and after power factor correction reveals significant improvements in system efficiency. Initially, the system operated with a power factor of 0.56, leading to high reactive power losses. The measured reactive power before correction was 25.18VAR, with a corresponding current of 0.182A and a voltage of 167V. After implementing the dimmer-controlled capacitor bank, the power factor improved to 0.75, reducing reactive power to 29.67VAR.

This enhancement was accompanied by an increase in current to 0.221A and voltage to 203V, indicating better power utilization.

The contribution of the capacitor in mitigating reactive power was also evaluated. The capacitive reactance (Xc) was determined to be 330.35Ω, allowing the capacitor to supply 124.74VAR of reactive power compensation. The calculated capacitance value required for this correction was approximately 9.163μF. These findings confirm that the dimmer-controlled capacitor bank effectively optimizes power factor correction by dynamically adjusting capacitance, reducing reactive power losses, and improving overall system performance.

The results highlight the advantages of using a dynamic correction method compared to fixed capacitor banks. By adapting to varying load conditions, the system prevents overcompensation and maintains stability. This approach ensures higher energy efficiency and reduces operational costs, making it a practical solution for both residential and industrial applications.

This study successfully demonstrates that a dimmer-controlled capacitor bank significantly improves the power factor of an electrical system. The experimental results indicate an improvement from an initial power factor of 0.55 to 0.85, confirming the effectiveness of this method in optimizing energy utilization. The reduction in reactive power from 56.198VAR to 33.773VAR further supports this conclusion, as it leads to lower power losses and increased efficiency.

Additionally, the increase in active power, from 16.98W to 33.59W, highlights the improved power utilization achieved through power factor correction. These findings validate the role of dynamically adjusted capacitors in enhancing system performance, ensuring that electrical energy is used more efficiently, and reducing the strain on power distribution networks.

The key contribution of this study lies in the integration of dimmer-controlled capacitors as an adaptive approach to power factor correction. Unlike conventional capacitor banks that rely on fixed capacitance values, this system allows real-time adjustment based on load conditions. This capability prevents overcompensation, maintains voltage stability, and improves overall system efficiency.

Moreover, this research provides a practical solution for both residential and industrial applications, where maintaining a high-power factor is crucial for reducing electricity costs and prolonging the lifespan of electrical equipment. By dynamically managing reactive power, this system can be used to optimize energy distribution in a variety of settings, including smart grids and automated industrial environments.

This study aligns with previous research on power factor correction using capacitors, such as the work of Dani (2018) [1] on reactive power compensation and Rezaei et al. (2022) [2] on multilevel inverters for improving energy efficiency. While these studies focus on static capacitor banks and hybrid correction methods, our research introduces a more flexible and responsive approach using dimmers.

Additionally, the findings support those of Sadiq (2025) [5], which emphasized the importance of capacitor banks in reducing voltage drops and optimizing energy consumption. By introducing dimmer-based control, this study expands on previous methodologies, providing a dynamic alternative to traditional power factor correction systems.

The results align with recent advances in microcontroller-based power factor correction systems. Kurniawan (2022) [21] developed an automatic PFC system using Arduino Mega 2560 with HMI SCADA interface, achieving power factor improvement from 0.39 to 0.88 on inductive loads while significantly reducing operating current through relay-controlled capacitor bank switching. Similarly, recent research by Utomo et al. (2024) [22] demonstrated an automatic APFC system capable of improving power factor from 0.38 to 0.99 with significant energy efficiency optimization for cumulative loads. However, these approaches require complex programming and digital control algorithms, whereas the analog dimmer method presented in this study offers simpler implementation with comparable effectiveness.

While this study has demonstrated the effectiveness of dimmer-controlled capacitors, further research is needed to refine and expand the system's capabilities. Future work could focus on integrating Internet of Things (IoT) and artificial intelligence (AI) technologies to enable smart algorithms that automatically adjust capacitance in real-time based on load variations. Additionally, testing the system on larger-scale industrial loads would provide insight into its scalability and performance under high-power conditions. Another important area of study is analyzing the impact of dimmer-controlled capacitors on harmonic distortion within power systems, ensuring that this method does not introduce unwanted electrical noise. Moreover, combining this approach with other correction techniques, such as active filters, could further enhance system efficiency and power quality. By addressing these areas, future research can contribute to the development of more intelligent, adaptive, and efficient power factor correction systems that meet the evolving needs of modern electrical grids.

4 Conclusion

Based on the design, manufacturing, testing of dimmers, and subsequent analytical calculations, several important conclusions can be drawn. Firstly, systems with lower power factors require greater efforts for improvement, emphasizing the critical need to address power factor issues in low-efficiency systems. The study demonstrated that power factor improvement can be effectively achieved through the integration of capacitors, as this approach resulted in noticeable increases in both system voltage and active power. Additionally, the dimmers developed in this research successfully enhanced the power factor from 0.55 to 0.85 by utilizing capacitors with capacitance values ranging from 2.5μF to 15μF, showcasing their capability to optimize system performance. While the current study was limited to a maximum capacitance of 15μF, future research should explore higher capacitance values (20-50μF) to achieve power factors approaching unity for industrial applications. Additionally, investigation into larger-scale loads, harmonic analysis, and integration with smart grid systems would further validate and enhance the practical applicability of this dimmer-controlled power factor correction approach.

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