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Arduino-Based Capacitor Bank Automation for Power Factor Optimization

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ABSTRACT

Electrical energy efficiency in PLN customers in the R1 category is a crucial issue due to the low value of the power factor (cos φ), which is caused by the dominance of the use of inductive equipment. This condition not only causes significant energy waste but also puts a strain on the power grid, where the urgency is amplified by various economic factors. This resaerch designed an automatic capacitor bank system to dynamically correct the power factor. By integrating the Arduino Nano microcontroller and the PZEM-004T sensor, the system monitors electrical parameters such as voltage, current, and cos φ in real-time. Based on this data, the system autonomously activates the relay to connect capacitors with the most optimal capacitance value to compensate for reactive power precisely. Its main innovation is an adaptive automation mechanism that is able to respond to load fluctuations. The implementation aims to increase the cost value φ close to 1.0, so that it has great potential to reduce power losses, reduce electricity bills, and improve the overall efficiency of the electrical system.

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1. INTRODUCTION

Electrical energy efficiency is a critical concern for households, and the power factor (cos φ) serves as a key performance indicator [1]. A low power factor, typically below the 0.85 standard set by PLN (Perusahaan Listrik Negara), indicates a high consumption of reactive energy. This type of energy doesn't perform any useful work, such as powering an appliance, but it still puts a strain on the electrical grid and adds to a consumer's electricity bill.1 The main culprits are inductive appliances like air conditioners, water pumps, and refrigerators, which are common sources of wasted energy and inefficiency in residential electrical systems [2].

The most effective technical solution to this issue is the installation of a capacitor bank. A capacitor bank acts as a local source of reactive power, offsetting the inductive loads of household equipment.2 This reduces the amount of reactive power that the main grid needs to supply, leading to a decrease in the total current.3 As a result, power losses are minimized, and the power factor can be corrected to a value closer to the ideal of 1 [3]. Implementing this solution for R1 PLN customers, who represent a significant portion of the nation's energy consumers, has the potential to bring about widespread energy savings and system optimization.

The need to adopt this energy-saving solution is becoming more urgent due to increasing economic pressures on households. Several factors, such as the planned increase in the Value Added Tax (VAT)

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to 12% in 2025 [4], the significant weakening of the rupiah against the US dollar [5], and the downward trend of the Composite Stock Price Index (JCI), all signal a challenging national economic outlook. These conditions will directly and indirectly increase household expenses, making electricity consumption efficiency a highly relevant strategy for easing financial burdens.

While the concept of using capacitor banks is not new, existing research and systems have limitations. Previous solutions were often manual, requiring users to activate capacitors with static values that were only suited for a specific load. This method is impractical and ineffective for households, where electrical loads fluctuate significantly throughout the day [6].

This research introduces an innovative solution: an automatic and adaptive capacitor bank system. The system's core is an Arduino Nano microcontroller, which is integrated with a PZEM-004T sensor. This sensor continuously monitors crucial electrical parameters in real-time, including voltage, current, and the power factor.4 Based on this live data, the system intelligently controls relays to connect or disconnect capacitors with the most appropriate capacitance values to match the current load.

The primary objective of this research is to thoroughly analyze the impact of an automatic capacitor bank on power factor improvement and energy efficiency in R1 PLN customer installations. The research will compare electrical conditions before and after the system's installation to measure its effectiveness.

In addition to technical performance, the research will also evaluate the economic benefits. This includes quantifying the reduction in electricity bill costs that result from improved efficiency.

The findings of this research are expected to provide concrete evidence and a solid technical foundation for implementing a practical and affordable energy-saving solution for households. This will empower consumers to take control of their electricity usage and manage their household finances more effectively.

2. RESEARCH METHOD

2.1. System Design

The hardware structure of this system is built with a modular philosophy, which breaks down its functionality into three main parts that interact with each other: the sensor module, the central control unit, and the actuator device. This separation of functions aims to create a more structured and systematic workflow, thus simplifying the process of designing, developing, and maintaining the system in the future [7].

As a subsystem of data acquisition, the sensor module is in charge of collecting various electrical parameters in real-time. The data obtained becomes crucial input for the control algorithm run by the system. Therefore, these modules must have sensors with a high level of accuracy and the ability to respond to load fluctuations quickly and precisely [8].

To meet these needs, this research relies on the PZEM-004T sensor. This sensor was chosen because of its capable ability to measure voltage, current, power, energy, and power factors simultaneously. In addition, PZEM-004T is known for its high reliability, ease of integration with microcontrollers, and adequate accuracy for power factor optimization applications. The collected data is then sent to the main control unit for further processing.

The core of data processing and decision-making lies in the main control unit implemented using Arduino Nano. This device is responsible for executing a pre-programmed control algorithm, by processing the input data from the sensor module. The Arduino Nano is the top choice thanks to its compact size, power efficiency, and wide compatibility with a wide range of additional components.

The actuator device is the physical executor of this system, consisting of five DC relays that function as electronic switches. These relays dynamically connect capacitor banks of a certain capacity into the electrical system to perform power factor corrections. Each relay is independently controlled by Arduino Nano, based on the results of the data analysis that has been processed.

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For easy monitoring and configuration, the system is equipped with a 20x4 I2C LCD screen as a visual interface. This display presents important parameters such as voltage, current, power factor, total energy, instantaneous power, operating mode, and relay status in real-time. The functional relationships and workflows between these components are visualized in more detail through the system architecture diagram.

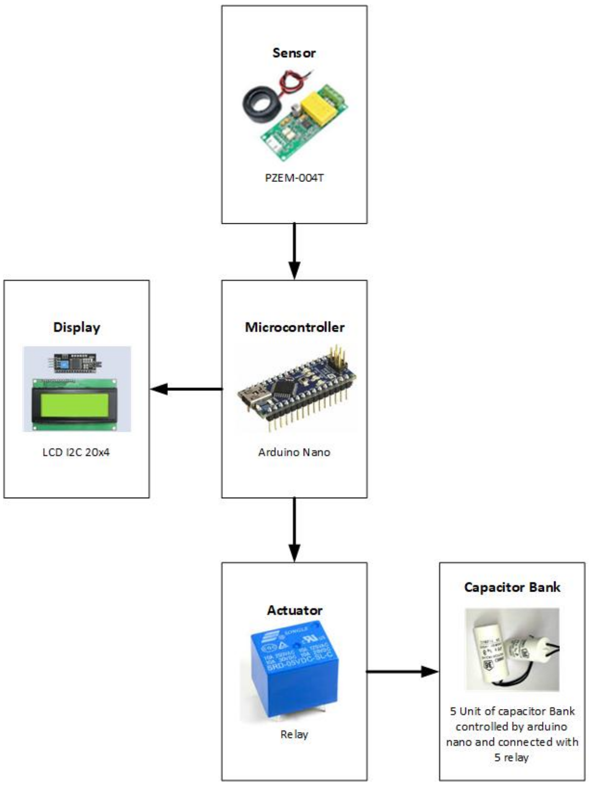

Figure 1. Work System Chart Design

2.2. System Workflow

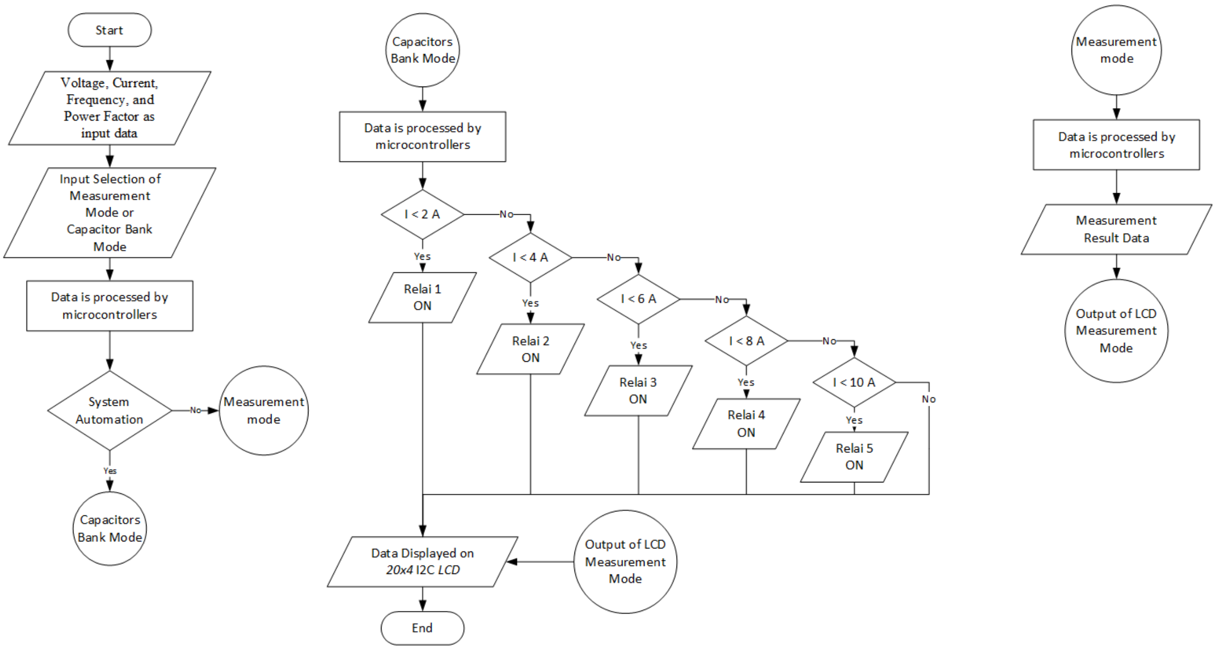

Figure 2. Flowchart diagram of the working system

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Based on the flowchart in Figure 2, the system workflow can be outlined as follows:

1. The process is initiated by a PZEM004T sensor that is in charge of measuring vital electrical parameters such as voltage, current, frequency, and power factors. All data from these measurements is then forwarded to the microcontroller for further processing.
2. Next, users can determine how the system will operate by selecting one of the two modes available through a switch. The options are "measurement mode" which is passive, or "capacitor bank mode" which is active and auto-corrects.
3. The two inputs, namely data from the sensor and the mode selection from the user, are received by the Arduino Nano. The way Arduino processes data is highly dependent on the mode it is on. In "capacitors bank mode", the load current data is the reference for automatically activating the capacitor. This activation occurs gradually whenever the load current increases in multiples of 2 Ampere. In contrast, in "measurement mode", the incoming data is only prepared for display without any further automation process.
4. As a final stage, the execution of the command and the appearance of the results will be different according to the mode. In "capacitors bank mode", after the Arduino Nano processes the current data, it will send a signal through the digital pin to activate the relay. This relay is in charge of connecting capacitors with the appropriate value to the consumer's electrical installation (PLN R1 household). Meanwhile, if the system is in "measurement mode", the processed data will be displayed immediately. In both modes, all information and process results are displayed to the user through the 20x4 I2C LCD screen.

2.3. Calculation of the Capacitors Required to Fit the Needs.

In this research, the determination of the capacitance value needed for household electrical installations with PLN R1 customer calcification requires special calculations. This calculation is important so that the installed capacitor does not become excessive and instead becomes a new capacitive load [9]. For this reason, the calculation is carried out in several stages, starting from the first step:

1. Classify the load.

Classifies loads based on their current value. In this case, a current of 2 Amperes is used as a reference for load classification.

2. Calculating the tan value

Calculating the tan value of the power factor value (cos φ), it can be done using the following formula:

$$\tan(\cos^{-1}\phi) \quad (1)$$

Description:

tan	=	Tan value
$\cos^{-1}\phi$	=	Phasa angle

3. Calculating reactive power

Calculating reactive power can be done with the following formula:

$$Q = V \times I \times \sin\phi \quad (2)$$

Description:

Q = Reactive power (VAR)
V = Voltage (Volt)
I = Current (Ampere)
sin φ = Reactive power angle

Calculating reactive power can also be done with the following formula:

$$Q = P \times \tan\phi \quad (3)$$

Description:

Q = Reactive Power (VAR)
P = Active power (Watt)
tan φ = The tan value of the change result of the φ

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4. Calculate the required power compensation

The reactive power data that has been obtained can then be used to calculate the required power compensation. The calculation of this reactive power compensation ratio can be done using the following formula:

$$Qc = Q_0 - Q_1 \tag{4}$$

Description:

Qc = Reactive force compensation (VAR)
Q_0 = Pre-intervention reactive power (VAR)
Q_1 = Post-intervention reactive power (VAR)

5. Calculating the current flowing through the capacitor (Ic)

Calculating the current flowing through the capacitor (Ic) can be done using the following formula:

$$I_c = \frac{Q_c}{V} \tag{5}$$

Description:

I_C = Current passing through the capacitor (Ampere)
Q_C = Reactive power compensation (VAR)
V = System nominal voltage (Volt)

6. Capacitive reactance (Xc).

The capacitive reactance value (Xc) is used to determine the most appropriate capacitor size in power factor repair using a capacitor bank. The calculation of the value of capacitive reactance can be done using the following formula:

$$X_C = \frac{V}{I_C} \tag{7}$$

Description :

X_C = Capacitive reactance (Ω)
V = System voltage (Volt)
I_C = Current passing through the capacitor (Ampere)

7. Calculate the required capacitor value.

Once the capacitive reactance value is obtained, the next step is to calculate the required capacitor value. This calculation can be done using the following formula:

$$X_C = \frac{1}{2\pi FC} \tag{6}$$

Description :

X_C = Capacitive reactance (Ω)
F = Frequency (Hz)
C = Capacitor value (F)

8. Converting the amount of capacitor value.

It is important to convert the calculated capacitor value into microfarad units (μF). This conversion is necessary because in the Indonesian market, capacitors are generally sold in these standard units. This conversion calculation can be done using the following formula:

$$C(\mu F) = C(F) \times 10^{-6} \tag{8}$$

Description :

C (μF) = Capacitor Values (μF)
C (F) = Capacitor Values (F)
10^6 = Multiplier factors

2.4. Calculation of the Analysis of the Results obtained by the Capacitor bank Automation System

Analysis of the performance of the capacitor bank automation system that has been designed can be carried out through a series of careful calculation stages [10]. First, electrical data that has been collected in real-time—such as voltage, current, and power factors—is the main basis for evaluation. With this data, we can compare the conditions before and after the installation of the device to see the difference quantitatively. A variety of relevant mathematical formulas were applied to this data to

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measure the effectiveness of the system as a whole, including how far the power factor was successfully corrected close to the ideal value of 1 [11]. In addition, the calculation will also include the energy efficiency generated and the potential for electricity cost savings for consumers. Each of these calculation stages is designed to provide a clear and concrete picture of the positive impact of the system on household electrical installations. This whole process will generate powerful data to prove that this solution is not only technical, but also provides significant economic benefits. To analyze the work results of the capacitor bank automation system that has been made before, it can be done in several calculation stages using the following formula:

a. Improvement Results on Power Factor Testing

In calculating the improvement results of power factor testing, pre-intervention data and post-intervention data are needed. The data is obtained from direct measurements using a pre-built system. To analyze the results of improvements in the power factor test in percentage (%) by using the following formula:

$$\text{Result Cos } \varphi \text{ Repair } (\%) = \frac{\text{Cos } \varphi_1 - \text{Cos } \varphi_0}{\text{Cos } \varphi_0} \text{ x } 100\% \quad (9)$$

Description :

$\text{Cos } \varphi_0$ = Power Factor pre-intervention

$\text{Cos } \varphi_1$ = Power Factor post-intervention

From the results of the calculation, data on the percentage (%) of improvement that can be achieved in post-intervention data compared to pre-intervention data is obtained.

b. Improvement Results in Testing Electrical Power Consumption

In calculating the results of electrical power consumption test improvements, pre-intervention data and post-intervention data are needed. The data is obtained from direct measurements using a pre-built system. To analyze the results of improvements in the test of electrical power consumption in percentage (%) by using the following formula:

$$\text{Improvement Result of electrical power comsumption} (\%) = \frac{P_1 - P_0}{P_0} \text{ x } 100\% \quad (10)$$

Description :

P_0 = Electrical Power Consumption pre-intervention

P_1 = Electrical Power Consumption post-intervention

From the results of the calculation, data on the percentage (%) of improvement that can be achieved in post-intervention data compared to pre-intervention data is obtained.

c. Improvement Results in Customer issued electricity cost

In calculating the results of customer issued electricity cost test improvements, pre-intervention data and post-intervention data are needed. The data is obtained from electricity costs paid by customers every month. To analyze the results of customer issued electricity cost in percentage (%) by using the following formula:

$$\text{Improvement Result of customer issued electricity cost} (\%) = \frac{IDR_1 - IDR_0}{IDR_0} \text{ x } 100\% \quad (11)$$

Description :

IDR_0 = Customer issued electricity cost pre-intervention

IDR_1 = Customer issued electricity cost post-intervention

From the results of the calculation, data on the percentage (%) of improvement that can be achieved in post-intervention data compared to pre-intervention data is obtained.

2.5. Data acquisition methodology

Direct measurement methods are also needed to collect data after the device is installed in the customer's household installation for PLN's R1 tariff. Both sets of data are required for analysis of the device's success rate. Each set of data is collected over a 2-month period, specifically 2 months before and 2 months after the installation of the capacitor bank. Data collection is done weekly to observe the effectiveness of the capacitor bank, which uses an automation system to optimize the power factor for each power group, as per the calculations and planning conducted before installation. Data is collected

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from 2 kWh meters installed in 2 different PLN R1 power scopes where data collection is feasible: 900 VA and 1300 VA, simultaneously over a total effective period of 4 months. From these two power ratings, data on the power factor improvement and electrical energy usage are obtained. Using this data, a comparison between the two power ratings is necessary in the data analysis sub-section to confirm the degree of success and error in the research.

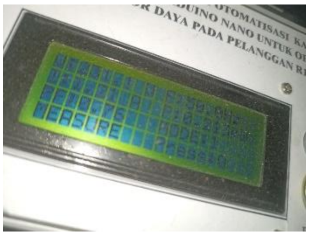
3. RESULTS AND DISCUSSION

Using formulas (1) to (8) and a nominal voltage of 220 Volts, the calculation results are presented in table 1 which contains the following calculation results:

Table 1. Table of calculation results

Current (Ampere)	Cos φ Pre-intervention	Tan φ Pre-intervention	Cos φ Post-intervention	Tan φ Post-intervention	Pre-intervention reactive power (VAR)	Post-intervention reactive power (VAR)	Reactive power compensation (VAR)	Current passing through the capacitor	Capacitive reactance (Ω)	Capacitor value (uF)
2	0.85	0.62	0.95	0.33	231.78	137.39	94.39	0.43	512.74	6.2
4	0.85	0.62	0.95	0.33	463.57	274.78	188.79	0.86	256.37	12.4
6	0.85	0.62	0.95	0.33	695.35	412.17	283.18	1.29	170.91	18.6
8	0.85	0.62	0.95	0.33	927.14	549.5598	377.578	1.72	128.19	24.85
10	0.85	0.62	0.95	0.33	1158.922	689.9498	471.9721	2.145	102.55	31.06

This system is made based on the calculated value of the capacitor. The device operates according to a pre-established working method, using the number of capacitors that have been measured and detailed in the calculation result in table 1. The data collection process in this research began with the installation of a power factor correction system in household electrical installations. Once the system is installed, the electrical parameters are measured in real-time. The PZEM-004T sensor serves as the primary tool for collecting voltage, current, and power factor data. The data obtained is then sent to Arduino Nano, which is in charge of processing the information. The results of this data processing are displayed on a visual interface in the form of a 20x4 LCD screen. This data collection was carried out in two periods: before the intervention (before the system was installed) and after the intervention (after the system was operational). The comparison of data from these two periods aims to analyze the effectiveness of the system that has been installed.


(3.1)

(3.2)

Figure 3.1. Result Pre-Intervention in device 1 and **Figure 3.2.** Result Pre-Intervention in device 2


(4.1)

(4.2)

Figure 4.1. Result Post-Intervention in device 1 and **Figure 4.2.** Result Post-Intervention in device 2

In this research, electrical data was collected from two different conditions. Figures 3.1 and 3.2 present pre-intervention data, which show parameters such as actual power factor, usable power, and

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active relay status via the LCD interface. In contrast, Figures 4.1 and 4.2 show the same data in real time post-intervention has been performed. Regular measurement and recording of data from these two conditions is essential to ensure that the results of the study are valid and accurate. Data were collected through random weekly sampling, which was conducted for two months in the pre-intervention period and two months in the post-intervention period. The data obtained are then presented in Table 2, 3, and 4 below.

Table 2. System Measurement Results for power factor

Num	Weeks	Device 1				Device 2			
		Pre-Intervention		Post-Intervention		Pre-Intervention		Post-Intervention	
		Current (Ampere)	Power Factor	Current (Ampere)	Power Factor	Current (Ampere)	Power Factor	Current (Ampere)	Power Factor
1	First	2.89	0.83	2.43	0.99	1.68	0.81	1.38	0.98
2	Second	2.85	0.83	2.39	0.99	2.67	0.8	2.2	0.96
3	Third	1.17	0.77	0.95	0.95	0.98	0.79	0.73	0.95
4	Fourth	3.12	0.82	2.61	0.98	1.28	0.78	1.03	0.9
5	Fifth	0.96	0.82	0.8	0.98	1.57	0.79	1.4	0.95
6	Sixth	2.75	0.75	2.22	0.93	1.08	0.8	0.87	0.94
7	Seventh	3.22	0.81	2.66	0.98	1.35	0.81	1.12	0.97
8	Eighth	2.99	0.82	2.48	0.99	1.32	0.79	1.05	0.91

Table 3. System Measurement Results for Electrical Power Consumption

Num	Weeks	Device 1 (kWh)		Device 2 (kWh)	
		Pre-Intervention	Post-Intervention	Pre-Intervention	Post-Intervention
1	First	31.8	26.2985	78	72
2	Second	29.6	24.4856	79	73
3	Third	30.5	25.1267	65	62
4	Fourth	29.2	24.2356	93	88
5	Fifth	26.9	20.1534	80	74
6	Sixth	27.9	22.4587	78	73
7	Seventh	27.6	21.8675	75	70
8	Eighth	27.4	21.6574	66	62
Sum of kWh		230.9	186.2834	614	574

Table 4. System Measurement Results for Customer-Issued Electricity Costs

Num	Months	Device 1		Device 2	
		Pre-Intervention (Rp)	Post-Intervention (Rp)	Pre-Intervention (Rp)	Post-Intervention (Rp)
1	First	100000	75000	500.589	468.806
2	Second	90000	65000	475.162	443.378

Using formulas (9), (10), and (11) for data analysis, it can be done and presented for each type of data in the following analysis results table 5 and 6 below:

Table 5. Results Analysis of power factors and electrical power consumption data

Num	Weeks	Result Cos φ Repair (%)		Improvement Result of Electrical Power Cosumption (%)	
		Device 1	Device 2	Device 1	Device 2
1	First	19.28	20.99	20.92	8.3333333
2	Second	19.28	20	20.89	8.2191781
3	Third	23.38	20.25	21.39	4.8387097
4	Fourth	19.51	15.39	20.48	5.6818182
5	Fifth	19.51	20.26	33.48	8.1081081
6	Sixth	24	17.5	24.23	6.8493151
7	Seventh	20.99	19.75	26.22	7.1428571
8	Eighth	20.73	15.1898	26.52	6.4516129

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Table 6. Results Analysis of Customer Issued Electricity Cost

Num	Months	Improvement Result of Customer Issued Electricity Cost (%)	
		Device 1	Device 2
1	First	33.3333333	6.7795634
2	Second	38.4615385	7.1686011

The analysis was also strengthened by validation and reliability tests carried out with the help of SPSS software whose results were presented as follows:

Table 7. Results of Validation and Reliability Test Analysis using SPSS software

Power Factor Validation Test Results		Electrical Power Cosumption Validation Test Results		Customer-Issued Electricity Costs Validation Test Results	
Device 1	**Device 2**	**Device 1**	**Device 2**	**Device 1**	**Device 2**
0.986	0.849	0.976	0.995	1.000	1.000
Power Factor Reliability Test Results		**Electrical Power Cosumption Reliability Test Results**		**Customer-Issued Electricity Costs Reliability Test Results**	
Device 1	**Device 2**	**Device 1**	**Device 2**	**Device 1**	**Device 2**
0.970	0.839	0.996	0.979	1.000	1.000

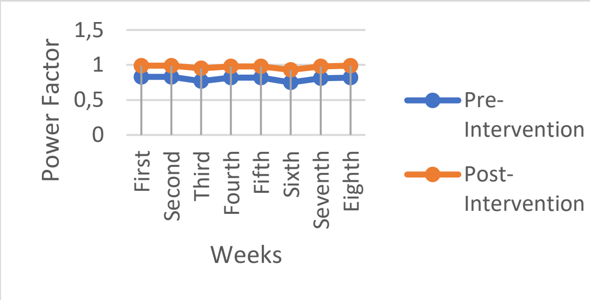

Figure 5. System Measurement Results for power factor in Device 1

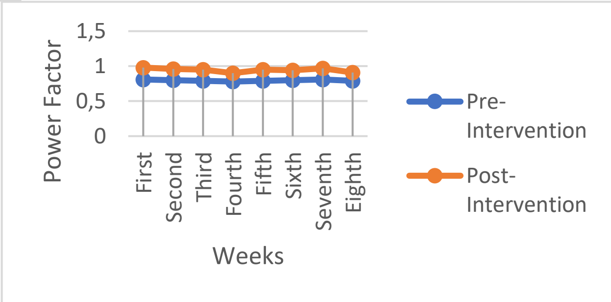

Figure 6. System Measurement Results for power factor in Device 2

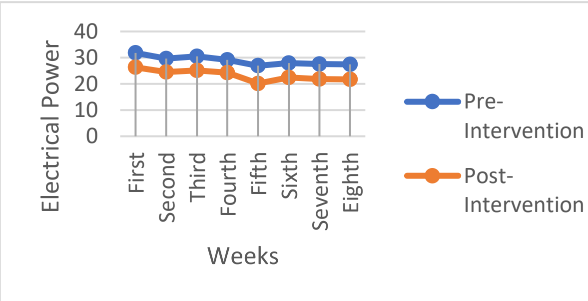

Figure 7. System Measurement Results for Electrical Power Consumption in Device 1

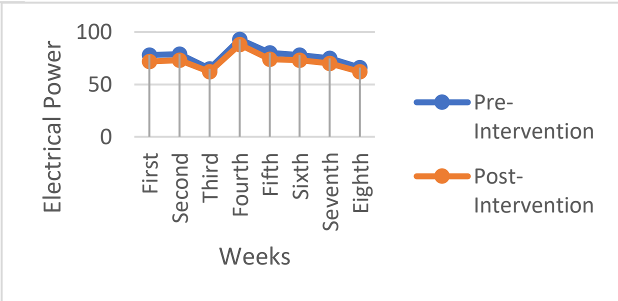

Figure 8. System Measurement Results for Electrical Power Consumption in Device 2

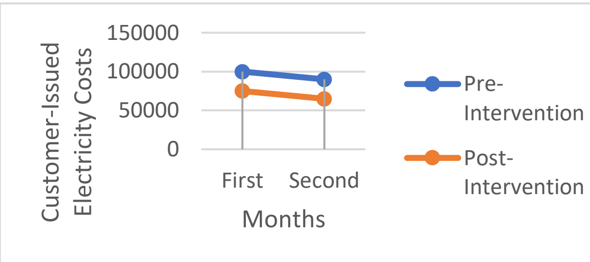

Figure 9. System Measurement Results for Customer-Issued Electricity Costs in Device 1

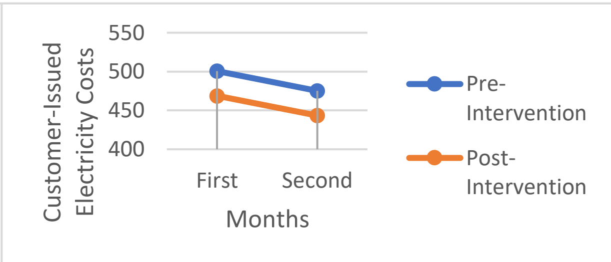

Figure 10. System Measurement Results for Customer-Issued Electricity Costs in Device 2

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4. CONCLUSION

This research successfully designed and implemented an effective capacitor bank automation system for the improvement of power factors in household electrical installations.

1. Increased Power Factor (Cos φ). The system successfully significantly increased the power factor from an average of 0.75-0.83 in pre-intervention conditions to 0.9-0.99 in post-intervention conditions. This proves that the system is capable of correcting the power factor close to the ideal value of 1.0.
2. Savings in Electrical Power Consumption (kWh). There is a significant decrease in electrical power consumption after the system is installed. This is shown by a decrease in average kWh consumption by 20-30% in Device 1 and 5-8% in Device 2.
3. Economic Benefits. Improved energy efficiency directly results in savings in electricity costs for consumers. The analysis showed that electricity costs decreased by an average of 35% in Device 1 and about 7% in Device 2.
4. Validity and Reliability. Validation and reliability testing using SPSS software confirms the reliability of the data. All validation and reliability values are above acceptable thresholds (above 0.8), with most approaching 1.0. This shows that the results of the measurement and analysis of the data have high validity and consistency, reinforcing the research findings that these systems work effectively and reliably. The varying success between Device 1 and Device 2 can be attributed to the difference in electrical load characteristics and usage profiles in each household.

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